Optimization models and solution methods for intermodal transportation

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Publication date:
2005

Document Version
Publisher's PDF, also known as Version of record

REPORT 2005-3

Optimization models and solution methods for intermodal transportation

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DTU

Optimization models and solution methods for intermodal transportation

PhD thesis

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Sponsored by:

The virtual Centre for Logistics and Freight Transport (CLG)

and

Atkins Denmark a/s

ATKINS

Subject: Intermodal Transportation
Operations Research
Optimization models
Tabu Search
Scheduling and timetabling

This Report has been published by:
Centre for Traffic and Transport
Technical University of Denmark

Report 2005-3

Published in 30 copies.

The report may be purchased from the
Centre for Traffic and Transport (CTT)
Bygningstorvet, Building 115
Technical University of Denmark
DK-2800 Kongens Lyngby

Att: Bente Svensson,
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The price is DKK 250,00 + tax + postage

ISSN-1600-1575
ISBN-87-91137-17-9

Foreword

This PhD was written in the period 1st of May 2002 to 15th of August 2005 at the Centre for Traffic and Transport at the Technical University of Denmark. The PhD was part of the virtual centre for logistics and freight transport (CLG) project and was funded partly by CLG and partly through employment at Atkins Denmark in the period 1st of June 2002 and 31st of May 2005.

The work presented in this thesis has been made in many parts of the world and in various alternative locations. Apart from the “normal” or expected location such as at CTT and Atkins in Denmark and the CRT in Montreal, a significant part of the work has been done in various alternative locations. To name some of the more peculiar ones: the airports in Copenhagen, Brussels, and Montreal, over the Atlantic on different airplanes, the Second Cup on Parc st. and Milton st. and the Starbucks on Mansfield st. and Sherbrooke st. in Montreal.

I would first of all like to give my biggest thanks to my supervisor Oli B.G. Madsen for his support and guidance throughout my PhD. Oli has been a fantastic coach throughout the project and showed faith and confidence in my ability to finish this project and was the main reason for not quitting half way through.

I would like to send a special thank to everything that gave me the favourable financial conditions to participate in conferences and visiting the C.R.T. at the University of Montreal several times. The acknowledgement is directed at the CLG project, Atkins Denmark and CEO Preben Olesen in particular, the ‘Reinholdt W. Jorck og hustru’ foundation, and the ‘Vera og Carl Johan Michaelsen’ foundation.

Visiting professor Teodor Crainic at the C.R.T has been the main source of academic influence in this PhD. I would like to thank him many times for accepting me at the CRT and assisting me in the development of my PhD which has resulted in two of the papers included.

My colleagues at Atkins and CTT have also provided invaluable support. First I would like to thank Leise Janssen (previously CTT) for our cooperation in our Master thesis and Otto A. Nielsen which eventually led to the 1st paper included in this thesis. Furthermore, in no particular order, I would like to thank Rene Munk Jørgensen from CTT, Steen Hansen from Atkins, and Morten Brok previously from Atkins.

Three years is a long period of time at any age. A lot of things have happened during that time, and I would like to thank the following persons for being around; my lovely girlfriend Mette, Jens Pontoppidan, Carsten Vinternes, and David Jacoby from Denmark, and Jean-Michel Sotiron, Jean-Phillipe Guguy, Max Descoteaux, and Moira Warner from Montreal.

Copenhagen, August 19th 2005,

Resume

Denne Ph.d.-afhandling er sammensat af tre artikler, som forholder sig tre forskellige problemstillinger inden for intermodal transport, og en sammenfatning. Sammenfatningen introducerer generelle problemstillinger, der opleves inden for intermodal transport og sammenkæder de tre artikler.

Sammenfatningen starter med at introducere miljø- og trængselsproblemerne, som ses inden for transportsektoren i Europa, og forklarer hvorfor EU anser genetableringen af jernbanesektoren, som strategisk transportmiddel i den intermodale transport, som løsningen på problemerne. Sammenfatningen fortsætter med eksempler på afsluttede, igangværende og fremtidige tiltag, med formålet at forbedre forholdende for intermodal transport. Sammenfatningen tager dernæst udgangspunkt i de succesfulde rejseplaner anvendt inden for kollektiv trafik og introducerer et konceptuelt grundlag for en godsrejseplan. Det forklares hvorfor en sådan godsrejseplan med fordel kunne anvendes i transportsektoren og introducerer de barrierer, som det kan forventes der opstår ved en eventuel implementering. Sammenfatningen fortsætter derefter med at diskutere mere avancerede problemstillinger inden for planlægning af intermodal transport, med særligt fokus på køreplanlægning, og opsummerer indholdet af de tre artikler.

Den første artikel præsenterer en matematisk model til optimering af køreplaner i kollektive trafik med henblik på at minimere skiftetider for passagerer. Ved at indføre en tidsværdiomkostning søger modellen at minimere summen af tidsværdiomkostningen for passagerernes skiftetider mellem de kollektive trafikruter. Modellen løses ved en heuristik baseret på tabusøgning og er anvendt i HUR's kollektiv trafiknetværk. Resultanterne illustrerer, at der er et potentiale i at anvende optimeringsmetoder i planlægningen af køreplanerne til at minimere skiftetiderne i den kollektive trafik. Resultanterne peger på, at skiftetiderne vil kunne reduceres med hvad der svarer til 30 millioner kroner målt i tidsværdiomkostninger.

Den anden artikel præsenterer en matematisk model til at bestemme køreplaner for intermodale godstog i en europæisk sammenhæng. Det antages, at køreplanlægningen skal foretages på en jernbaneinfrastruktur opdelt i togkanaler, som er ved at blive almen praksis på det europæiske jernbanenetværk. Derudover medtager modellen terminaloperationer på et aggregeret niveau for at fange omlastningsomkostningerne i godsterminaler. Endelig introducerer modellen en tidsværdiomkostning for gods. Denne tidsværdiomkostning kan anvendes til at vurdere betydningen mellem operationelle omkostninger og transittid. Dvs., at en lav tidsværdiomkostning vil medføre lavere operationelle omkostninger og høje transittider, mens en høj tidsværdiomkostning vil medføre højere operationelle omkostninger med kortere transittider til følge. Modellen viser hermed, at den vil kunne anvendes som beslutningsstøtteværktøj af intermodale godstogsoperatører til vurdering af balancen mellem kundeservice (her opfattet som transittid) og operationelle omkostninger. Modellen løses ved hjælp af Xpress-MPs heltalsløser, som ikke overraskende viser sig ikke at være velegnet til at løse problemet pga. dets store kompleksitet.

Den tredje artikel præsenterer en løsningsalgoritme baseret på tabusøgnings til at løse et netværksdesignproblem med faste omkostninger, kapacitetsbegrænsninger, flow af flere varer og balancebegrænsninger i knuder på kantvalg. Uden balancebegrænsningerne er modellen en standard netværksdesignmodel (også kaldt CMND), men balancebegrænsningerne tilføjer et nyt element til modellen som kræver at antallet af åbne kanter ind i en knude er lig med antallet af åbne kanter ud af knude. Det nye sæt begrænsninger er udledt fra modellen præsenteret i den anden artikel medtaget i denne Ph.d. afhandling, og den nye model (kaldet DBCMND) danner basis for en generaliseret model med henblik på at udvikle effektive løsningsalgoritmer til modeller med lignende begrænsninger. Løsningsmetoden er afprøvet på netværksdesignproblemer tidligere anvendt til løsningsalgoritmetest i litteraturen, og resultaterne sammenlignes med resultater opnået ved at anvende Xpress-MPs heltalsløser på problemerne. Resultaterne viser at løsningsalgoritmen generer gode løsninger til DBCMND-modellen og, at den er anvendelig på store problemstillinger. Løsningsalgoritmen kan dermed anvendes som byggesten til at udvikle løsningsmetoder til netværksdesignproblemer med balancebegrænsninger, som kan anvendes til køreplanlægning inden for transportsektoren.

Abstract

This thesis is composed of three papers each dealing with different aspects in optimization of intermodal transportation and a summary introducing the perceived issues within intermodal transportation and placing the three papers into context.

The summary starts by introducing the congestion and environmental problems seen in transportation in Europe and why the European Union sees the reestablishment of the rail sector in an intermodal setting as the solution to the problems. The summary continues by illustrating some of the measures and initiatives that are taken to improve intermodal transportation. The summary presents the concepts behind developing a freight route planner similar to route planners seen in public transit and discusses how that could be beneficial to the transportation sector as a whole while presenting some of the barriers that may be expected in case of implementation. The summary continues into discussing more advanced methods for planning intermodal transportation with scheduling of transportation services as the main focus and gives pointers to the three papers.

The first paper present a mathematical programming model to determine optimal timetables for public transit systems with respect to passenger transfer waiting time. By adopting a value of time cost the model opts to minimize the total sum of the transfer waiting time cost for transferring passengers between public transit routes. The model is solved using a Tabu search heuristic on a large scale network instance taken from the public transit system of the greater Copenhagen area. The results show that there is a potential benefit for passengers in applying models for transfer optimization. The savings in transfer waiting time for passengers may account for as much as 4 million € a year expressed in value of time cost.

The second paper presents a mathematical programming model to determine intermodal freight train schedules in a European setting. By the latter is meant that trains are assumed to run on an infrastructure divided into train paths as is becoming common practice in European railways. Furthermore the model includes terminal operations on an aggregated level to capture the transfer costs at terminals. Finally, the model introduces a value of time cost for freight. The level of the value of time determines the trade-off between operational cost of trains and the total transit time, i.e. a low value of time cost means low operational cost and high transit times, while a high value of time means higher operational costs and lower transit times. The model shows that it can be used as a decision support system for intermodal train carriers to determine their trade-off between customer service (in form of transit time) and operational cost. The model is solved using Xpress-MP's mixed-integer programming solver which not surprisingly due to the complexity of the model did not prove to be an efficient solution method.

The third paper presents a Tabu-search based algorithmic framework to solve a modified version of the fixed-charged capacitated multi-commodity network design model (CMND). The modification is derived from the model presented in the second paper where vehicle balance constraints are added in nodes. The constraints add a restriction on the design arcs requiring that the number of open arcs entering a node must be equal to the number of arcs leaving a node. These constraints are dubbed design balance constraints and are added as a new set of constraints to the CMND model resulting in a model denoted the design balanced capacitated multi-commodity network design model (DBCMND). The new set of design balance constraints prevents the use of existing solution methods developed for the CMND model and thus requires a new algorithmic framework. The Tabu search framework presented in the paper offers a solution method to solve the DBCMND model. The algorithm is tested on previously used network design instances in the literature and the computational results are compared to results achieved using Xpress-MP’s mixed integer programming solver. The results show that the algorithm produces good solutions to the DBCMND model and that it is applicable to large-scale instances. The algorithmic framework thus creates a starting point to create solution methods network design models with design balance constraints that can be applied to scheduling problems in transportation.

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1. Introduction – what is intermodal transportation… and why?

In the introduction to Ben Elton's fiction book 'Gridlock' from 1992, a group of Brainian television researches from the Planet Brain have assimilated everything about humanity "in only a quarter, of a quarter, of a single second"… except for one human activity; transportation. The book continues, "The Brainians could see long, thin arteries along which the humans travelled. They noted that after sunrise the humans all travelled one way and at sunset they all travelled the other. They could see that progress was slow and congested along these arteries, that there were endless blockages, queues, bottle-necks and delays causing untold frustration and inefficiency". When confronted with the facts the Brainian TV-producer states "You're trying to tell me that they're all going the same direction, travelling to much the same destinations and yet they're all deliberately impending the progress of each other by covering six square meters of space with a large, almost empty tin box?" and continues "A society sufficiently sophisticated to produce the internal combustion engine has not had the sophistication to develop cheap and efficient public transport?".

The real situation of transportation is not as bleak as depicted by the Brainians in 'Gridlock'. Nevertheless it does address some of the problematic issues in transportation. First of all, congestion is an important issue. It is not only seen in urban transportation, but also to a large extent in intercity transportation, both passenger and freight. Second, given the large amount of congestion, it is impressive that people still obstinate driving alone in cars or send small freight loads by truck, when it should be possible to consolidate the transportation effort onto efficient means of transportation. The easy explanation to these issues must be that the current transportation practice is the most effective. So why are there no better alternatives to car and truck transportation as seen today?

The answer to that question has several facets. The political structure of the transportation sector, the available transportation infrastructure, the organization of transportation businesses, the education of the work force in the transportation sector, the planning methods, and the available technology all affect how decision are taken in the transportation sector.

1.1. Defining intermodal transportation

Before being able to give any reasonable indication to answer the question presented in the previous section it is necessary to define clearly what is meant by better transportation alternatives. In the European Union's white paper of 2001 on its transportation policy for 2010 ([White paper 2001]) emphasis is put on promoting intermodal transportation as the solution to the problems seen in the transportation business.

Intermodal transportation can be interpreted in several ways. Nevertheless, the literal meaning is transportation using several modes of transportation in the same trip. Intermodal and multimodal transportation are often used as synonyms although the words are not entirely interchangeable. Multimodal transportation means transportation using several modes, but in its definition does not require any interoperability between modes. For example one can plan multimodal transportation for a region which does not mean the modes need to interact on individual transportation tasks. Intermodal transportation on the other hand refers to performing a transportation task by interaction of several modes of transportation including the transfer between the modes.

The reason why this distinction is made here is because the transfer between modes is an important factor in intermodal transportation. The purpose of transportation is moving commodities (passengers or freight) between their origins and destinations possibly within a time limit. The time spent making transfers is therefore a part of the transportation journey where no physical distance is covered. However, a significant amount of time is spent on performing the transfer eventually increasing the transportation time. It is intuitive that a direct transport between a commodity's origin and its destination is faster than a transport journey combining and transferring between several modes. Obviously this stipulation is only valid for comparable choices assuming similar transit times. The cost of performing a transfer is also important. The facilities needed to make transfers are significant. Examples of these are container terminals, rail yards, and airports. These facilities all have equipment that all require large capital investments and incur significant terminal operation costs. The increased time and cost of transportation with transfers is a nuisance that make it less attractive.

Although the literal meaning of intermodal transportation is transportation where several modes of transport are used sequentially with transfers to perform a transportation task, the word has some implicit associations to it. It is generally assumed when talking about intermodal transportation that freight is consolidated. The advantage of consolidating freight is achieving economies of scale by transporting commodities in large quantities using a single transport. This can be illustrated using several examples. Intercontinental container traffic is a prime example. Container ships are getting larger and larger, and although their operating costs are increasing, the cost per container decreases. Similarly, airplanes for passenger transportation have gotten larger since the introduction of air transportation culminating recently with the Airbus A380. Rail transportation was basically invented to be able to transport large quantities of commodities across land. Finally even in road transportation the Australian road trains, with trucks over 50 meters long, are an example of consolidating freight. Intermodal transportation is not a synonym to consolidated transportation, nevertheless, to overcome the negative effect from performing the time and cost consuming transfer operations, commodities are commonly consolidated to achieve the economies of scale.

To benefit from the economies of scale of consolidating freight, intermodal transportation systems are often designed in a network structure. Most commonly a hub-and-spoke system is adopted. This is true for large intercontinental airlines where one (or a few) airport functions as a central hub. Similarly for intercontinental container transportation a few big ports on different continents are connected by major sailing routes (deep-sea shipping). To connect smaller ports and airports to the big hubs, feeder traffic routes are adopted (also referred to as commuter flights and short-sea shipping). These are often smaller ships or planes whose sole purpose is to bring commodities from their origins and to their destination on shorter travel distances from hubs. In intercontinental container traffic, trains are also used to bring freight from the hinterland to the container port and thus function as feeder routes. It is not hard to imagine that planning a network structure including transfers is harder than planning direct transportation. There are issues concerning hub-locations, feeder system and main-line routing, commodity routing, consolidation policies, and fleet acquisition and management. Often these networks operate on schedules. This is the case for intercontinental container transportation, trains in Europe, and airlines. Using schedule-based transportation removes a significant degree of flexibility from the user. A direct transportation can be planned for whenever needed, i.e. when the commodity is ready or available. In a schedule based system the commodity will have to wait until a service departs allowing it to leave its point of origin. In an intermodal system, or any kind of transportation system where transfers are made, there can furthermore be waiting time at transfer points from the arrival of a service until a departure on another service.

Operating scheduled transportation systems where freight is consolidated and is transferred between services and possibly different modes is therefore not an easy task. For certain areas of the transportation sector it is the only possible choice and is therefore widely adopted. This is true for intercontinental container shipping, where no other alternatives are possible and for passenger air transportation (especially medium and long distance) where the short transit time of the individual services practically renders all other alternatives unattractive. However, for other areas, where there are direct transportation choices available, it is not difficult to see why this option is favoured. This is the case for public transportation, both urban and intercity, where the alternative is car, and for intermodal rail transportation in Europe where the alternative is long-haul trucking. For both of these examples the direct transportation alternatives have similar transportation times.

To summarize the definition of intermodal transportation used in this thesis assumes that commodities (freight or passengers) are consolidated and transportation services are scheduled. Furthermore, the thesis does not deal with intercontinental traffic such as container shipping and does not deal with airline transportation in particular. The area of interest is the struggling intermodal systems of intermodal rail freight and urban public transit where massive competition is seen from respectively long-haul trucking and private car transit.

1.2. Why is intermodal transportation the solution?

The definition and complexity issues presented in the previous section gives plenty of reasons to why intermodal transportation is hard to manage, but no reason as to why it is a potential solution to the problems in the transportation business. And what are the problems the transportation sector is facing?

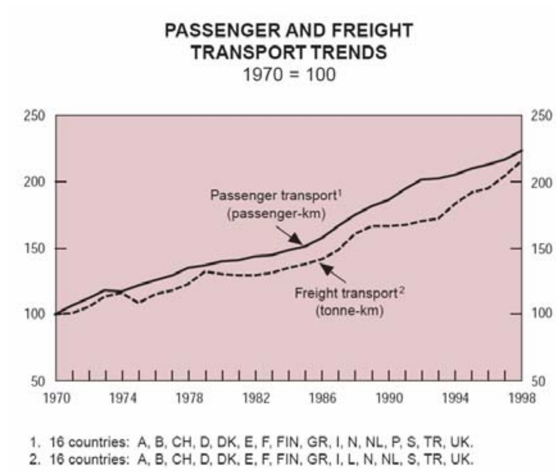

Figure 1. Development of passenger and freight traffic in the EU 1970-1998 (1970 = index 100)

A very common media buzz-word is globalization. Globalization affects transportation demand and creates transportation over greater distances while efficient transportation over greater distances makes globalization possible, thus together creating an upward spiral. Currently the transportation sector generates over 10% of the European Union's GDP and employs over 10 million people. An interesting trend to observe is the development in transportation demand freight and passenger transportation. Figure 1 shows the development in freight and passenger transportation in the European Union since 1970 (from [ECMT 2000]). With 1970 representing index 100 both freight and passenger transportation has risen to above index 200 effectively more than doubling the passenger-km and tonne-km in the 28 years. However, the modal split, the distribution of transportation demand amongst modes, has not remained constant. Figures 2 and 3 shows the growth in traffic by mode for passenger and freight transportation respectively.

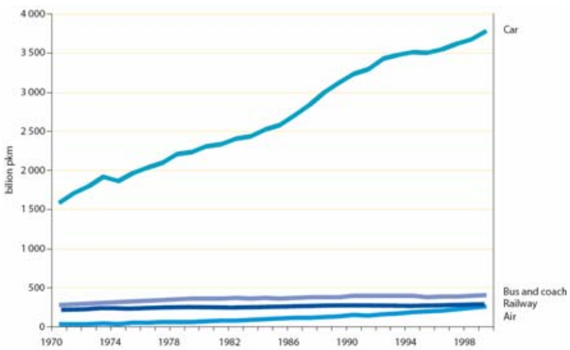

Figure 2 – Growth in passenger traffic by mode 1970-1998

As can be seen in figures 2 car transportation has absorbed most of the increase in passenger traffic. From figure 3 it can be seen that for freight transportation, short-sea shipping and road-haulage have increased, while rail actually has had slight decline. In total, road transportation accounted for 79% of passenger transportation and 44% of freight transportation in 1998. More noticeably the total passenger-km of road transportation (figure 2) and the total freight tonnage of road transportation (figure 3) have approximately doubled and tripled respectively between 1970 and 1998. The white paper quotes "The motor car – because of its flexibility – has brought about real mass mobility, and remains a symbol of personal freedom in modern society".

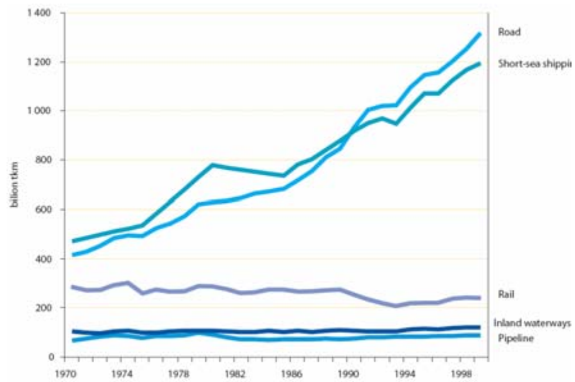

Figure 3 – Growth in freight traffic by mode 1970-1998

Based on the figures of the development in road transportation it is not hard to understand why congestion has become a major problem in the European Union. Around 7500 km, or 10%, of the trans-European road network is daily affected by congestion. Furthermore, road-haulage is expected to grow an additional 50% until the year 2010 while the estimated demand increase for transportation is only 38% for freight and 24% for passengers. It is estimated that congestion will account for 1% of the European Unions GDP in 2010 if nothing is done. That is why the European Union would like to see a shift in the modal split away from road transportation, especially to rail transportation.

So the answer to the congestion problems could be to shift the modal split in favour of alternative modes of freight transportation, i.e. short-sea shipping, inland water-ways, and rail for freight. While short-sea-shipping has followed the trend in the increase in

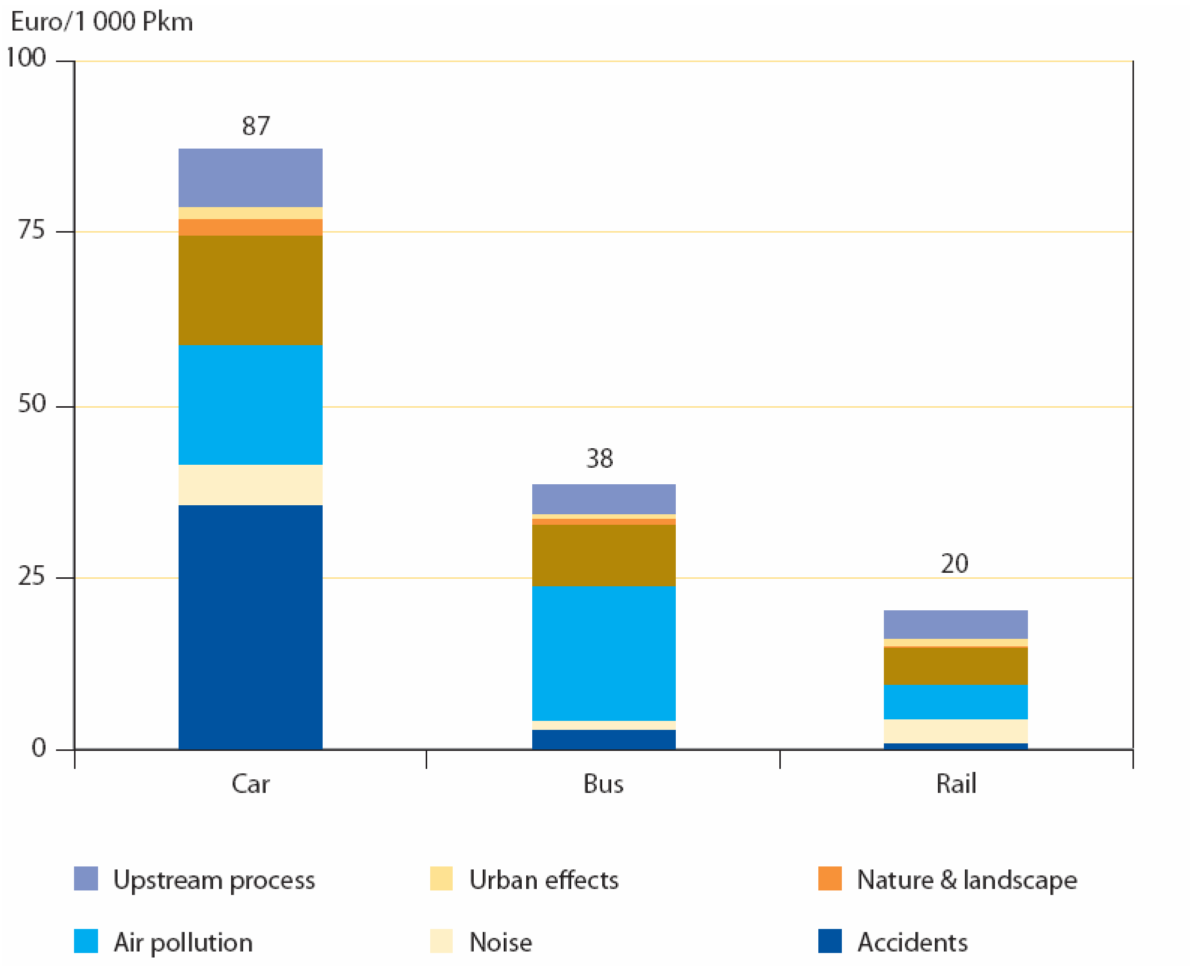

Figure 4 – Average external costs (1995) by mode of transport, freight

freight transportation and holds a 41% share of freight transportation, inland water-ways and train transportation hold a 4% and 8% share respectively. More noticeably, train transportation's share has dropped from a 21.1% share in 1970 to the 8% share in 1998. A reason for this is that the rail sector is experiencing congestion problems as well. 16.000 km of the railways, or 20% of the network, is classified as bottlenecks. Nevertheless, the European Union would like to see rail transportation's share of the freight transport increase from 8% to 15% and 6% to 10% for passenger transportation by 2010.

So why is the European Union interested in rail transportation, especially for freight, as the solution when congestion is predominant both in the road and the rail sector? One of the reasons may be that highway maintenance could be reduced to a sixth of the current costs if only cars were using them. A more interesting reason though is environmental issues. The transportation sector was in 1998 responsible for 28% of the CO_2 emission in the European Union. Road transportation alone accounted for 67% of the demand for oil and accounted for 84% of the total CO_2 emissions from the transportation sector. In total, transportation is 98% dependent on fossil fuels. Even

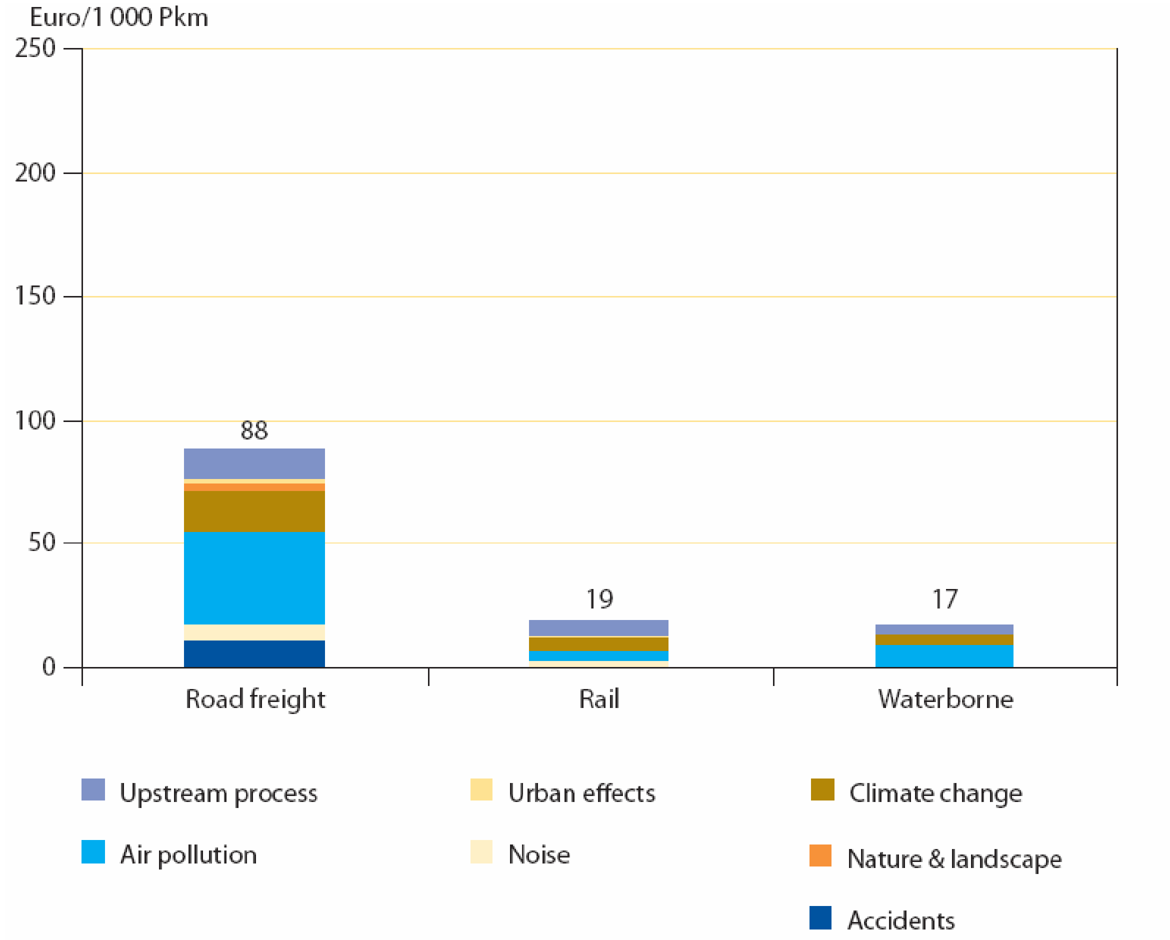

Figure 5 – Average external costs (1995) by mode of transport, passenger

more noticeably, it is expected that the transportation sector will see a 50% increase in $C0_2$ emissions by 2010.

Naval transportation and rail transportation are genuinely considered cleaner and more environmentally friendly modes of transportation. The European Union has made a cost-benefit calculation of the externalities incurred by the different modes of transportation. These are illustrated in figures 4 and 5 (from [White paper 2001], aviation has been omitted). Figures 4 and 5 show that the external costs (or socio-economic costs) for road freight and car transportation are, excluding congestion effects, 88€ per tonne-km and 87€ per passenger-km. Rail transportation's external cost is only 19€ per tonne-km and 20€ per passenger-km for freight and passenger rail respectively. Even without congestion costs road transportation has quadruple external costs compared to rail transportation. It is noticeable that bus transportation has a considerably lower external cost than car transportation, 38 vs. 87 € per passenger-km, indicating that consolidation of commodities (here passengers) has a beneficial effect on the environment. Considering the growing lack of tolerance towards the external costs of transportation it can from these figures be deducted that road transportation is not a sustainable transportation mode and attempts to limit it growth is appropriate.

What is also seen in figure 4 is that waterborne transportation has low external costs compared to road transportation. It also holds a significant share of the modal split for freight transportation (41% for short sea shipping and 4% for inland waterways). The question is then why the European Union focuses on re-establishing rail transportation when waterborne transportation provides environmentally sound transportation and does not have the same congestion problems experienced by rail transportation. The answer is the reach of the different modes' networks. Waterborne transportation is, as is obvious, restricted to water. Although Europe's geography means most regions have close access to water, it also means long travelling distances by water to get around islands peninsulas etc. Furthermore the demography of Europe has most people living in the 'blue banana' stretching from southern England through Benelux, the Ruhr, and down to the Po valley. To connect these regions by sea, a large detour has to be made around the Iberian Peninsula. Inland waterway transportation is a possibility, using the Rhine and the Danube, but still has a limited uptake area and capacity. Waterborne transportation is also a focus area for the European Union, but rail is seen as the strategic sector to enable the shift of the modal split. The European rail network stretches out to most areas of the European Union but still doesn't provide direct access to rail for all customers. That is why intermodal rail transportation is seen as the way forward. By combining the positive aspects of consolidated and environmentally friendly rail transportation with the flexibility of road transportation to give customers access to the rail network, the European Union hopes to reduce the effects on congestion and the environment. However, before intermodal rail transportation can take on a more dominant role the business needs to improve within several areas.

1.3. The focus of this thesis

The question is, what can intermodal transportation systems do improve their market position in relation their direct transportation competitors? From a planning point of view the answer is twofold; one, reduce operational cost in order to provide a cost efficient alternative and two, reduce transit times.

This thesis will not attempt to give a fulfilling answer to all the issues in intermodal transportation. The focus is on applying operations research to planning issues within intermodal transportation. More specifically the focus is placed on proposing models and solutions methods for optimizing schedules in scheduled and consolidated intermodal transportation networks. Furthermore, the models presented here all focus on tactical planning of intermodal transportation.

The thesis is constructed as such. The summary presents intermodal transportation and identifies the issues within the transportation sector. The summary introduces some of the developments on a structural level, in the infrastructure, and technology that affects intermodal transportation now and will affect it in the future. The summary leads up to the eventual focus of the thesis which is scheduling of intermodal transportation networks in transportation service networks. The thesis includes three papers that are linked together in the summary. The first paper presents an optimization model for public transit networks. By considering the passenger transfer flows the model finds the overall optimal timetable by minimizing the value of time cost incurred by the transfer waiting times. The model is solved using a Tabu Search heuristic. The second paper presents an optimization model to determine intermodal freight train schedules in a European setting. The scheduling is done on train canals that are predefined time dependent paths on the rail infrastructure network. The model includes an aggregated representation of terminal operations and a new notion of including vehicle balance constraints in tactical planning. The model is solved using the MIP-solver from the Xpress-MP optimization package. Finally, motivated by the mediocre results obtained by solving the model proposed in the second paper using a standard MIP-solver, the third paper presents a Tabu search based algorithmic framework intended to solve efficiently a generalized network design model derived from the model in the second paper.

The overall contribution of the thesis is to one, advance the planning model frameworks for both public transit scheduling and intermodal train network scheduling, and two, propose solution methods that can lay the foundation for efficient tailored heuristics to solve network scheduling models.

2. Going intermodal – issues of harmony and development of the sector

Given that developing intermodal transportation is the way forward in the transportation sector, what are the areas that need to be improved? The Union's white paper ([White paper 2001]) has some proposals, which will to some extent be presented here. Furthermore, a work shop was held by the University of Roskilde with actors from the intermodal train sector in Denmark ([RUC 2003]). The outcome of the work shop was a list of issues that hamper the use and development of intermodal transportation and a list of utopian visions on what could benefice the development of it. Some of these points of critique and visions have been included along with the European Union's proposals in the remainder of the summary.

2.1. Transportation network improvements

Recognizing the congestion of the trans-European rail network, the European Union has launched a series of infrastructure projects to improve capacity, eliminate bottlenecks, and improve the network connectivity for the rail sector. This subsection describes some of the current projects.

2.1.1. Physical infrastructure

There are a number of physical infrastructure projects that are devoted to the improvement of the transportation sector and the rail sector in particular. The main projects are part of the TEN-T projects ([TEN-T 2002]) to improve the trans-European transport network. Some of the projects have already been completed (such as the Öresound Bridge between Copenhagen and Malmö), some are under construction, and some are on the drawing board. Some of the most interesting ones will be described here to give an indication of the devotion to the improvement of the rail sector.

Project 1 is a high-speed train line from Berlin through Munich to Northern Italy (see figure 6; from [TEN-T 2002]). The line is supposed to attract both freight and passengers, in order to remove congestion on the highways surrounding the corridor. For passengers the travel time from Berlin to Munich will be reduced by as much as 2½ hours. The total cost of the project is 15.877 million €. Project 6 links Lyon to Trieste through Milan. This corridor is heavily congested, especially around the French-Italian border and will improve the capacity. The travel time from Paris to Milan for passengers will be reduced from 6 hours and 35 minutes to 3 hours and 40 minutes. A ‘rolling road’, a train where trucks including their tractors are loaded onto a train, is planned from Aiton in France (near Grenoble) to Obrassano in Italy (outside Turin) to reduce road-haulage in the Alps. The project costs are 26.590 million €. The improved transit time benefits for both projects illustrate that transit times between origins and destinations are important for establishing rail transportation as a competitive alternative to road transportation. Figure 6 shows the geographical placement of the two projects. Project 17, linking Stuttgart and Vienna is also partly shown in the figure (although Vienna can not be seen).

Figure 6 – Interconnection between 3 of the TEN-T projects

2.1.2. Intermodal systems development

Apart from the physical infrastructure projects a number of projects are aimed at providing better intermodal transportation systems. From a Nordic point of view, two systems provide interesting options. The reason why the Nordic region is interesting is because of its geography. Most of the region is separated from continental Europe (unless going through Russia), forcing almost all transportation to be intermodal. With the opening of the Öresound Bridge, and eventual construction of the Fehmarn Bridge, a potential land connection will be available though. However, areas like Western Norway and Finland, and traffic going to Eastern Europe will not profit much from the axis formed by the Öresound Bridge/Fehmarn Bridge connections. Therefore intermodal solutions based on waterborne transportation for crossing the Baltic Sea are interesting.

Figure 7 – The motorways of the sea and its connections to continental Europe

One of the interesting projects is the ‘Via Mare Balticum’ developed by the short-sea shipping company Scandlines ([VIA 2002]). The project is also known as ‘the motorways of the sea’ and its purpose is linking up the peripheral Baltic region to the rest of the Union by fast and efficient freight ferries. The network’s reach is illustrated in figure 7 (from [VIA 2002]). The southern continental Baltic ports would eventually be linked with the central European hubs and the large container ports on the European west coast either by truck or by intermodal trains in order to connect the ‘motorway’ network with the rest of the European freight network and the international access points. To make the sea-motorway system attractive, new specially designed ships and ports to accommodate them would be designed with the main purpose to make the modal transhipment as seamless as possible; especially as fast as possible. This proves the point that the transfer between modes is an important issue if interesting intermodal transport alternatives need to be competitive.

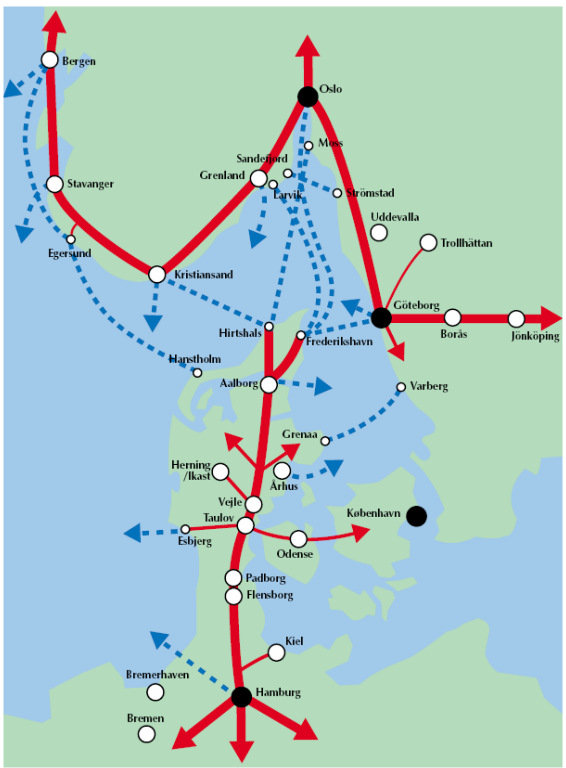

Figure 8 – The Nordic Link corridor from Western Scandinavia to continental Europe

The European Union has also proposed three other motorways of the sea systems. These are located in Western Europe, linking the Iberian Peninsula with the Irish Sea, in South West Europe, connecting Spain, France, Italy, and Malta, and in South East Europe connecting the Adriatic Sea, the Ionian Sea, and Cyprus. As for the Baltic motorways of the sea the purpose of the other three motorways of the sea is to link up peripheral and island regions. All of the motorways of the sea are expected to be operational by 2010.

Another interesting Nordic project is the ‘Nordic Link’ corridor. Figure 8 (from [Nordic Link 2000]) shows the geographical placement of the project. From the figure it is clear that central part of the system is the intermodal transfers between land-based transportation on the Jutland peninsula and waterborne transportation to the North-Scandinavian southern shoreline. Apart from the infrastructure investments included, the projects main focus is to provide an effective intermodal transportation system between continental Europe and western Scandinavia. The project proposes solutions for both road and rail intermodal transportation.

2.1.3. Terminals

Since terminals contribute significantly to the cost and transit time in intermodal transportation, there should also be focus on the development of terminals to facilitate modal transfers. Nevertheless, the European Union’s white paper talks very little about terminals, and mainly discusses congestion issues in airports. This is somewhat surprising considering the importance of terminals.

The location of terminals plays an important role in the selection of intermodal transportation. It is often the initial drayage move and terminal operations that increase the transit time and costs of intermodal transportation services ([Konings 1996]). Physical proximity of terminals reduces transit time from the origin point to the intermodal transhipment point. The location of terminals affects the area within which customers can be expected to use intermodal transportation. [Nierat 1997] presents a method based on spatial theory to determine the uptake areas for intermodal terminals depending on the service frequency and efficiency. The main conclusions are that intermodal services are only efficient for customers in a relatively small geographical area around the terminals with commodities travelling distances over 400 km. These results support the claim that terminal location is important for intermodal transportation services to be efficient.

Most terminal operations are still performed manually today. This means that a significant amount of human resource is used to perform the terminal operations along side the terminal equipment requirements. The labour intensive operations contribute to the high cost of terminal operations. In [Trip et al. 2002] it is stated that these costs could be reduced if new generation terminal, where much of the handling process is automated, were used. The paper further claims that this new generation of terminals could provide better integration of small flows into the general intermodal service network thus effectively increasing the customer base and making it attractive over shorter distances. There are presently very few of these new generation terminals in operation. The port of Hamburg has in one of its terminals installed an Automated Guided Vehicle (AGV) system to move containers from the gantry cranes on the docks to the storage areas. However, in intermodal road/rail transportation automated terminal operations are not common. It is therefore legitimate to expect that a new generation of terminals will be employed in the future and thereby improve the modal transfers in intermodal transportation.

2.2. Harmonization and integration

Although infrastructure projects, new transportation systems, and eventually new automated terminals will increase capacity, decrease transit time, and improve connectivity of the transportation network on a geographical level within the European Union, one of the big problems for the intermodal rail sector is still a structural issue within the organisation of the entire transportation sector. Also within individual transportation modes there might by discrepancies in the ways of operating. This is especially true for the European railway systems that originate from several independent countries, each with their own technical systems, operational rules, and legislation. Running trains across Europe thus requires adaptation to several different railway systems. This subsection first presents some of the main interoperability issues between the European railway systems. Afterwards developments on a structural and technological level are presented.

2.2.1. Connectivity problems in the European railways

The average speed of international freight trains in the European Union is approximately 18 km/h. Part of the reason for this slow speed is the very different railway systems in Europe. Take for example electrical systems. There are five different electrical systems used in the European Union. These are illustrated in figure 9 (from [White paper 2001]).

If a train runs from Sweden through Denmark to Germany it has to pass from the electrical system used in Sweden to the one used in Denmark and back to the electrical system used in Germany which is the same as in Sweden. This means that at the Swedish-Danish border and again at the Danish-German border locomotives must be changed, unless the more expensive locomotives that can run on several electrical systems are used. The later are becoming more common, but locomotive changes have been widely adopted in the past. Furthermore there are two different gauges used in Europe. Finland and the Iberian Peninsula uses a different gauge, 1524 mm and 1668 mm respectively, as opposed to the standard gauge of 1435 mm used in the remaining Union countries. Finally, there are different labour regulations in the Union's countries. For example the Italian laws require two locomotive drivers, while the French only require one, meaning that running a train from France to Italy is not only a technical issue but also one of regulation. The regulation and technical differences between the Union's member countries requires coordination at the borders, which has proven to be a major problem. It is not uncommon to have experienced so-called 'ghost trains'. These are trains that arrive at a border crossing and find that the locomotive they need to proceed, e.g. on the new electrical system or complying with a different regulation, is not present.

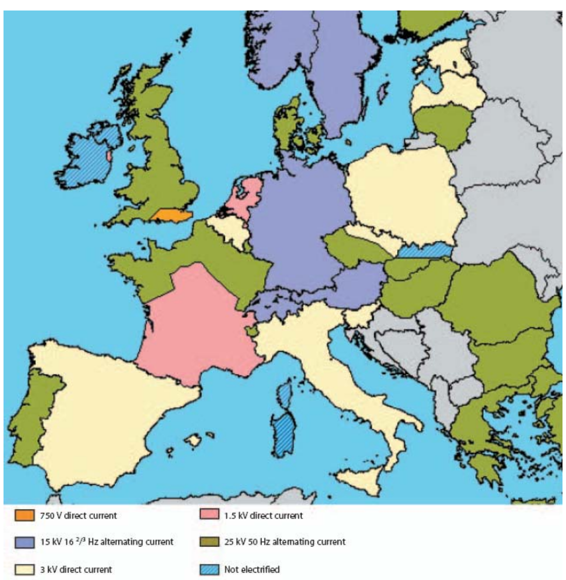

Figure 9 – The different electrical systems in the European Union

One of the reasons for the big differences between the European states' railway system is because railways traditionally were seen as a national affair. To protect the national railways from external competition, artificial borders, such as the technical and regulatory differences, were set up. Nowadays, with the integration of the European Union and the free flow of goods across borders, the segregated railway networks of the member countries is a problem for the railway sector. The problem is not smaller when put in perspective that truck transportation, its direct competitor, does not have the same problems with crossing borders.

2.2.2. Structural changes to improve competitiveness and interoperability of intermodal transportation

The railway sector has been faced with a number of issues which eventually has lead to its decline, especially in freight transportation. The European Union has been determined to restore the railway sector and has, apart from the previously mentioned infrastructure projects, launched a series of initiatives. The European Union and its member countries believe that one of the reasons for road transportation's success is because it does not pay for all the external costs it assumes, resulting in heavily congested roads. Several countries are planning to introduce road taxes or road pricing as has already been done in Germany and Austria for trucks on highways. Introducing road taxes for dense urban areas is also contemplated by many, as has been done with the toll system in London. The idea behind road taxes is to introduce pay-per-use on the road networks so that users actually pay for the sparse capacity they use. The expected result is to see a shift from car and long-haul truck transportation to public transit and intermodal freight transportation. The expectation of the modal shift in freight by introducing road taxes is legitimized from studying the impact of the severe regulation imposed by Switzerland on truck transportation. To use highways in Switzerland a significant access fee has to be paid, and there is a limit on the weight of trucks of 28 metric tonnes as opposed the 40 tonnes limit used in the Union. The eventual result is that several intermodal services are available to cross through Switzerland from Germany to Italy.

Nevertheless, the rail sector can not solely rely on the “harmonization” of external costs. To break down the barrier of the traditional national railways, the European Union introduced a deregulation of the national railways. Different models have been applied by different countries. England has privatized the entire railway sector, meaning both track ownership and operation is on private companies’ hands. Other countries, such as Denmark, have commercialized the railways by keeping track ownership public, and privatized operations.

The purpose of either privatization or commercialization is to have operators that are not nationally linked, and that therefore are able to operate according to market demand. There are several examples of operators assuming operations in foreign countries. German operator Deutche Bahn separated their freight division into a company called Railion. Railion has since then overtaken the freight divisions of the old national railways in the Benelux countries and in Denmark. Danish passenger operator DSB has submitted a tender for a passenger service in England to name another example. Intermodal operators too are operating across several countries. CargoNet is an intermodal rail company partly owned by the Norwegian operator NSB and Swedish operator Green Cargo. It offers intermodal rail services from Scandinavia to continental Europe, most through alliances with other intermodal operators. Similarly Swiss operator Hupac offers intermodal services from Italy through Germany to Benelux, Germany and Poland. Its continental services are shown in figure 10 (from [Hupac 2005]).

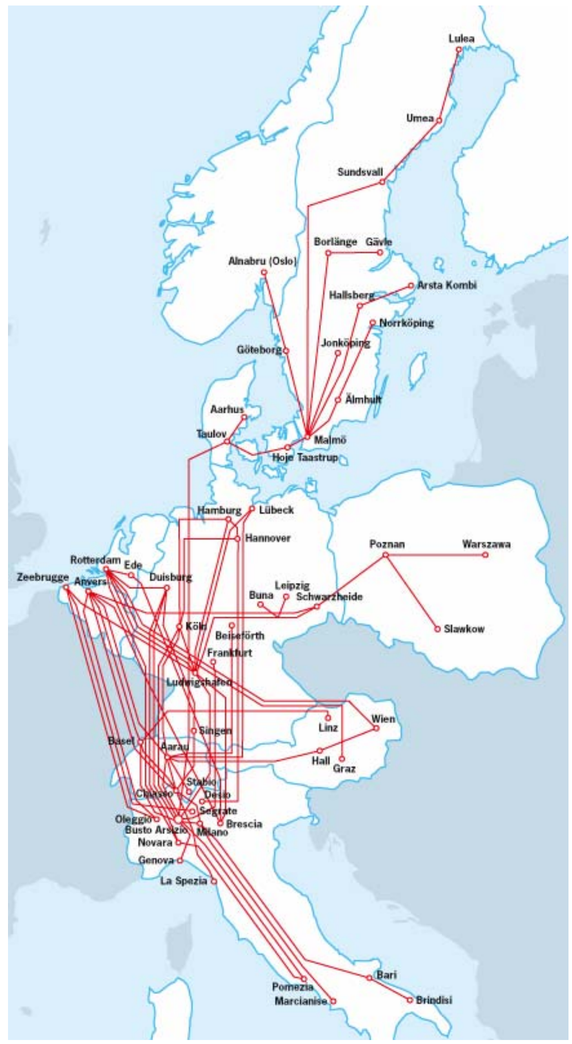

Figure 10 – Hupac’s network of continental services

For companies like CargoNet and Hupac to run trains across several countries, the European Union was obliged to integrate the traffic regulation on the networks of the member countries. As opposed to the American continent, passenger trains occupy a significant amount of capacity on the rail networks. Given the high time sensitiveness of passengers, passenger trains were traditionally given priority over freight trains. That meant that in case of coinciding trains, the freight trains were sidetracked. Part of the explanation for having the slow average speeds of freight trains is due to this prioritization of passenger trains. The conflicts often occurred at border crossing when switching from one country's traffic regulation to another's awaiting an available time slot in between passenger trains.

In order to overcome the capacity conflicts, and eventually increasing freight train efficiency, a project called 'freight freeways' was launched. The purpose was to dedicate part of the capacity to freight trains, and coordinate capacity across borders to allow freight trains to run efficiently from one country to another. This was done by dividing the network capacity into train paths. Train paths are time slots on the network with departure and arrival times at stops and terminals. Thus to run a train on the network the rights to a train path need to be acquired. Intuitively, dividing capacity into time dependent paths is an initiative to subject freight trains to the operational characteristic of passenger trains, i.e. by operating according to schedules. The freight freeways is a European cooperation intended to devote part of the train paths to freight trains, and making sure train paths in different countries fit together. Furthermore, a one-stop-shop concept has been adopted, so that freight train operators only purchase the train paths from one place, instead of having to acquire pieces from the national railway agencies.

2.2.3. Technical developments to improve connectivity in the railway business

Although infrastructure projects, both terminals and network connections, and structural changes, such as the freight freeways, are improving the connectivity of the European rail networks there is another area where developments may be seen; equipment. The transportation sector uses different loading units. E.g. ISO containers are adopted for intercontinental container transportation, while for road transportation trailers are the most common transportation unit. Container transportation has experienced an exponential growth since Sea-land's first transatlantic container shipment arriving in Bremen and Rotterdam in 1966 marked the start of the container revolution in Europe [Muller 1999]. 92% of intermodal freight on railways in Europe is moved in containers. However, although containers can be stacked due to their structural stability they are inefficient when adapted to European land transportation due to trailers having higher capacity. For instance a 40 feet ISO container only has a 25 European pallets surface capacity, while a standard truck trailers can carry 33 European pallets. Trailers on the other hand do not posses the same structural strength of containers and are therefore not stackable. This means there is a compatibility problem when integrating rail and road in intermodal transportation because of the different types of equipment used.

The European Union, operators, and users of intermodal transportation services believe that a new loading unit is necessary to blend the structural quality of ISO container with the larger capacity of trailers. The "one box for all modes" is known as the intermodal loading unit (ILU). It combines the structural strength of ISO containers and can accommodate 33 European pallets [COM 2003]. If the

ILU is introduced and accepted in the market it would allow all modes in Europe to use the same loading unit, enabling more seamless modal transfers. The expected benefits are a 2% reduction in logistics cost through better equipment integration and up to 10% in transportation costs. The legislation for the standardization of the ILU is expected to be concluded by 2005 and the measures could enter into force by the end of 2006.

3. Doing intermodal – what is used now… what is needed now?

No matter how many infrastructure projects are constructed, new generation terminals are built, intermodal equipment is conceived, or structural changes are made in the transportation sector, the fundamental issue will always be one of planning efficiently according to the circumstances. This section will focus on some of the planning issues that intermodal transportation is confronted with. In [Giannopoulos 2004] information and communication technologies are introduced as fundamental changes in the way transportation services are planned and monitored. The section will present some of the IT developments and current planning practices in intermodal transportation. It will further present concepts for a system which may benefit intermodal freight transportation by making it more accessible to customers.

3.1. Distinguishing passengers and freight commodities

Before discussing which IT systems are used or could be beneficial for planning intermodal transportation, the difference between passengers and freight as commodities needs to be considered. The one element transportation of any commodity has in common, it being freight or passengers, is moving the commodity from its origin to its destination. However, the similarities end here. Commodities have different requirements to cost, time, and safety to name some characteristics. For example passengers are more sensitive to time than bulk commodities are, and safety is a bigger issue for hazardous materials than for general cargo. Furthermore, the transit operations also depend on the type of transportation and commodity.

The main difference between passenger commodities and freight commodities is that passengers make their own routing decisions. Any transfer operation made in transit is done by the passenger itself, and in case of disruptions the passenger can reroute himself according to the circumstances. Freight commodities do, by its non-conscious nature, not posses the ability to perform transfer operations. That means, unless someone (or something if transfer operations are automated) makes the transfer nothing will happen. Previously, it was not unusual to see freight wagons ‘disappear’ in rail yards, proving the point that significant attention has to be devoted to freight transfer operations.

Although passengers can perform their own transfers with ease, they still represent an important barrier from a passenger’s point of view. For example airline companies market themselves on offering direct connections between airports, instead of having to make one or two hub-transfers. The nuisance experienced by passengers when making transfers can by accredited the actual physical transfer effort, the waiting time spent when waiting for connections, and the risk of missing connections leading to even longer transfer waiting time. The physical barriers can be partly eliminated by good terminal lay-outs etc., but the perspective of eventual waiting time of any size will always be an issue.

For freight the actual transfer waiting time has no importance as such. However, its impact on the total transit time matters. Where time sensitiveness of passengers is mainly a question of 'getting there as fast as possible' regularity is the dominant factor in freight transportation. There is a trend of establishing production supply chains with just-in-time delivery of sub-components. However, late deliveries of sub-components can freeze the production process and have severe implications down the supply chain. As described earlier, rail transportation traditionally was both slow and irregular due to the poor connectivity of the rail networks and bad management of transfer operations.

Because of the different perspectives of time and non-consciousness of freight, routing passengers and freight differs as well. Passengers will in general not accept to travel by any other route than the shortest (fastest). Some passengers are willing to accept longer transit times if the cost reduction is significant, but all passengers make their own autonomous decision on how to route themselves based on the available service network. Passengers are very reluctant to accept any re-routing decision imposed on them prior to departure or in transit. Freight however does not posses the ability to make autonomous routing decisions and is indifferent to the actual routing decided upon it. The important issue is the delivery time. How freight gets to its destination as long as it gets there on time is less important. With the introduction of track-and-trace there is a slight tendency in customers questioning the routing dispositions adopted by a carrier eventually adding pseudo-consciousness to freight. However, this is not an issue as long as the routing does not diverge extensively from what customers expect. This means that carriers can make their own routing dispositions and adapt freight itineraries according to the available capacity and hence use it more efficiently.

3.2. Technologies enhancing planning methods

As for most business sectors, the information technology revolution has opened new possibilities for planning and monitoring transportation operations. This sub-section will present three new technologies that already are, and could further improve, the planning of transportation

3.2.1. The internet

The big impact of the internet on modern society goes without saying. The impact is also seen in all areas of the transportation sector. The most important from a customer service point of view is the introduction of e-commerce, especially on-line booking systems [Roy 2001]. The most visible example is from airline transportation where most air-line tickets are purchased on-line either directly by the customer or through a travel agency with access to all airline companies. In freight transportation on-line booking systems are becoming widely used. They are however, not as widely adopted as for passenger transportation. One of the reasons is the big diversity seen in freight transportation rates. Where passengers generally pay the list prices determined by the carriers, prices are significantly more negotiable in freight transportation depending on customer loyalty, freight volumes etc. Hence the booking mechanisms seen in passenger transportation booking systems are less obvious for freight transportation.

There is a new freight transportation service trading concept arising whose development will be interesting to follow; transportation auctions. The concept is that customers can place a request for a load on auction and operators or forwarders can bid on the load. Similarly, operators can offer their services on the auction and have customers bid on it. These on-line auctions mean that customers can reveal demand in real time to a wide range of transportation service providers. Furthermore the bidding process may result in revealing real transportation prices eventually leading to more realistic and possibly more competitive prices. Auctions are not only applicable to the spot market. To get cheaper transportation prices customers often negotiate long term contracts with carriers. These contracts often guarantee a certain volume of freight, e.g. a number of flat-bed wagons on an intermodal train, in exchange for lower costs and/or distribution rights on a set of itineraries. Auction mechanisms can also be applied for the tender process for long term contracts.

3.2.2. Passenger route planners

One of the successful applications improving conditions for intermodal passenger transportation, that has become possible because of the internet, is the introduction of passenger route planners for public transportation systems. Passengers can enter their origin, destination, and time of departure or time of arrival and find possible routing options through the public transit network. Some route planners also have other options that users can change. These are commonly restrictions on the maximal number of transfers, exclusion/inclusion of various modes, and access and egress distance/time limitations to an access point (stop) of the transit system. These route planners are priceless for non-common users of transit systems, or current users diverting from their regular routes. The big benefit from the internet is that schedules may be updated regularly, giving users access to the newest schedules and temporary changes. A routing mechanism then allows passengers to automatically determine routing alternatives without having to compose them themselves by studying schedules.

Some of the route planners have been coupled with booking systems. This is generally the case for airline systems and intercity trains. The capacity in these systems is limited as a seat is required and therefore reservation is necessary. For urban transit systems, where capacity is not as tight as for intercity rail and air traffic (you can always squeeze an extra person on the bus), ticket booking is superfluous and hence not incorporated.

3.2.3. GPS, GIS and mobile communication

One of the European Union’s TEN-T projects is the development of the GALILEO satellite positioning system. The project was developed in order for the European Union to have access to a satellite positioning system independent of the American GPS. The system is expected to result in services worth more than 9 billion € from the year 2015.

From a transportation point of view, GPS systems can monitor and manage the status transportation systems and thus offer significant benefits to the sector ([Mintsis et al. 2004]). Applications such as automatic vehicle location systems (AVL) can determine the accurate position of vehicles and using a geographic information system (GIS) it can be mapped and give a user friendly representation of the GPS data to decision makers. The position information can be used to monitor if operations proceed as planned or, in case of disruptions, to adapt plans in real time. Furthermore the monitoring can increase the safety of transportation, with respect to theft, accidents, and sabotage, and assist customs in determining potentially illegal operations.

One of the requirements customers are starting to demand in freight transportation is the ability to track-and-trace shipments. Customers want to be able to follow their shipments while they are in transit. Intuitively the information should be worthless, as customers cannot influence the routing of their shipments. Nevertheless, disruptions do occur and carriers do not always have the ability to provide this information to customers let alone discover disruptions within their own system. By being able to monitor their own shipments customers may use the information to plan their own operations (production etc.) according to the expected arrival time and inform the carrier if no action is taken.

The next step for transportation planning is moving to deliver information to mobile communication devices. Already some public transit companies (e.g. the STM in Montreal) offer the possibility for passengers of getting departure information on routes using SMS services on their mobile phones. The next step could be to allow dynamic planning of itineraries so that passengers in case of disruptions can re-plan their itinerary while in transit. This will be possible if public transit companies start using electronic ticketing. The idea behind electronic tickets is for users to carry a card with a chip on it that registers when they embark and disembark vehicles and automatically debit the users' accounts. If a mobile phone is registered along with the card it would be possible to pinpoint the position of the customer using the vehicles GPS system and inform passengers about disruptions or other information he or she may find interesting. In freight transportation mobile communication devices are also useful. These can be used to provide information to vehicle drivers or conductors. For example new tasks or possibly revision of tasks can be sent in order to adapt the transportation services in real time.

Apart from the real time monitoring and planning possibilities in cooperation with GPS, GIS can be used to for assisting tactical and strategic planning. GIS systems enable modelling of intermodal systems in more detail which was not possible before ([Southworth et al. 2000]). The mapping feature of GIS is an apt visualizing tool when planning networks. For example, by illustrating flows, bottlenecks can be visualized and areas of the network that need capacity upgrading identified. The database feature can store attributes such as transit time, distance, accident probability, congestion probability etc. used to route commodities.

3.3. A route planner for freight

Although route planners are common in public transportation, they have not been adapted to freight transportation. It would be possible to imagine that such an open system is not necessary in the freight sector because carriers make their own routing dispositions. There is however a belief from customers that the rail sector lacks IT-system to manage their operations and assist their customer relations [RUC 2003]. The European Union also acknowledges that freight transport management systems (FTMS) are necessary to increase efficiency, reliability, and responsiveness in the freight transportation sector. Furthermore, operators in the rail sector believe that customers do not possess the knowledge of the routing possibilities with intermodal rail transportation. So could a route planning system for intermodal freight transportation similar to those available for public transit systems provide an interesting tool for the freight transportation sector?

The motivations for having one are plentiful. The European Union talks about a concept called ‘freight integrators’ whose purpose is to break away from the traditional division of modes. According to the European Union freight forwarders should start having a multimodal or intermodal vision of transportation instead of solely operating within their own mode. Relating this statement with other Union statements on improving intermodal transportation the purpose is to get freight forwarders operating in road transportation to use intermodal options using waterborne or rail transportation in an intermodal cooperation with their own sector. Freight forwarders, given the contacts they have in their sector, know how to find cost efficient transportation services. They lack the knowledge of alternative modes and therefore will have problems finding cost efficient solutions there. Furthermore, intermodal solutions are harder to plan because of the shift between operators and modes. Therefore some reluctance to shift to intermodal transportation solutions is expected. A route planner that could reveal intermodal routing possibilities could encourage freight forwarders to use intermodal transportation.

For a freight route planner to be effective its scope has to capture the entire spectrum of actors in the freight transportation sector. In order for a freight route planner to gain any significance all service providers and users need to benefit from it. For example the one-stop-shop concept adopted for the freight freeways could be incorporated in the route planner for train operators. Using a routing device, train operators could find possible routing options on the train paths added by the rail authorities for their train services. When a train service is in place, freight forwarders could then book capacity on the trains. Similarly, forwarders could book capacity on other modes to create an intermodal network that customers could book capacity through the forwarders. By capturing the whole spectrum of freight transportation providers and users in addition to integrating all transportation modes, the system could provide a basis for the integration of the freight transportation sector eventually promoting intermodal transportation.

The next sub-section describes some of the attributes, and their requirements, a freight route planner could adopt. All the requirements and possibilities take on a utopian vision of what is realistic, not so much from a technical point of view, but from an implementation point of view. The following sub-section describes some of the barriers such a system would experience in case of implementation.

3.3.1. Technical requirements

The main attribute at the centre of a freight route planner is the routing device. The routing device creates a geographical and temporal reference that users can relate to and base decisions on. It is envisioned that the freight route planner is a tool that can be used by both transportation service providers as well as transportation service buyers. The European infrastructure must be added to the system in form of train paths, road networks, time slots at terminals etc. Operators can then search for service path through the network to cover the origin and destination. E.g. shipping companies could find port times; rail companies find train paths and trucking companies could calculate transit times on the road network. Given these possibilities operators can select when and how to run services.

If all operators enter their operations in the route planner a big integrated service network could be created. Some of the services would not be available to other users, as they would be dedicated services designed at specific transportation needs for given customers. However, for other services there would be an interest in displaying the availability to customers. This is true for intermodal train operators. If the entered services are repetitive, having them available in an open system allows transportation service customers to find them when searching for alternatives. This means customers can use the system for tactical planning of their transportation needs.

3.3.1.1. Freight routing method

There are ultimately two criteria which users should be able to select when using the freight planner; time and price. Intuitively finding the lowest priced route is still the predominant criterion. However, as planning paradigm shifts towards shorter response times, finding the shortest time route may become more adopted by some. It is still reasonable to assume that time can be considered a side constraint, within which the cheapest possible path must be found.

The basic method behind a route planner is a shortest path algorithm. Shortest path algorithms are plentiful and have become very efficient. Nevertheless, the requirements for a shortest path method in a freight routing planner extend beyond the basic method. The first issue is the size of the network and the complexity of calculations. The envisioned scope of a freight route planner, where all the infrastructure and transportation services are incorporated, results in a large infrastructure and service network. In addition to the large geographical scope, all train paths and services have a temporal dimension that increases the network size. It is unclear how big a time period the route planner needs to span, but it is estimated that a minimum of 2 weeks is required for operational planning and several months for tactical and strategic planning. It is therefore expected that the shortest path calculations have to be performed on a very large network. Making one shortest path calculation on even a very large network may not be complex. However, supposing the system is used by all operators and customers the number of calculations made will also be large, demanding significant computational power.

Assuming the computational complexity encountered by the significant network size can be handled there are a number of attributes the shortest method should comply with. Handling side constraints or restrictions is an important attribute for a useable freight route planner. For instance if an operator wishes to run a train carrying hazardous materials the path proposed by the system should respect the safety requirements dictated by regulation. There may also be side-constraints capturing routing restrictions imposed by the user. These could be restricting the search to a sub-set of modes or carriers, or even restricting the routing alternatives to certain geographic areas or excluding others. Furthermore the search has to capture the modal transfer options in nodes. It is probable that some transfers (between modes or carriers) are less obvious than others, less wanted, or outright impossible. The many types of equipment in use (trailers, swap-bodies, ISO containers) may also have different requirements to terminal handling equipment which should also be considered in the search. The routing tool should offer a wide pallet of options the users can use to build possible routing alternatives.

There might be other qualitative parameters that criteria and side-constraints may not capture. Thus the route planner should propose several distinct options in order for the user to have a broader foundation on which to base routing decisions. The paths proposed for the services operators wish to offer need to include the operational constraints specified. It may however be required for the route planner to also propose paths where the added constraints are relaxed. This allows the user to see the implications of his imposed constraints and eventually reconsider the necessity of them. This could for example be proposing paths that extend past the required delivery time, but providing a lower cost alternative. The user may then reconsider if the increased transit time is outweighed by the cost savings.

3.3.1.2. Capacity handling and booking

A side constraint that was not mentioned in the previous section is capacity restrictions. For strategic planning where routing alternatives are examined for potential future use, capacity restrictions are not important. The route planner would identify routing alternatives after which price negotiations and capacity reservation would be performed outside the system. However, if the system, as intended, has to be applicable for short-term planning, capacity restrictions must be included. The problem as seen today is that most short term demand is met by trucks because no system is available to identify intermodal alternatives and instantaneously reserve available capacity. To encourage the use of intermodal transportation it is therefore imperative that a freight route planner can assist short-term planning with the eventual capacity constraints that follow.

The notion of available capacity is not straightforward however. In passenger transportation passengers decide on their own routing, and thus when they book a service they reserve the capacity deduced directly from their chosen routing. It is inconceivable that passenger itineraries can be changed prior to execution which can be illustrated by the fuss passenger rerouting because of aircraft overbooking can cause. This first come first serve paradigm on combined routing and capacity booking is very easily implemented as service capacity is filled up as reservations are made. However, the first come first serve paradigm is not necessarily the most efficient. Carriers express clearly that they want to retain their rights to decide freight itineraries on their services in order to achieve a more efficient use of capacity.

If carriers have to retain the right to decide their own routing of freight the transition from route search to actual booking becomes complicated. Essentially it follows that customers cannot book itineraries for their freight as the carriers will make the eventual routing decision. From a customer point of view that is not a big problem. If customers can make a reservation on the origin/destination of their freight and imposing a time restriction on the time of availability and the delivery time the actual transportation itinerary performed is less of an issue. Depending on the booking time customers could expect a response on the reservation from the involved carriers or more probable from the involved forwarder. If the reservation is accepted the forwarder (or carrier) would be liable to perform the transportation within the imposed restrictions.

However, allowing ‘floating’ itineraries that are eventually decided by the carriers requires a good cooperation between carriers for intermodal and inter-carrier itineraries. If a customer reservation is accepted based on an expected itinerary and one of the carriers changes its own leg on the itinerary, the other carriers will have to comply with that change. Unless this is done efficiently disruptions may follow, eventually undermining the use of the freight route planner.

The question is whether a change in paradigm in freight transportation to approach the concepts of e.g. airline transportation would be beneficial. Because of the technological advances and globalization, companies are required to, and have the possibility of, making fast adjustments resulting in more planning being done on short-term conditions. It is therefore questionable if long-term contracts between carriers, customers, and forwarders will be as widely adopted in the future or if the fast changing and dynamic environment will transcend to the transportation sector as well. This sets high expectations for the flexibility of transportation services. Thus when transportation service buyers enquire about a reservation for capacity the confirmation should be instantaneous. This is only possible if direct booking is possible, as it is the case for airline and intercity train transportation. Carriers may have to accommodate to the fact that they eventually will loose some of the rights to deciding upon freight itineraries.

3.3.1.3. Efficient document handling as a starting point

The first step towards the integration of all carriers and customers in an open system, eventually leading to a viable implantation, is to collect all the necessary data required. This would be achieved by first integrating the transportation documents (bill of lading). Popularly stated the bill of lading can be compared to a boarding card or ticket in airline or train transportation systems. It contains information and terms concerning on the contents of the shipments and is issued by the carrier to acknowledge that the shipment is received and has been placed on a vessel bound for a given destination.

3.3.2. Structural challenges in implementing a full scale freight route planner

The technical challenges in implementing an integrated freight route planner are an issue. However, more important is the question of whether such a system would be accepted, and whether the necessary data would be provided to the system. A series of interviews with Danish users and providers of intermodal transportation was conducted by the Technical University of Denmark and the University of Roskilde to investigate the structural barriers in implementing a full scale integrated freight route planner. This section includes some of the perspectives uncovered at these interviews.

For a freight route planner to be effective data needs to be provided to the system. These data include departure and arrival times, capacities, price, data on reliability and safety, prices etc. Data such as departure and arrival times are not sensitive data. These can be acquired on carriers' web-sites or by making a phone enquiry. There would therefore not be any problem in including those in the system. It becomes more complicated when transportation price data is considered. For some reason service providers seem reluctant to provide data on prices. The reason for this has to be found in the extensive competition there is on transportation rates in the sector. Service providers seem to believe that they will loose competitive edge if they provide their transportation rates on-line for anybody interested.

What seems to be a major challenge in implementing an integrated freight route planner on a European level is the unwillingness to cooperate and share data with competitors. Part of the unwillingness is not justified. Sharing data in a system needn't necessarily imply cooperating with competitors. Nevertheless, the challenge is to convince service providers that using the system is a benefit not only to the entire transportation sector, but also to them. It is important that the system is constructed in such a way that service providers can decide on which data are available publicly and which data are protected. Basically the whole problem can fundamentally be seen as unwillingness to enter any kind of cooperation with competing companies.

A big challenge for an effective freight route planner is integrating the different standards and cultural traditions inherited by the different modes. As previously mentioned ISO containers is the standard for sea shipping, while trailers are standard in road transportation. Although the intermodal loading unit (ILU) may eventually set the standard for intermodal transportation the other standards will still be in use for a long time. On a more structural level the procedures adopted by the different modes is more complicated. Different modes have different rules with respect to liability in case of loss or damage of freight. In general the stakeholders are the shipper, the freight forwarder, carriers, and the insurer. In addition terminal operators, warehouse operators and track owners (i.e. rail authorities) may also be stakeholders depending on the type of transportation. Although the number of claims is limited, under 1% for 90% of the stakeholders, there are still issues concerning the responsibility of freight in intermodal transportation given the modal legislations. It is generally recommended that the European Union should invest effort on harmonization of the modal/intermodal legislation in order to facilitate the use of intermodal transportation.

From a transportation service procurement point of view the adoption of the system in the transportation sector may also pose a challenge. As it is known most transportation service provided by carriers are handled by forwarders and sold on to transportation service buyers. Introducing an integrated freight planner system might enable transportation service buyers to procure their services directly from the carriers. The fear of third party forwarders is that their use could eventually be limited by this. This may be true for uni-modal forwarders. However, for intermodal forwarders the art of providing intermodal transportation services by combining services offered from different modal carriers is essential to the system. The system itself can only provide the data; the actual services (both uni-modal and intermodal) including the liability and responsibility still have to be provided by a forwarder effectively acting as the wished for freight integrators by the European Union.

To achieve the implementation of a freight route planner, that eventually would be beneficial to the entire freight transportation sector, it is believed that the intended participants also have ownership of the system. By constructing a company where dominant members of the transportation sector hold the shares it would be possible to one, involve the trend setting companies in the implementation, two, attract these companies customers and partners to use the system, and three, keep the system from being controlled by one stakeholder. This construction is also adopted in the development of a standardized electronic ticketing system for all public transit companies in Denmark. To initiate the system however there must be a short term economical benefit to invest in the system. This could either come as a subsidy from the European Union or by charging a cost from using the system. The first would require significant political navigation in order to collect the necessary funds and the later would require value added services from the system in order for users to benefit from its use. It will hence be a difficult task to initiate such a system on a full-scale implementation. It might therefore be worth considering a less ambitious approach before blowing the system up to full-scale.

4. Advanced intermodal – the new frontier in planning method

In the previous section it was assumed that transportation services were added and that customers could use these to meet their transportation demand, e.g. through the use of a freight route planner. The question is how operators make the decision to offer a service. Stepping one step back, how are the decision to build network infrastructure projects and new terminals made? From a business point of view the answer is clearly that the demand is there and thus some party is willing to supply the service or infrastructure to meet demand. Dealing with transportation networks means dealing with large-scale networks that are difficult to manage manually. This means there is a good foundation for decision models to provide quantitative measures based on which decisions can be taken. Although not as widespread as one might expect it, quantitative models have and are being used to assist decision making in the transportation sector.

It is generally accepted that planning is divided into three phases; strategic, tactical, and operational/real-time. The time scope of the different planning levels go from long term strategic planning to short-term or instant operational planning. The level of detail on the other hand is generally limited for strategic planning and very detailed for operational planning. Decision support systems can be applied to all levels of planning within intermodal transportation.

At the highest strategic level there have been several descriptive methods to analyze a regions transportation pattern. In [Crainic et al. 1990] the system STAN is presented for strategic analysis and planning of national freight transportation systems. For urban public transit transportation systems descriptive traffic assignment models and algorithms are presented in [Florian et al. 2001]. The purpose of descriptive models is to model the transportation flows in a region given the infrastructure network and possibly the service network available. The models are calibrated to the existing lay-out and can be used to evaluate the impact of changes in the networks.

Where descriptive models describe networks and impacts of changes, normative models take on an optimization approach to achieve the best design configuration for network planning. The models are generally known as logistics system design models. Given a set of possible links, costs, and demand the goal is to determine the best possible network configuration to minimize cost. There are a number of contributions in the field of facility (terminal) location. Given transportation demand the models attempt to locate terminals in order to meet demand and minimize transportation costs. [Labbé et al 1997] present an annotated bibliography concerning discrete location problems.

With given facility locations the next step is determining links to open between them. These models are often referred to as network design models. [Balakrishnan et al. 1997] and [Magnanti et al. 1984] present a review of network design problems and their applications, mainly in freight transportation. In public transit specifically [Chakroborty et al. 2002] present a network design model for public transit systems using a genetic algorithm heuristic to find “optimal” routes based on link transit time and demand. Network design models are easy to formulate but are difficult to solve because of the constraints binding the capacity of the links modelled with binary (or integer) variables and the flow of the commodities. Several methods have been applied to solve network design models. [Costa 2005] presents a survey for the application of Bender's decomposition to network design problems. [Chouman et al. 2003] presents a survey on valid inequalities for network design problems. [Holmberg et al. 1998] presents a lagrangean approach to solving network design problems. Finally a wide range of heuristic contributions can be found for solving network design problems. To name a few [Ghamlouche et al. 2003] and [Ghamlouche et al. 2004] present a Tabu search based meta-heuristic using cycle-based neighbourhoods to solve the general fixed-charge network design problem. [Crainic et al. 2000] also use a Tabu search based approach with a combination of pivot moves and column generation to solve the same general fixed-charge network design problem.

Moving a step down in the planning horizon to tactical planning we find a wide range of models within the field of service network design. Given an infrastructure, costs, and transportation demand, service network design models can be used to plan transportation services. Whereas the network design models in general are easy to formulate, service network design models are more complex given the higher level of operational detail they need to include. A general description of service network design models for freight transportation can be found in [Crainic 2000]. A wide range of applications of service network design models can be found. [Huntley et al. 1995], [Gorman 1998], [Joborn et al. 2001], [Crainic et al. 1984], and [Armacost et al. 2002] present service network design applications for CSX transportation, Santa Fe railways, Green Cargo, Canadian National, and UPS respectively. Service network design models can be separated into two types of models; one where service frequencies are determined, and one where schedules are determined (eventually determining the service frequency). The first types can be considered strategic/tactical and the later as tactical/operational because of the higher level of detail represented by schedules as opposed determining just frequencies.

Specifically for intermodal freight transportation (or consolidated freight transportation) a number of contributions deal with terminal operations. On the border between service network design and actual terminal operations lies a number of train dispatching models. These models determine the optimal arrival and departure times for trains in accordance with a single terminals operational characteristics. [Newman et al 2000], [Yano et al. 2001], and [He et al. 2003] present dispatching models for rail terminals. A common approach for managing terminal operations is to use simulation models. There are numerous contributions for simulating terminal operations. [Sarosky et al. 1994] and [Rizzoli et al. 2002] specifically deal with rail/road intermodal terminals. Optimization approaches have also been used for terminal operations. Contributions can be found in [Gambardella et al. 2001], [Kozan et al. 1999], [Newton et al. 1998], and [Bostel et al. 1998]. The later contribution deals specifically with transhipment of containers between trains and trucks in intermodal rail/road terminals. [Newton et al. 1998] deals with railway blocking plans for conventional trains. The complexity of the operations and the costs explain why many intermodal services in Europe operate with a fixed make-up policy to avoid train composition and limit wagon handling in terminals.

Also specifically for intermodal transportation some research has been conducted on the drayage transportation at each end of the intermodal trip chain. [Regan et al. 2000] present an analysis of the congestion issues on the American west coast experienced by trucking companies. The analysis shows that the congestion issue may prevent the further growth of the traffic in and out of the busiest ports proving that attention must be paid to the management of drayage moves. [Morlok et al. 1995] reckon that in order to improve drayage operations closer cooperation between intermodal shippers, intermodal train operators and drayage move operators. [Taylor et al. 2002] present a method for terminal selection in order to minimize empty vehicle movements and thus the total truck mileage used to perform drayage moves.

A general survey of opportunities for operations research in intermodal transportation can be found in [Macharis et al. 2004]. The survey covers all facets of intermodal transportation, although several contributions of interest in service network design are not included.

4.1. Scheduling transportation services

One issue stands out having a big impact on intermodal transportation performance; scheduling. The issue is inevitable for intermodal transportation where commodities are consolidated onto services (busses, trains, ships etc.) and the overall transit time for the commodities needs to be minimized. There are few examples though where schedules are less of an issue. For high-frequent public transit lines, such as metros, precise schedules needn’t be publicly available. From a passenger point of view these run all the time (almost like a rolling carpet), and thus timetables are superfluous. For lower frequency lines such as suburban busses, intercity trains, intermodal trains, and ships schedules have to be available for the customers or forwarders in order to be able to plan transportation itineraries.

A question arises: how does one design schedules for service networks? There is no easy answer to give. The difficulty arises from the many design issues that have to be considered, and their trade-offs. The first issue is what type of service to offer. There might be several different configurations for a service in terms of capacity, speed etc. The necessary capacity goes hand in hand with the available demand but also with the cost. Having a low capacity utilization but capturing all demand might be less efficient that running a lower capacity service but at full utilization. Another issue is frequency. Running frequent low capacity services, as opposed to scarce high capacity services, may from a total demand point of view be equal in terms of total capacity. Nevertheless, running at higher frequencies means less expected waiting time for commodities. The trade-off is the cost of running more services. The economies of scale are less apparent on the low capacity, high frequency services, as the fixed cost of performing the service presumably is lower per capacity unit on the high capacity, low frequency services.

Ultimately transportation services are performed according to customer needs, i.e. cost, time, etc. Thus schedules and timetables have to match customer requirements of when commodities are available at their origins and need to arrive at their destinations. This alone is not a trivial task for consolidated freight. Assuming commodities appear continuously the scheduled service times will under no circumstances match the availability time of all commodities when these are consolidated. The schedules have to be designed so that it matches the demand as well as possible. Additional complexity is added when considering a network of services with potential transfers. The schedule of a service now has to match time constraints of commodities subject to the connection to other services and their schedules. If the schedules do not correspond in transfer points excess transfer waiting time is added to the total transit time, thus deteriorating the commodity itineraries in the network. The question is though, is it possible to construct models that can determine optimal schedules for transportation systems that can be solved, and furthermore what can be gained from them.

The answer is yes; it is possible to construct models for optimizing intermodal transportation, and yes, there are potential gains in applying them. Both in public transportation and freight transportation there are several contributions focussing on schedule optimization. The big challenge arises in the application of the models due to the excessive solution times.

In public transportation most methods are either applied to a single line, or to a relatively small network. No methods have been applied to large-scale urban networks. The first paper included in this thesis contributes to the body of research in the area by presenting a model to optimize schedules in order to minimize passenger transfer waiting times and applying to the large-scale urban public transportation of the greater Copenhagen area.

In freight transportation there are several contributions on scheduling freight trains. There are also contributions on optimizing terminal operations, but only few combine the two together. Delivery times are always considered having fixed departure and arrival time. No contributions however, consider the trade-offs between transit time and operational costs or trains operating on a network of train canals. They are therefore not applicable in a European setting where scheduling on train canals represents an operational constraint and where transit times are important in the competition with road transportation. The second paper presents a service network design model that introduces a value of time cost for the transit time. The objective is to minimize the cost of transit time and the operational cost while obeying the availability of train canals and the capacity restriction incurred in terminals.

The model presented in the second paper can be simplified to resemble the well known fixed-charge capacitated multi-commodity network design model, with the exception of a new set of design balance constraints that complicate the model. The third paper included in the thesis proposes an algorithmic framework to solve network design models with design balance constraints and shows that heuristic approaches are interesting if not the only feasible approach to solve scheduling problems for large-scale transportation networks.

The following three subsections resume the main contents of the three papers and present the main results obtained.

4.2. Timetable optimization for public transit systems

The problem of scheduling service networks is particularly relevant for public transit, where many routes with many runs each day make up a large scale service network. Furthermore passengers' transit time is important. It is intuitive that when designing timetables for public transit networks the aim is to capture the transportation demand. That means high frequency routes are adopted where many passengers travel, and low frequency routes where few passengers travel. Expecting short passenger transit time by adopting this rule of thumb is probable, but not guaranteed. There is the issue of transfer waiting times when transferring between two different routes.

Public transit companies are aware of the issue and do attempt to synchronize route arrivals and departures in intersecting stops. Nevertheless, most the effort comes from manual planning. It is inconceivable that manual planning methods can capture the network wide effects of such large scale networks. Take for instance the network of three routes in figure 11.

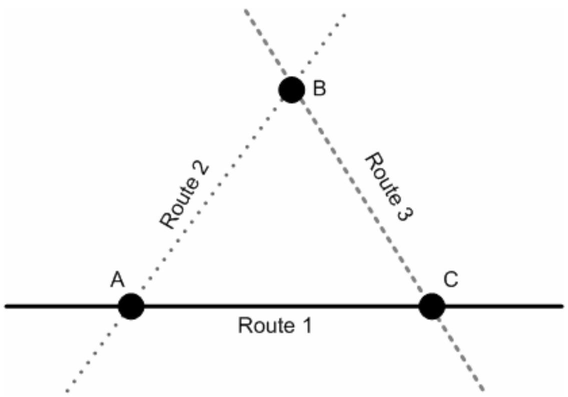

Figure 11. Example of three public transit routes intersecting in three stops

The three routes intersect each others in pairs in three stops. If we consider the intersection in stop A between routes 1 and 2 it is possible to organize the arrivals and departures of the two routes so that the transfer times between them is minimized. Next the synchronization between routes 2 and 3 in stop B could be considered. The runs of route 2 are already fixed given the synchronization in stop A. Thus the runs of route 3 are organized accordingly. Finally we turn our attention to stop C. Routes 1 and 3 are both fixed given the local optimization in stops A and B and unless the runs coincidentally correspond, routes 1 and 3 are not coordinated in stop C. In a small system like this, it is easy to see the interaction of the three routes in the three stops, and how a timetable change of one route affects the synchronization of the. Generally, public transit companies have a plan according to which routes have to be coordinated in intersecting stops. However, in a large scale network it is not trivial to see how a timetable changes in a stop affects the synchronization throughout the network in other stops.

Most of the focus from public transit companies has been on operational cost reduction. There are systems that can optimize crew and vehicle schedules given a fixed time table. These systems however, do not include the possibility of optimizing timetables. There is therefore a potential in developing a system that can handle the network wide effects of timetable changes. There is only very few examples of methods that have been developed to optimize timetables, few of which are very advanced or applied to large-scale systems. The first of the three papers that makes up this thesis is entitled ‘Minimizing Passenger Transfer Times in Public Transport Networks – An optimization model’ presents an optimization model that optimizes the timetables with respect to the transfer waiting times of passengers. The model is applied to the large-scale bus public transit system of the greater Copenhagen area and is solved by a Tabu search based heuristic. By having a non-linear global measure for the value of time cost of passenger incurred by the transfer waiting time the model finds a minimum cost configuration of the timetables. The model can verbally be expressed as

- Minimize the cost of time multiplied by the sum of all the transfer waiting times
- Transfer waiting times are calculated between connecting runs
- Arrival and departure times of a run in stops must obey the operational restrictions in stopping time in stops and the transit times between stops

- There must be equal headway (equal time spacing) between the runs of a route

The non-linearity of the model is due to the variation in passenger transfers according to the time-table. The number of transferring passengers depends on the configuration of arrivals and departures, i.e. long transfer waiting times, few passengers, short transfer waiting times, more passengers. The total cost of time of is a function of the number of passengers and thus implicitly becomes a function of the transfer waiting times, which it is multiplied by in the objective function.

The model is solved using a Tabu Search algorithm (TS) applied to the public transit network of the greater Copenhagen area. To handle the non-linearity of the model an approximation method is applied. It is assumed that the total number of passengers transferring between two routes in a stop during a time period (here from 16:30 to midnight) is constant. That number is redistributed within each iteration of the algorithm so that connections between runs that have short transfer waiting times have more passengers than the ones with longer transfer waiting times. The search process in the algorithm is a random search. Within each iteration a number of random routes are picked out and their time tables are modified by a random number of minutes. The best modification is saved and the search proceeds to the next iteration.

Although the TS algorithm is very simple and has long computational times the results achieved in the paper are promising. The best result obtained depending on the configuration of the algorithm's parameters show a cost reduction of 11% on the value of time. With an estimated guess it can be expected that the annual value of time cost reduction can be up to 4 million €. There are however a number of assumptions and issues not considered by the model that should be considered before an eventual implementation in the planning process of a public transit company. First of all the model should be expanded to include passenger itineraries. The model only treats transfers in stops without considering the passenger itineraries. The addition of passenger itineraries will make the model more complex, as a traffic model or itinerary estimation method has to be included, i.e. given a timetable how will passengers travel. The simple intuitive approach is to assume passengers always travel by the fastest path. This is not true though, as slower, but direct options, are often preferred to avoid the possibility of missed transfers. Even if the fastest path approximation is adopted, the model has to consider the interaction between the timetable of routes and the passenger itineraries. Furthermore the model is developed to minimize transfer times and does not consider the operational costs of changing timetables. In addition to adding passenger itineraries, an improved model should include operational aspects such as vehicle scheduling. This too adds extra complexity to the model. It is not clear how the trade-off between passenger travel time costs and operational costs should be handled.

There is however no guarantee whether a system for optimization would be a commercial success. The question is whether public transit companies believe that improving customer service by reducing transit time will attract more passengers to their network. And if passengers are attracted it is hard to prove that the improved service level is the cause and not some other factor. One may argue that political encouragement may be necessary for public transit operators to adopt such a system.

4.3. A model for intermodal train scheduling

Where the motivation to optimize schedules is straight forward for public transit the issue is more conceptual for intermodal trains; at least in Europe. First, intermodal train service networks are not as extensive as public transit networks in terms of number of routes and departures. Second, the transfer waiting time for freight is from the customers' point of view insignificant, as only the total transit time matters. For passengers the transfer waiting time has a higher value of time (i.e. bigger nuisance). However, all things equal, reducing transfer waiting time for freight will reduce the overall transit time and thus still provide better service to customers. Considering the interest from the European Union, the structural changes in the sector, and the investment in infrastructure it is legitimate to believe intermodal train networks will expand. Given bigger networks it will, just as for public transit systems, be difficult to plan services in order to achieve the best possible service for customers, i.e. the shortest possible transit times. Therefore there will be a need for planning systems that can design service schedules for large-scale intermodal train networks.

The second paper included in this thesis entitled 'Optimization of Intermodal Freight Train Service Schedules on Train Canals' presents a mixed-integer mathematical programming model conceived to design optimal service schedules for intermodal train networks in a European setting. The scheduling is done on a network of train canals according to the practice being introduced in Europe. Only one train can use a specific train canal. Therefore we implicitly assume that selecting a train canal is equivalent to performing a service between two terminals. Furthermore, terminal operations are considered in the model. Terminals have limited handling capacity etc, and this is included in the model in order to prevent congestion in terminals. To bring the commodities to terminals from their origins and deliver them from terminals to their destinations, drayage moves are used. Finally, it is assumed that commodities needn't be delivered at a particular time. The delivery time is controlled by a value of time cost. The higher the cost, the higher the value of transit time, forcing the model to schedule trains to achieve shorter transit times. The trade-off is higher operational costs if shorter transit times are to be achieved. The objective of the model is thus to minimize the sum of operational costs and the value of time cost. The model can verbally be expressed as:

- Minimize the sum of train, drayage and terminal operating costs and the value of transit time costs.
- The flow of commodities through the network must be balanced (commodities must flow from their origins to their destinations).
- The capacity on trains must be obeyed (i.e. less flow than capacity).
- The capacity in terminals must be obeyed (i.e. number of train present less that track capacity, flow through terminal lower than handling capacity, and inventory less than inventory capacity).
- Trains arriving at terminals must leave them again (to maintain flow balance of equipment).

The model is applied to a generated network instance and solved using Xpress-MP's MIP-solver. The network instance is generated with 15 customer zones, 25 terminals, and 7 time periods. The total number of binary decision variables and continuous decision variables is 805 and 168210 respectively with 44155 model constraints. The problem can therefore be considered a large-scale network instance. The results obtained with the MIP-solver indicate, not surprisingly, that the model is hard to solve for large-scale instances. The gap between the best feasible solutions and the lower bounds were between 22 and 43% after 90 hours of computational time on a PC with a 2.26 GHz Intel 4 processor.

Although the gaps indicate that the obtained results are far from optimal an analysis of the results still indicate that the model does perform as expected. Nine different scenarios were generated varying the total load of commodities on three levels and the value of time cost on three levels (totalling 9 different scenarios). The results from the different scenarios show that the total transit time experienced by commodities decreases as the value of time increases. As expected the decrease in transit gives an increase in the number of performed services and the operational costs.

In a real application of the model the value of time cost is an unknown factor. Methods exist to determine the value of time for passengers, and similar methods are being developed for freight. Nevertheless, given the non-consciousness of freight determining a value of time remains a complex task. However, the model gives decision makers a chance to test different value of times and resulting operational plans. The decision makers can then determine the trade-off between the level of service (i.e. transit time) they wish to offer and the operational cost.

4.4. An algorithm to solve a network design model applied to scheduling problems

The results achieved by solving the intermodal train scheduling model on the generated network instance with the standard MIP-solver Xpress-MP indicates that in order to reach a point where such models can be applied to real large-scale instances additional effort needs to be put in developing efficient solution methods. An often preferred approach for large-scale problems is to develop tailored heuristics that can give good solutions although not optimal. This avenue of research is particularly interesting because a well designed heuristic can provide good results in a short amount of time. Considering that for real applications the ‘optimal’ solution to a model isn’t necessarily optimal in the real world. Good solutions, that can be manipulated before be put into operation, are often adequate.

The third paper included in this thesis entitled ‘Network Design with Design balance Constraints’ presents an algorithmic framework based on Tabu Search that can be applied to models similar to the one introduced in the previous section. The fundamental model behind of the intermodal train model is a fixed-charge capacitated multi-commodity network design model (CMND). The CMND model consist of a set of nodes connected by arcs that may be open or not and a set of commodities that have to be transported from their origin nodes to their destination nodes. In order to transport the commodities some of the arcs need to be opened to allow the flow. The arcs have a fixed cost associated to them representing the cost of opening the arc (e.g. building infrastructure or offering a service) and a unit cost associated to the cost of routing one unit of a commodity. Furthermore the arcs have limited capacity. The objective is to minimize the sum of the fixed cost of opening arcs and the variable cost of routing commodities on the open arcs subject to the capacity limits on each arc. The arc formulation for the CMND model is:

$$\min \; z(X,Y) = \sum_{(i,j)\in\mathcal{A}} f_{ij} y_{ij} + \sum_{p\in\mathcal{P}} \sum_{(i,j)\in\mathcal{A}} c_{ij}^{p} x_{ij}^{p} \qquad (1)$$

$$\sum_{j\in\mathcal{N}^{+}(i)} x_{ij}^{p} - \sum_{j\in\mathcal{N}^{-}(i)} x_{ji}^{p} = d_i^{p}, \quad \forall i \in \mathcal{N}, \forall p \in \mathcal{P} \qquad (2)$$

$$\sum_{p\in\mathcal{P}} x_{ij}^{p} \le u_{ij} y_{ij}, \quad \forall (i,j) \in \mathcal{A} \qquad (3)$$

$$x_{ij}^{p} \ge 0, \quad \forall (i,j) \in \mathcal{A}, \quad \forall p \in \mathcal{P} \qquad (4)$$

$$y_{ij} \in \{0,1\}, \quad \forall (i,j) \in \mathcal{A} \qquad (5)$$

where *X* and *Y* represent the vectors of flow and design variables respectively, $y_{ij}, (i,j) \in \mathcal{A}$ represent the design variables that equal 1 if arc (*i*,*j*) is selected (and 0 otherwise). x_{ij}^{p} stands for the flow distribution decision variable indicating the amount of flow of commodity $p \in \mathcal{P}$ on arc (*i*,*j*) with origin node *o(p)* and destination node *d(p)*. Furthermore

$\mathcal{N}^{+}(i) : \{ j \in \mathcal{N}^{+} \mid (i,j) \in \mathcal{A} \}$,

is the outward neighbours of node *i*,

$\mathcal{N}^{-}(i) : \{ j \in \mathcal{N}^{-} \mid (j,i) \in \mathcal{A} \}$,

is the inward neighbours of node *i*,

u_{ij} : capacity of arc (*i*,*j*)

f_{ij} : fixed cost applied on arc (*i*,*j*),

c_{ij}^{p} : cost of one unit flow of commodity *p* on arc (*i*,*j*),

and

$$d_i^{p} = \begin{cases} w^{p} & if \; i = o(p) \\ -w^{p} & if \; i = s(p) \\ 0 & otherwise \end{cases}$$

The CMND model and the intermodal train model are similar in that the train arcs and the terminals in the intermodal train model can be interpreted as the design arcs and the nodes respectively in the CMND model. Similarly a set of commodities needs to be routed from their origins to their destinations. The fixed-cost of the design arcs are similar to those of the train arcs and the variable cost is achieved by the value of time of commodities. The intermodal model does however distinguish itself on several ideas. First, commodities have possible multiple destination nodes in the intermodal train model as opposed to a single node in the CMND model. Second, the terminals in the intermodal model are more detailed and have capacity limits, which is not the case for the nodes in the CMND model. Finally, the intermodal train model poses a restriction on the arcs, requiring that the same number of train that enters a terminal (or node) also leave it again. There is no such restriction on the design arcs in the CMND model.

The most radical change in the intermodal train model is the balance constraints stating that the number of design arcs entering a node most be equal the number of design arcs leaving the node. Given the balance constraints it follows that there is a dependency between the arc choices which is not present in the CMND model. If an arc *(i,j)* going from node *i* to node *j* is opened the constraints require that there is one open arc entering node *i* and one open arc leaving node *j*. The dependency between arc choices calls for special attention when designing a heuristic to solve the model. To investigate the attributes of adding design balance constraints a generic network model resembling the CMND is formulated with the addition of the design balance constraints in nodes. The model is denoted the design balanced capacitated multi-commodity network design mode, or DBCMND. Using the same definitions from the CMND model the arc formulation of the DBCMND model can be written as:

$$\min\ z(X,Y) = \sum_{(i,j)\in\mathcal{A}} f_{ij} y_{ij} + \sum_{p\in\mathcal{P}} \sum_{(i,j)\in\mathcal{A}} c_{ij}^p x_{ij}^p \tag{6}$$

$$\sum_{j\in\mathcal{N}^+(i)} x_{ij}^p - \sum_{j\in\mathcal{N}^-(i)} x_{ji}^p = d_i^p \quad \forall i \in \mathcal{N}, \forall p \in \mathcal{P} \tag{7}$$

$$\sum_{j\in\mathcal{N}^-(i)} y_{ji} - \sum_{j\in\mathcal{N}^+(i)} y_{ij} = 0 \quad \forall i \in \mathcal{N} \tag{8}$$

$$\sum_{p\in\mathcal{P}} x_{ij}^p \le u_{ij} y_{ij} \quad \forall (i,j) \in \mathcal{A} \tag{9}$$

$$x_{ij}^p \ge 0 \quad \forall (i,j) \in \mathcal{A}, \forall p \in \mathcal{P} \tag{10}$$

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in \mathcal{A} \tag{11}$$

The difference between the two models is the set of constraints (8) stating that the sum of open in-going design arcs must be equal to the sum of out-going design arcs for each node.

Network design models are, although easy to formulate, difficult to solve. The issue is no less apparent with the addition of the design balance constraints effectively interconnecting the design arc choices. The approach used to solve the model is to use a Tabu Search framework with two local search phases. In the first local search phase the design balance constraints are relaxed, i.e. the solutions found in the local search needn't be feasible with respect to the balance constraints. In each iteration the search opens or closes one or more arcs while maintaining flow feasibility, i.e. even if the solution is infeasible with respect to the balance constraints the number of arcs opened still has to allow the flow of the commodities from their origins to their destinations. Solutions are penalized though by an imbalance measure introduced to measure the infeasibility of a given solution. The penalty measure is used to guide the search in the neighbourhood of feasible solutions. The second local phase search is a feasibility phase, i.e. the purpose is to take the current solution obtained in the first local search phase and guiding it towards a feasible solution. This is done by opening or closing paths of arcs between nodes where the balance constraints are not satisfied. Phase 2 is terminated when a feasible solution is found or it is not possible to open or close any paths and returns to phase one. The search procedure switches between phase one and two until a predetermined time limit is reached.

The algorithm was tested on generated instances previously used in the OR literature to test network design solution methods. Although the second phase does not guarantee feasible solutions the algorithm found feasible solutions for all the tested network instances. The computational results obtained with the TS algorithm are compared to the results obtained by using Xpress-MP's MIP-solver on the same network instances. Both the algorithm and the MIP-solver where allocated 1 hour of computation time and the best found feasible solutions were compared. For about half the instance the solutions found with the TS algorithm were better than the ones found with the MIP-solver baring in mind that some of the instances were relatively small allowing the MIP-solver to find the optimal solution. For most of the largest instances the TS algorithm outperformed the MIP-solver. For the very largest instances the MIP-solver failed to find a feasible solution within the time limit, while the TS algorithm found feasible solutions for every instance. The results show that the algorithmic approach used is appropriate to solve large-scale instances for network design models with design balance constraints.

4.5. Applying the algorithmic approach used on the DBCMND to the intermodal train scheduling model

Comparing the mediocre results obtained from solving the intermodal train model with the superior results obtained in solving the DBCMND model it would be interesting to investigate the performance of the algorithmic approach used on the DBCMND applied to the intermodal train scheduling model. Although this exceeds the scope of the thesis this section will give pointers to the future approach of applying the TS framework to the intermodal train model.

First, it is clear that the TS framework cannot be applied as it is directly to the intermodal train scheduling model given the additional attributes inherent in it. There is an issue concerning the multiple destination nodes of commodities not inherent in the DBCMND model. This attribute should be easily handled. Within the framework a series of shortest path calculations and multi-commodity minimum cost flow problems are solved. Solving the shortest path from one origin to multiple destinations does not add significant complexity to the model. Considering the worst case scenario one shortest path is calculated to each destination, and the shortest of the shortest path is chosen. The multi-commodity minimum cost flow problems are LP-problems. Changing the flow balance constraints to allow multiple destinations changes the structure of the LP-model, but it does remain an LP-model. Thus the complexity is not increased significantly there either.

The complexity of adopting the algorithmic approach lies in handling the terminal. As mentioned the nodes in the DBCMND are just connection points between arcs where commodities may flow freely between the arcs. In the intermodal train scheduling model node are terminals at time periods and can only handle a specific number of trains and commodities. Thus there is a capacity constraint in each node on both flow and the number of open design arc passing through it. It is not clear how to handle these capacity constraints in the algorithmic approach. An educated guess would be to relax the flow capacity constraints from the iterations and make a feasibility check every time a design feasible solution is found. If one or more nodes have excess flow a simple redirection procedure to find alternative itineraries for some of the commodities traversing the node could be attempted to find a flow feasible solution. If that is not possible additional arcs would have to be added (while maintaining design feasibility). This however is a complex operation and further investigation has to be done as to how to get to a feasible flow solution. The issue of the capacity limits on open design arcs passing through a node is necessary to consider while constructing design feasible solutions in phase 2. This can be done by closing paths of arcs to reduce the number of open design arcs passing through an over-capacitated node.

Nevertheless, the results obtained by the TS framework on the DBCMND model show that it can handle the problems of having design balance constraints on nodes, an although there will be issues to handle when applying it to the intermodal train model it is legitimate to expect that the resulting algorithm would outperform the results obtained using a standard MIP-solver.

5. Conclusion – where to go now

The conclusion of this thesis is divided into two parts. The partial conclusions from the three papers on future modelling and algorithmic development are resumed in section 4 and will thus not be repeated here. The first part of the conclusion will focus on the eventual deployment of the models and solution algorithms presented in the three papers in practice, discuss why this is not obvious, and finally discuss the necessary steps to take in order to make it happen. The second part of the conclusion will focus on how the technological advances in the field of communication and satellite positioning may provide a basis for the development of operational and real-time based scheduling models and why these may have an easier time penetrating transportation service providers.

5.1. Deployment of scheduling models in practice

The results obtained in the three papers indicate that applying scheduling models for intermodal transportation may provide a valuable decision support system to benchmark different service network configurations and even provide solutions that improve the efficiency of the transportation system. The value of time cost savings of transit waiting time of up to 11% found in the first paper indicate that passenger service may be improved by adopting OR based models in tactical scheduling of public transportation systems. The model developed for intermodal freight train networks in the second paper indicate that scheduling models can provide a decision support system that can determine the trade-off between operational cost and customer service (in the form of transit time). Based on different calculated scenarios schedulers are able to determine different service network configurations and pick whichever they find most appropriate. Furthermore, customized heuristics, as the Tabu search algorithmic framework presented in the third paper, do provide good solution methods to solve the complicated models used to describe intermodal scheduling problems. The results obtained with the algorithm show that even though the models are difficult to solve with standard methods it is possible to construct specialized solution methods to speed up solution time and make the application of these models in practice feasible.

Nevertheless, even if models and solution algorithms may provide tools for tactical planning of schedules, it is difficult to penetrate the barrier of implementing OR methods in practice. For example, the results achieved in the first paper have been presented on several occasions, both at conferences and directly to public transit companies and system developers for public transit operations. Although the results are promising, the interest, especially from the public transit companies, has been minimal. Obviously, the model developed is not ready to be deployed directly in a tactical planning framework, but it is legitimate to expect that a minimum of interest in the results would be found in public transit companies, which has not been the case. The system developers to which the results were presented were concerned with whether there would be an economical gain from developing such systems, i.e. whether it could be sold or not. This concern is legitimate considering the little interest shown by public transit companies. From the public transit companies the response seemed more like a stubborn belief in as “we already plan schedules the best way possible and no system can improve that”.

From the statement above a question arises; are models, such as the ones presented in this thesis, worthless or are transportation companies wrong in their assumptions? Given the widespread use of OR models in e.g. airline transportation it is tentative to conclude that other transportation companies are wrong. It is also believed by a few what one could call ‘visionary’ people in other parts of the transportation sector that the airline industry is a trendsetter in the transportation sector and that the other more conservative modes will follow. Nevertheless, even if the reluctance to accept OR-based methods in the transportation sector derives from a conservative way of thinking it is still necessary to consider whether the ‘OR–business’ can provide applicable tools for the transportation sector and are focused on doing so.

It is legitimate to conclude that there still is a big gap between the research and development effort in OR and the needs of transportation businesses. Standard models, such the vehicle routing problem of network design problems get a lot of attention from researchers, but are in the their standard form in most cases to simplistic to capture the issues in real planning problems. The timetable optimization model from the first paper also falls into that category. Basically what can be deduced from simple models is that there is a potential in optimizing; a conclusion that is little helpful to applied planning when the models themselves are not directly applicable and that applicable models are not developed.

Furthermore, even simple OR-models are very demanding about availability and quality of data. Take for example the very simple fixed-charge capacitated multi-commodity network design model (CMND). The model is very simple to formulate, so easy that it is inconceivable that it sufficiently captures all the constraints of a real application. Nevertheless, its data requirements are considerable. For all arcs a fixed cost and a variable cost needs to be determined. Furthermore, it requires knowledge of commodity origins destinations and amounts. All of these data are not easily uncovered, but are nevertheless, assumed to be available when formulating network design models.

Considering this large data requirements it is understandable that business are reluctant to implement OR-models, as that would require extensive data-warehousing projects to uncover this data in reasonable quality. The models presented in the first two papers are more complex than for example the CMND model, but because they have not been developed in cooperation with an actual company (although influenced by current practice) they lack touch with reality and therefore stand behind with results showing that there is a potential which may never be proved in practice.

It is therefore imperative that the next step in the development of these models is to include industrial partners in order to close the gap between potential and implemented improvement. This responsibility lies with the OR-practitioners. It is necessary to get out and do a better marketing effort on the research results that are achieved at research centres or at universities. If the marketing effort is performed well, the companies should be able to see the potential benefits that models such as the ones presented in this thesis offer. This would eventually involve the companies in the development process and start tuning the models towards being applicable in practical planning situations.

5.2. Potential for OR-based methods in transportation scheduling

Since the term OR was 'invented' more than half a century ago, the big break for OR has been expected to be right around the corner. Although OR has been applied in different industrial segments its impact is still significantly smaller than what was expected. From a positive point of view the application of OR in transportation is one of the few general success stories. Especially the airline industry has adapted OR-based methods in many parts of the planning process. However, other parts of the transportation sector, e.g. public transportation and most of freight transportation, have not adapted OR-based methods to the same extent and do therefore not hold a dominant position in the planning process (or only in parts of it). With the technological development seen over the past two decades in form of the internet, mobile communication, and now GPS applications is it legitimate to believe that OR-based methods may finally have a significant breakthrough to hold a central position in transportation planning? Answering the question would be predicting the future, which is not the intention with this thesis. Nevertheless, real-time collection of data e.g. through GPS and real-time communication through mobile communication does enable the reduction of response time. In many facets of modern society there is a tendency to shift from long-term planning to short-term planning because technology allows it.

Long-term planning allows thorough planning prior to operation, something which to a large extent can be done manually. However, if decisions need to be taken on large amount of data becoming available in real-time (e.g. GPS measurements) that effectively exceeds the cognitive ability of the human mind. Here quantitative methods and OR-based methods in particular implemented in decision support systems that can handle the large amounts of data, analyse them, and propose solutions than can assist decision makers in making real-time decisions. Eventually, when models become more advanced much of the decision process could be automated.

In this thesis the complexity of scheduling services in intermodal systems is illustrated. The many interactions and trade-offs that need to be considered makes it hard to establish the optimal configuration. Nevertheless, given the tactical nature of the problems presented here, a significant amount of time is available to consider planning a reasonable service network manually. Although possibly faster, the benefits offered by optimization methods are less obvious because results and decisions needn't be found fast and taken quickly. Let us for a moment assume that schedules planned manually are of equal value to those planned with optimization methods and that time is not an issue. These plans contain arrival and departure times of service along with a plan for which services are synchronised, i.e. transfer possibilities between services, or correspondences. If at execution time no disruptions occur, the schedule is executed as planned, allowing the transfer of commodities between services as allowed by the schedule.

However, disruption does occur, meaning services do experience delays in transit. If a service is delayed enough the planned correspondences with other services may not be possible to achieve unless these services a delayed as well. The current practice now is that each service operates independently of one another, effectively resulting in unachievable correspondences in case of delays. The new mobile technology and vehicle positioning systems allows real-time estimation of delays and communication between vehicles thus allowing services to be delayed purposely in order to retain the planned correspondences. However, if a service is delayed and the services it has planned correspondences with are delayed too it may eventually send a shock wave of delays throughout the transportation service network. So how does one decide on whether to purposely delay other serviced purposely in case of a disruption on another service? That depends on the number of commodities transferring between the disrupted service and other services and the intensity of the disruption; an evaluation that is difficult to make. Nevertheless, a decision needs to be taken in real-time on whether 'to go or not to go' where the objective is to minimize the overall disruption in the whole service network. This task is tailored for a quantitative decision support system although its response time and thereby its calculation time is critical.

Implementing OR-based methods to planning situations (generally real-time planning situations) may prove to be a perfect introduction for OR-based methods if the decision makers acknowledge their limitations and the benefit of getting assistance from a decision support system. If such decision support systems can penetrate transportation businesses in assisting real-time planning problems the road is cleared for adopting OR-based methods more extensively in tactical and strategic planning. The experiences and information collected at on operational/real-time level of the performance of schedules in different cases of disruptions may be used to investigate the efficiency of the pre-planned schedules. If the collected data support significant evidence of this, transportation businesses may then want to investigate whether schedules can be pre-planned more efficiently in order to avoid as many disruptions as experienced in operation. One may then argue that although the planning process sequentially moves from strategic to tactical to operational, the successful full-scale introduction of OR in transportation may have to happen in the inverse order and progress as good quality data becomes available on the various planning levels.

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Minimizing Passenger Transfer Times in Public Transport Networks – An optimization model

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Abstract

The paper presents a mathematical programming model that deals with the problem of minimising the transfer times of public transport passengers in large scale public transit systems. The model sets the routes of the public transport network such that the transfer time between routes and intersecting stop is as small as possible. Each transfer waiting time is weighted by the number of passengers making the specific transfer. It is obvious that transfers with little transfer waiting time are more attractive to passengers than other transfers and hence the number of transferring passengers depends on the transfer waiting time. This leads to a non-linear objective function. We discuss how to come around this non-linearity.

Because of the large scale of the model it is solved using a Tabu Search metaheuristic. The paper presents the results on a large-scale data set taken from the Greater Copenhagen region, a region of approximately 1.7 million inhabitants. The results of up to 11% improvement on the passengers value of time by minimising the transfers waiting times suggests that there is some potential in using this approach when designing timetables for public transport service networks.

1. Introduction

Congestion on highways and in cities is becoming a very significant factor in the modern economies. On a daily basis 10% of the highways in Europe are subject to congestion and the number of cities around the world, where mobility is restricted because of congestion, is large. It is estimated that congestion in 2001 accounted for 0.5% of the European Unions GDP and could account for 1% by 2010. Hence it has a significant impact on the affected region's productivity. All tendencies point to transportation increasing over the next decades due to globalization, increased economic activity within the EU and the increased mobility of people. Transportation accounts for 28% of the total human made emission of CO_2 into the atmosphere. Hence an increase of transportation under existing conditions would also increase levels of pollution.

Many authorities investigate and lobby for alternative transportation possibilities in order to have a sustainable development to meet the demand for transportation. For urban authorities the increased use of public transit is a way to minimize congestion and eventually pollution. Although increased use of public transit would improve congestion and pollution conditions, people are reluctant to use it for several reasons. Many people perceive the service level of public transit as poor, and consider they are more flexible and can travel faster using their car. This is certainly true in rural and to some extent suburban areas. However, the levels of congestion on highways and in urban centres somewhat show that perception is wrong. Nevertheless, car transportation is still dominant and action must be taken if the modal balance between car transportation and public transit must shift.

To shift the balance between the use of cars and public transportation one can either increase the attractiveness of public transit or impose barriers on car transportation. The most interesting way to improve public transits competitiveness is to reduce the transit times of public transit trips. Projects such as new light rail systems, new metro systems, dedicated bus lanes, priority at light signals etc. are examples of ways to improve public transit service. Common to them all is the fact that they require more or less substantial capital investment. The question is whether public transit service can be improved without significant investment in infrastructure.

It is obvious that it is economically infeasible to have direct connections between all origin and destination points in a public transport system. Transfers between routes are therefore an unavoidable aspect of travelling with public transport. This is at the same time one of the biggest nuisances in using public transit because they increase transit time of a trip without contributing to the spatial movement of the trip. By reducing the transfer waiting time the total transit time is reduced and the nuisance of making transfers is reduced.

This paper investigates the possibilities of minimizing transfer waiting times for passengers in a large-scale public transit system by determining the time tables. The paper presents a non-linear mixed-integer mathematical programming model that captures the interrelated decisions on how to synchronize routes in a public transit network. The output of the model is a proposition for a timetable that minimizes the sum of the transit time for all passengers in the system. Hence the models decision variables are the departure and arrival times of all the runs on all the routes in a public transit system. The paper also presents a heuristic solution method based on Tabu Search. The solution method is applied to a large-scale data set from the Greater Copenhagen area.

Section 2 presents a general description on how time tables are planned and further specifies the problem. Section 3 reviews related literature on timetable optimization and synchronization. In section 4, the modelling assumptions made are presented and discussed, while the mathematical model is presented in section 5. Section 6 goes through the details of the Tabu Search heuristic method used to solve the model. Section 7 presents the case used to test the solution method based data from the Copenhagen region while section 8 presents the obtained results. Finally section 9 further discusses the modelling assumption made and ideas on how to improve them and the method in future research, and section 10 concludes the paper.

2. Planning time tables

This section is based on the planning practice within the Copenhagen metropolitan area by the Copenhagen regional planning authority and the public transit operators. The procedures used there are similar to what is seen elsewhere though.

There are a lot of interconnected planning tasks when designing and revising a public transit system, both political and operational. The outcome of the planning is a public transit system consisting of runs and a timetable visible to the passengers using the public transit system.

Public transit systems are usually revised few times every year. This means that planning timetables can be seen as a tactical planning exercise with a time horizon of a few months to half a year approximately. However, revisions rarely lead to big changes. The biggest changes are seasonal adjustments in frequencies. Only small changes are usually made to the network design and only rarely are new routes added. Revisions are mainly considered using manual methods. Software systems exist to calculate the impact of the changes on operating costs such as vehicle and crew scheduling. However, only few planners use systems to measure the impact on the perceived service level by the users.

A high level of service in a public transit system is synonym with having high frequencies on the routes. When deciding on frequencies the obvious consideration is to have high frequencies on routes with many passengers and lower frequencies on routes with fewer passengers. However, high frequency routes attract more passengers and low frequency less. Thus there is an enhancing effect that has to be considered and it is therefore not a trivial exercise to find optimal frequencies.

Some routes that run very frequently do not have a fixed time table from a customer point of view. This is especially true for metros or downtown bus lines in rush hour. Nevertheless, all lines operate with a time table from an operator's point of view. Timetables publicly available for customers often have fixed headways between departures. E.g. a bus route with 20 min headway would have even spaced departure times at 03, 23, and 43 every hour. This makes it easier for customers to memorize time tables and is thus perceived as better than timetables with variable headways.

When passengers choose their travel path through the system, referred to as route-choice, they obviously tend to choose paths with short transit times. As mentioned in the introduction transfer waiting times increase transit time, thus passengers choose paths including routes that have good transfer connections between them. Hence some attention is paid to on how to connect routes to give passengers good connections when travelling through the system.

Even small changes in a timetable may lead to changing a connection between two routes from having a short transfer waiting time to having a long one. Deteriorating one connection or improving another can, because of the change in transit time, make passengers shift from one route choice to another. Thus managing connections manually in a large public transit system is difficult due to the many intersections connections between routes and the difficulty in predicting passenger travel behaviour. Generally planners have a notion of where to synchronize routes' to achieve good connections e.g. big terminals on main transit routes, but it is not possible to consider all connections simultaneously manually.

3. Previous Work

This section presents literature relevant to the work in this paper. The section illustrates the contribution of the work in this paper in relation to the existing body of literature and what previous results contribute to the assumptions made here.

[Constantin et al. 1995] proposes a model to minimize total waiting time in a public transport system by finding optimal frequencies for each route, by taking into account travellers' behaviour regarding route-choice. However, the model does not include fixed time tables, thus synchronisation is not an issue. Transfer times are modelled as an expected value based on the frequencies.

[Ceder et al. 2001] presents a model for maximizing synchronization in timetables. The model defines a synchronisation as an event where two vehicles arrive at a stop simultaneously, enabling passenger transfers. The model seeks to maximize the number of synchronizations. However, synchronisation is only achieved if busses arrive simultaneously at stops, and the model doesn't consider the possibility of one-sided synchronisation where one bus can connect to the other but not vice-versa

[Klemt et al. 1987] presents a quadratic semi-assignment programming model with set covering constraints. The model assumes time-independent passenger transfer-flow patterns. A similar model is presented in [Daduna et al. 1993]. Here too there is the assumption of transfer-flow patterns being independent of the transfer waiting time. This assumption means that the number of passengers using a transfer is independent of the transfer waiting time. If there are only a few connections in a network the assumption holds, due to the fact that passengers will not have alternative choices. However, in networks with many path choices bad synchronization at one transfer will have passengers choose alternative paths with better synchronization. In this paper passenger transfer flows are not constant but determined based on the actual transfer waiting times.

[Bookbinder et al. 1992] present a model based on the model in [Klemt et al. 1987]. The model includes stochastic transfer waiting times. Arrivals are described using a shifted truncated exponential distribution. Furthermore a second-degree polynomial relationship is used to describe the disutility as a function of the transfer waiting time. As for the original model proposed by [Klemt et al. 1987] passenger flows are considered independent of the actual transfer waiting times. An interesting result is that when optimizing simultaneous connections in the network, deterministic and stochastic models only defer when arrival time of the feeder line is close to the departure time of the connecting line. Hence in this paper we are going to assume deterministic times and apply a buffer time to achieve this.

Other models that consider stochastic times are presented in [De Palma et al. 2001], [Knoppers et al. 1995] and [Carey 1998]. However, common to all three papers only the schedule of a single line is considered. Hence, system wide interaction of routes is not considered when scheduling.

4. Modelling the synchronisation of timetables

First the syntax used in the paper when describing a public transit system needs to be defined. A *stop* is a place where a public transit vehicle stops to embark and disembark passengers. A *route* is defined as a sequence of stops. A *run* is a time-dependent instance of a route. *Arrival* and *departure times* are associated to each stop for each run. An *intersection* is a stop where several routes cross, allowing passengers to make transfers. The time between a runs arrival time and departure time in a stop is named *stopping time*. Finally the time difference between a run's departure time from a stop to its arrival time at the next stop is named *in-vehicle time*.

As it was stated in section 2, the problem is to determine the arrival and departure times of all the runs in each of the routes. Prior to formulating a mathematical model to determine the times, some assumptions need to be made.

4.1. Public transit system service network assumptions

First of all the problem is limited to only determine arrival and departure times for buses. Because of their planning complexity we are going to assume that rail/light rail/metro timetables are planned separately and thus are available exogenously and are fixed in the model.

To further simplify the problem it is assumed that the routes and their stopping patterns are fixed. Thus the geographical routing and stopping patterns is not considered. It is also assumed that the frequencies of the routes are determined prior to determining the arrival and departure times. Furthermore we assume that we keep a fixed headway between the runs. It is thus implicitly assumed that each route has a fixed number of runs in the planning horizon because of the constant frequencies, and that if one run is changed, the other change accordingly to obey the even headway constraint.

Stopping times and in-vehicle times are assumed to remain constant and deterministic. To change in-vehicle time in the system, improvements to the infrastructure (e.g. prioritised bus lanes, prioritised light signalling systems etc) or improved equipment needs to be invested in. The purpose of this work is to improve timetables based on the existing system infrastructure and equipment characteristics, which is why in-vehicle times remain constant. Obviously in-vehicle times are subject to disruptions, and are not deterministic in real public transit system. Thus it is necessary to consider the stochasticity of public transit operations. It is customary when planning timetables in real public transit systems to plan transfer connections with some slack in the form of an arbitrary buffer time to prevent to some extent missing connections. This approach is incorporated into the model to avoid the complexity of handling stochastic in-vehicle times.

Assuming constant stopping times means waiting time for on-board passengers (passengers in a vehicle not performing a transfer in a stop) can be neglected. This is because the combination of constant stopping and in-vehicle times keeps the on board part of the total transit time unaffected by the arrival and departure time. Only transfer waiting times vary depending on the arrival and departure times and thus only the transfer waiting times are considered in the model.

By assuming fixed headways between runs, constant stopping times, and constant in-vehicle times the problem is reduced to finding the departure time of the first run in the first stop in each route. The arrival and departure times of the remaining stops in the first run and all the departure and arrival times of the following runs can be calculated as a sum of in vehicle times, stopping times, and headway spacing time.

4.2. Connection and transfer assumptions

In order to calculate transfer waiting times it is necessary to define what is meant exactly by a connection. Initially a connection is defined as the possibility to change from a run on one route to a run on another route. However, the reverse change is not necessarily possible. This is illustrated on figure 1. On the left side of the figure a two-sided connection is shown. The two runs arriving at the stop (full line and dashed arrows) can have passengers transferring between them (slim arrows). On the right we have shown a one-sided connection. Here only the full-line route can have passengers transferring to the dashed-line route. The reverse transfer is not possible because the dashed line route arrives after the departure of the full-line route. When a connection is mentioned here it refers to a one-sided connection. A two-sided connection is considered as two separate connections.

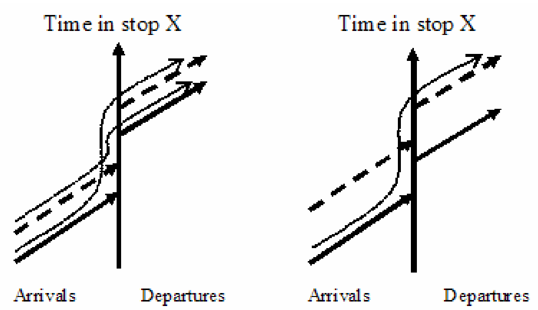


Figure 1. Illustration of two-sided connection (left) and one-sided connection (right)

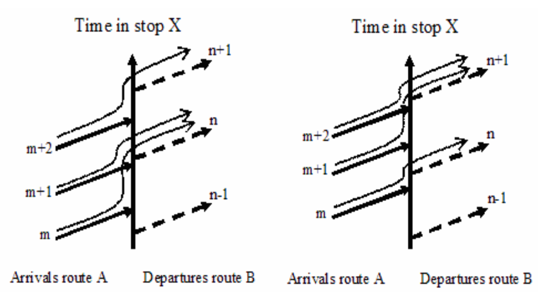


Figure 2. Definition of a connection between an arrival and a departure

A run may connect to several later runs on another route. However, if it is assumed passengers always transfer to the first departing run following their arrival the definition of a connection can be tightened by saying that there is a one-run connection for an arriving run. Figure 2 shows three arriving runs on one line and three departing runs on another line. Each arriving run is connected to one departing run. The slim arrows show the connections between arrivals and departures.

The right part of figure 2 is slightly different from the left. The arrival and departure times of the runs of both lines have been modified. The result is that e.g. run *m+1* is now connected to run *n*+1 instead of run *n*. It must e.g. be expected that more passengers use run *m+2* in the right configuration, while more passengers use run *m+1* in the first configuration. Hence it is assumed that the number of connecting passengers is a function of the transfer waiting time.

Obviously it is not possible to obtain good connections between runs for every single intersection. Hence the model needs to identify which runs have to be connected to obtain the optimal time table.

4.3. Evaluating a timetable

To measure how good a timetable is transfer waiting times of all connections need to be considered. The objective of the model is to minimize the weighted sum of transfer waiting times. It is not sufficient to minimize the sum of the transfer waiting times alone, because some connections are more important than others. A reasonable measure for a transfers' importance is the number of passengers that use it. Hence if the transfer waiting time of each connection is weighted with the number of passengers using it, the sum of all of these values returns a system value which the model seeks to minimize in order to find the optimal time table.

For an existing system and its timetable the number of passengers making transfers between routes in a public transit system can be counted. However, this figure does not apply to eventual time table changes. Instead an estimate of passenger flows on the routes can be calculated using a route-choice model, from which the number of transferring passengers can be deducted.

In route-choice models, passengers are not considered equal. Passengers placed in groups that have different disutility perceptions of waiting time. Generally a value of time is estimated for each passenger group that puts a price on the time of passengers. By dividing the passengers into groups and having passenger flows for each of these, the groups may be treated separately. The weights are obtained by multiplying the passenger flows with the value of time for each passenger group and adding the products together. The weights as a product of number of transferring passengers and their value of time now capture the total disutility perception for a given transfer measured in currency units. The objective function is thus the sum of the transfer waiting times multiplied by the "value" of each transfer.

The problem with using the number of passenger transfers to weight the transfer waiting times is that passenger route-choices are timetable dependent. Given a timetable, passengers will adopt some route-choice based on the transit time of the different route choice alternatives. By changing the timetable the route-choice alternatives are altered. If the time table is changed considerably passengers' route-choice also changes considerably because some transfer connections will get worse, others disappear, others improve and finally others occur. Because the route-choices change depending of the timetable implemented the number of passengers using a transfer is a function of the transfer waiting times. Thus the weights used in the objective function are functions of the transfer waiting times and the objective function is therefore non-linear.

5. A Tactical Non-linear MIP-Model for Minimizing Transfer Times in Timetables

This section presents a non-linear integer programming model for the problem described. First a set of times is defined. The number of elements in the set is equal to the number of minutes in the planning period considered:

$$\mathfrak{T} : \textit{set of minutes in the planning time period}$$

Second a set of lines is defined. The lines are used to distinguish between different routing possibilities of routes within the same line (e.g. a route in each direction):

$$\mathfrak{L} : \textit{set of lines in the network}$$

For each line a set of routes are defined:

$$\mathfrak{R}_l : \textit{set of routes for line } l$$

The fixed frequencies means each route has to perform a number of runs defined by the following ordered set:

$$\mathfrak{N}_r = \{n_r^1, n_r^2, \ldots, n_r^{\psi}\} : \textit{set of ordered runs for route } r$$

Although public transport lines stop a several places only the intersecting stops are considered:

$$\mathfrak{S} : \textit{set of intersecting stops in the network}$$

We define an ordered subset of stops for each route representing the order of intersection stops the route visits:

$$\mathfrak{S}_r = \{s_r^1, s_r^2, \ldots, s_r^{\omega}\} : \textit{set of ordered stops for route } r$$

A subset of stops is also defined for stops where two routes intersect:

$\mathbb{S}_{pr}$ *: set of stops where route p and r intersect*

The following parameters are used. The weight of the waiting times in between the runs in the network in the intersection stops is a function of the arrival and departure times of all runs on all routes for all lines. The vector *T* is the vector of arrival and departure time:

$\beta_{m,p,k,n,r,l,s}(T)$ *: weight of the waiting time for transfers between run m on route p for line k and run n on route r on line l in stop s*

$t^{\tau}_{p,k,r,l,s}$ *: Minimum transfer time between route p on line k and r on line l in stop s*

f_r *: headway of route r*

$t^{i}_{r,s,t}$ *: In vehicle time for route r between stop s and t*

$t^{\sigma}_{r,s}$ *: stopping time for route r in stop s*

t^{λ}_{r} *: latest time the last run for route r may start*

t^{φ}_{r} *: earlist time the first run for route r may start*

The following decision variables are used. For each run on each route for each line a departure and arrival time needs to be defined in each of the stops along the route:

$T^{d}_{n,r,l,s}$*: departure time for run n on route r of line l in stop s*

$T^{a}_{n,r,l,s}$*: arrival time for run n on route r of line l in stop s*

The waiting time for transferring passengers between two runs:

$T^{w}_{m,p,k,n,r,l,s}$ *: waiting time for transfers between run m on route p for line k and run n on route r on line l in stop s*

The following variable is an integer variable that controls which runs are connected (i.e. which runs passengers can transfer between)

$$\rho_{m,p,k,n,r,l,s} = \begin{cases} 1, \text{if run } m \text{ on route } p \text{ of line } k \text{ is connec-} \\ \text{ted to run } n \text{ on route } r \text{ of line } l \text{ in stop } s \\ 0, else \end{cases}$$

Given the preconditions, limitations and definitions from section 3.1 and 3.2 we present an optimization model that solves the problem of finding the optimal timetable with respect to passenger transfers for a public transit service network.

The objective function (1) states that the optimal timetable is found by minimizing the sum of the weighted transfer waiting times. Given the weights are a function of the arrival and the departure times the function is non-linear:

$$Min \sum_{\substack{m\in\mathfrak{N}_p, p\in\mathfrak{R}_k, k\in\mathfrak{L}, \\ n\in\mathfrak{N}_r, r\in\mathfrak{R}_l, l\in\mathfrak{L}, s\in S_{pr}}} \beta_{m,p,k,n,r,l,s}(T)\cdot T^{w}_{m,p,k,n,r,l,s} \quad (1)$$

Equation (2) limits the number of connections from an arriving run to other runs to one:

$$\sum_{m\in\mathfrak{N}_p, p\in\mathfrak{R}_k, k\in\mathfrak{L} | s\in\mathbb{S}_{pr}} \rho_{m,p,k,n,r,l,s} = 1 \qquad (2)$$

$$\forall n\in\mathfrak{N}_r, r\in\mathfrak{R}_l, l\in\mathfrak{L}$$

On the right hand side of equation (3) the transfer waiting times are calculated as the difference between the time of arrival and time of departure minus the minimum transfer time between the arrival point and departure point. If there is a connection between the two runs, i.e. ρ=1, the first half of the left-hand side will be zero, and the transfer waiting time variable is set equal to the right hand side. However, if there is no connection, the first half will become M (M being a sufficiently large number) and the waiting time can be chosen arbitrarily. Since the objective function in equation (1) will minimize the total weighted waiting time, all the ρ will be chosen so that the transfers are the connections to the first possible runs and the remaining transfer waiting times will be chosen arbitrarily to zero because of the non-negativity constraints:

$$M(1-\rho_{m,p,k,n,r,l,s}) + T^{w}_{m,p,k,n,r,l,s} \geq T^{d}_{m,p,k,s} - T^{a}_{n,r,l,s} - t^{\tau}_{p,k,r,l,s} \quad \forall n \in \mathfrak{N}_p, m \in \mathfrak{N}_r, p \in \mathfrak{R}_k, r \in \mathfrak{R}_l, k \in \mathfrak{L}, l \in \mathfrak{L}, s \in \mathfrak{S}_{pr} \tag{3}$$

Equations (4) and (5) are time constraints connecting the departure and arrival times at the stops for each run. Equation (4) states that the arrival time at the next stop is equal to the departure time of the previous stop plus the in vehicle time between the stops. Equation (5) states that the departure time at a stop is equal to the arrival time plus the stopping time at the stop:

$$T^{a}_{n,r,l,t} = T^{d}_{n,r,l,s} + t^{i}_{r,s,t} \quad \forall n \in \mathfrak{N}_r, r \in \mathfrak{R}_l, l \in \mathfrak{L}, s \in \{s^1_r, s^2_r, ..., s^{\omega-1}_r\}, t \in \{t^2_r, t^3_r, ..., t^{\omega}_r\} \tag{4}$$

$$T^{d}_{n,r,l,s} = T^{a}_{n,r,l,s} + t^{\sigma}_{r,s} \quad \forall n \in \mathfrak{N}_r, r \in \mathfrak{R}_l, l \in \mathfrak{L}, s \in \{s^2_r, s^3_r, ..., s^{\omega}_r\} \tag{5}$$

Equation (6) is a headway constraint that spaces out the runs of a route:

$$T^{d}_{n,r,l,s} = T^{d}_{n-1,r,l,s} + f_r \quad \forall n \in \{n^2_r, n^3_r, ..., n^{\psi}_r\}, r \in \mathfrak{R}_l, l \in \mathfrak{L}, s \in \{s^1_r\} \tag{6}$$

Equations (7) and (8) constrain the departure time of the first run on each route. By setting the earliest and latest departure time to be equal all runs on a route may by fixed (e.g. for train routes):

$$T^{d}_{n,r,l,s} \leq t^{\lambda}_r \quad \forall n \in \{n^{\psi}_r\}, r \in \mathfrak{R}_l, l \in \mathfrak{L}, s \in \{s^1_r\} \tag{7}$$

$$T^{d}_{n,r,l,s} \geq t^{\varphi}_r \quad \forall n \in \{n^1_r\}, r \in \mathfrak{R}_l, l \in \mathfrak{L}, s \in \{s^1_r\} \tag{8}$$

Finally, equations (9)-(11) are domain constraints on the arrival, departure, non-negativity constrains on the transfer waiting times, and binary constraints on the connection variables.

$$T^{d}_{n,r,l,s} \in \mathfrak{T}, \; T^{a}_{n,r,l,s} \in \mathfrak{T} \quad \forall n \in \mathfrak{N}_r, r \in \mathfrak{R}_l, s \in \mathfrak{S} \tag{9}$$

$$T^{w}_{m,p,k,n,r,l,s} \geq 0 \quad \forall n \in \mathfrak{N}_r, m \in \mathfrak{N}_p, p \in \mathfrak{R}_k, r \in \mathfrak{R}_l, k \in \mathfrak{L}, l \in \mathfrak{L}, s \in \mathfrak{S}_{pr} \tag{10}$$

$$\rho_{m,p,k,n,r,l,s} \in \{0,1\} \quad \forall n \in \mathfrak{N}_r, m \in \mathfrak{N}_p, p \in \mathfrak{R}_k, r \in \mathfrak{R}_l, k \in \mathfrak{L}, l \in \mathfrak{L}, s \in \mathfrak{S}_{pr} \tag{11}$$

The model is a non-linear integer programming model and thus difficult to solve. The number of connection variables, $\rho_{m,p,k,n,r,l,s}$ (binary variables), depends on the number of route intersections in the network. The number of integer departure and arrival variables depends on the length of the planning horizon. Although the integer variables presumably can be relaxed the binary connection variables and non-linear weights renders the model intractable by standard solvers for large scale instances. As we are considering a large scale urban transit system a tailored heuristic is considered.

6. Solution Method Based on Tabu Search

It is assumed that it is impossible to solve this non-linear integer-programming model for large scale public transit systems to optimality. Some alternative needs to be considered. There is the possibility to linearize the objective function by making the weights independent of the transfer waiting times. Instead of using passenger transfers as weights some arbitrary value based on the importance of a transfer may be attributed to a connection. E.g. a transfer between bus and a train could be more important than a transfer between two buses, because more passengers usually transfer from bus to train than from bus to bus. However, having fixed values does not capture the changes in passenger route-choices.

Thus, a heuristic solution approach based on Tabu Search (TS) is considered here to solve the model with the non-linear objective function. The choice of using TS is made because of two reasons. First, TS has proven to be efficient in solving complex models in many areas of application (see for instance [Glover et al. 1997]). Second, the principles behind TS are very intuitive and resemble the manual procedure used when revising time tables for public transit systems.

TS has been used in several applications before. It is a general algorithmic framework that is independent of the application it is used in. Only the most common elements of TS will be presented here. Based on an incumbent solution (here a feasible timetable), a number of neighbour solutions are examined (here alternative timetables), after which the best feasible neighbour solution is selected as the new incumbent solution. Based on the new incumbent solution the neighbourhood search is repeated until the procedure is put to a stop given some criterion. A neighbour solution refers to a solution that resembles the existing solution with a small change. TS thus performs a local search in the solution space. To start of the search an initial solution is needed. In case of a real life application an existing timetable for the transit system may be used. The word Tabu refers to a selection rule that is imposed on the possible neighbour solution. In order to prevent cycling between neighbour solutions and slow the search for the optimal solution a tabu list is kept. A solution on the tabu list cannot be chosen as the new incumbent solution.

6.1. Neighbourhood definition and size

The main issue in applying TS is how to design a neighbourhood of solutions. In our case a solution is a feasible time table for the public transit system. We define a neighbour solution to a given timetable as another feasible timetable, where the departure and arrival times of the runs on one route in the system has been changed by +/- n minutes. The value of n is any value in the range $1 \leq n \leq N$. The value of N is here set to either 10 or 20 minutes representing the most common frequencies of urban public transit routes. Attempting to skew one route at a time resembles the trial and error approach used by public transit planners when revising timetables. A graphical example can be used to better explain the definition of a neighbour solution. Figure 3 shows a small public transit system. The black numbers represent the stop numbers and the grey numbers are the in-vehicle time between stops. The stopping times in the stops are in this example set to one. The transit network is composed of three lines, each including two routes; one in each direction. The three lines run between stops 1-2-3-4, 5-2-8-9, and 7-8-3-6 respectively.

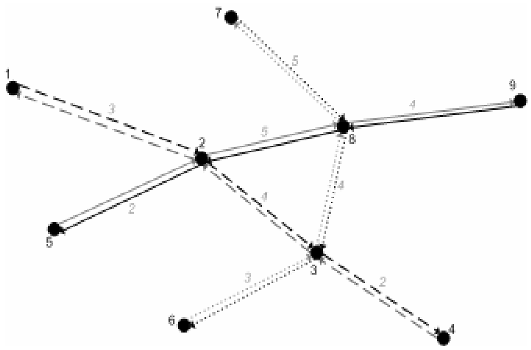


Figure 3. Example of a small public transport system with 3 lines and 6 routes

The system as it is illustrated in Fig. 3 shows the geographical lay-out of the system and holds no timetable information. In order to show time table information for this network graphically it is transformed into a time-space network as shown in figure 4. Here the geographical lay-out is omitted to have the time-dimension of the problem included. The routes are shown with arrival and departure times. The figure thus represents a possible timetable for the system in figure 3.

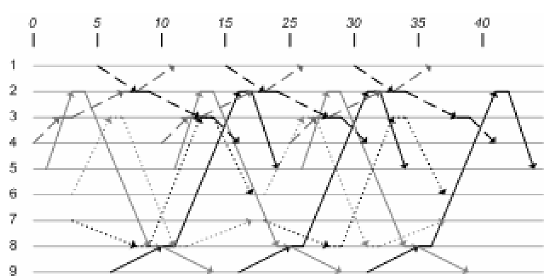


Figure 4. Time-space representation of network in figure 3.

I figure 4 it can be seen that the black dashed route departs from stop 1 at times 5, 15, and 25. Figure 5 illustrates a neighbour solution to the timetable network representation in figure 4, where the departure times of the black dashed routes have been moved forwards by 2 minutes (as illustrated by the large arrow). The two timetable solutions shown in figures 4 and 5 are each others' neighbours.

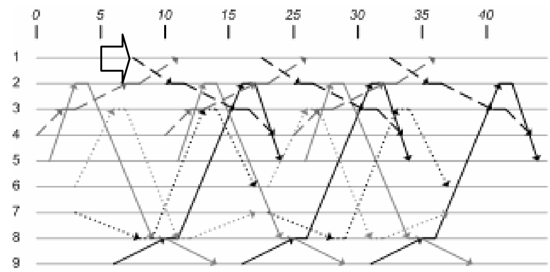


Figure 5. Alternative neighbour solution where the black dashed route's departure times are moved forward by 2 minutes

In a network with *r* routes the size of the neighbourhood for each incumbent solution will be $n \cdot r$. For large scale networks the number of neighbour solutions thus is very large. Evaluating each neighbour solution within each iteration is too computationally time consuming. Therefore only a subset of solutions will be evaluated in the algorithm. It would be preferable to examine only those neighbour solutions that could lead to potential improvement. However, identifying these is non-trivial. Therefore it is chosen in this research to select *m* neighbour solutions randomly and examine those. It is left to future research to determine a better neighbour sub-set selection method. The number *m* is set to either 10 or 20 neighbour solutions.

6.2. Evaluating a neighbour solution

Each time a neighbour solution is chosen it has to be evaluated to be able to compare it to the incumbent solution. The evaluation is based on the objective function from the model. In order to compute the

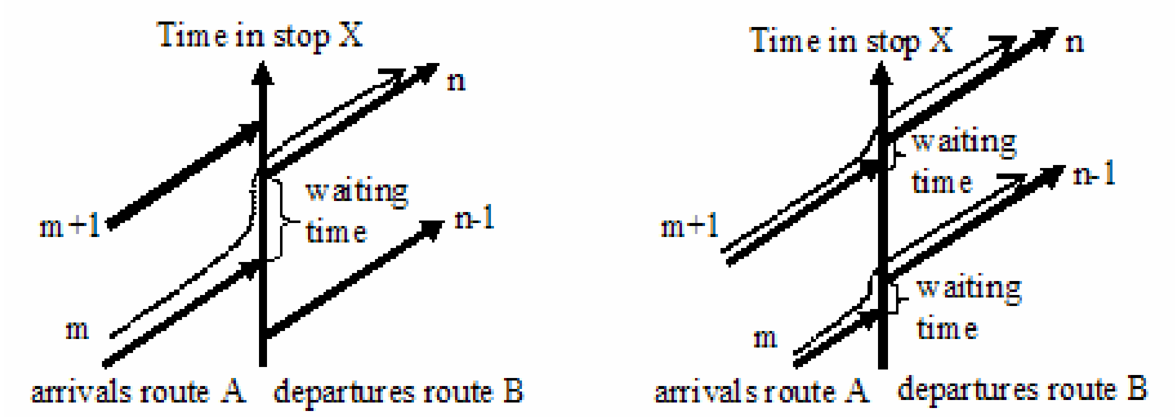


Figure 6. Displaying the problem of breaking connections

objective function we need to compute its two components, the waiting times T^w and the weights β.

6.2.1. Calculating transfer waiting times

Every time a change is made to a route, the connections between the runs of the route and the runs of other routes in intersection stops needs to be recomputed. This is because changing a route may lead to breaking some connections between runs. This is illustrated in figure 6.

Figure 6 shows that runs n-1 and n of route B have been changed (moved forward in time). This leads to a different connection configuration between runs m and m+1 of route A and the runs of route B. We denote a connection between a run m and a run n as $m \rightarrow n$. In order to be able to calculate the right waiting time, connections need to be re-evaluated for each move. This eventually means transfer waiting times need to be recalculated for all connections affected by the route change. These are all the routes in all the intersection stops the changed route passes. For the initial solution this calculation has to be performed for every route to all other routes in an intersection and for all intersections. This is a very time consuming computation. However, to calculate the transfer waiting times for a neighbour solution only the intersections on the route changed need to be recalculated. The transfer waiting times in the remaining intersections are unaffected by the change. This is still computationally demanding though.

6.2.2. Calculating the number of transferring passengers for the weights

In our model in section 5 the weights β were represented as functions of the Transfer waiting times. This section presents the function used in the TS algorithm to compute the weights. Principally the route-choices have to be recalculated every time a new neighbour is proposed. Due to the demanding computational effort to calculate route-choices this is not a feasible option. To overcome this problem an approximation is adopted. The passengers' route-choices are only calculated for the initial solution. To avoid recalculating the route-choices for each iteration we are going to assume that if we aggregate the sum of the passengers on connections between two routes for the initial solution, that number remains constant for any neighbour solution. This is a rough approximation but the relative value of the different route to route transfers should still give a correct indication of the importance of each of the route to route transfers.

Having aggregated the transferring passengers on route to route transfers these transfer flows need to be re-distributed on the connections between the runs for a given timetable. First the number of passengers is re-distributed equally on the departing runs that have at least one connection from an arriving run. This is illustrated in figure 7 where two of the three departing runs have connections from the arriving runs. Each of the runs is allocated *P/2* of the total flow *P*.

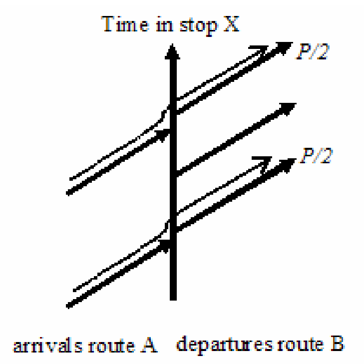


Figure 7. Passenger flow redistribution on departing runs

To calculate the further distribution of the passenger flows on the arriving runs given the distribution on the departing runs it is necessary to make some assumptions on passenger behaviour. Experience from public transit systems shows that passengers travel intelligently (i.e. check the time tables before travelling) if they use low frequency routes, and travel more or less randomly when using high frequency routes. It is assumed that this behaviour is reflected in the passenger transfer patterns; hence more passengers use connections with short waiting times. However, analysis made for the Copenhagen region public transit system show that passengers travel randomly on routes with a headway spacing of 12 minutes or less, while they travel intelligently on low frequency routes (headway spacing larger than 12 minutes).

Figure 8 shows two departing runs on a route with a headway that is less than 12 minutes. The first run in figure 8 has only one connection and hence all the *P/2* passengers come from the first arriving run. The second run in figure 8 however has two arriving runs connected to it, and hence the *P/2* passengers are equally distributed on the two arriving runs with *P/4* passengers on each. The situation illustrated in figure 8 is expected to occur only seldom. In most cases we can expect mostly having one connection to each departing run of high frequency routes.

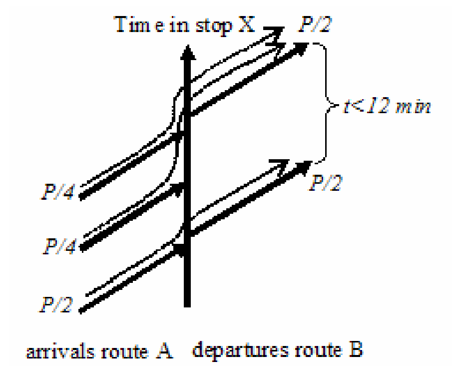


Fig. 8. Illustrating redistribution on arriving runs having high frequency departures

Although it is assumed passengers arrive intelligently when transferring to a low frequency route it cannot be assumed that all passengers will arrive with the best connection (i.e. travel intelligently). It is assumed that all connecting arriving runs have their share of the flow on the departing run in order to approximate the randomness in some passengers' travel patterns. We have chosen to use a distribution function that calculates the passenger flow as a function of the transfer waiting times. The function is given by the following equation:

$$P_{m,n,s} = P_n \frac{\sum_{m|m \to n} T^w_{m,p,k,n,r,l,s}}{\sum_{m|m \to n} \left(\frac{\sum_{m|m \to n} T^w_{m,p,k,n,r,l,s}}{T^w_{m,p,k,n,r,l,s}} \right) \cdot T^w_{m,p,k,n,r,l,s}}$$

Given that run *m* is connected to run *n* the function calculates the number of passengers transferring from run *m* to run *n* in stop *s*, $P_{m,n,s}$. The symbol, P_n, is the number of passengers transferring to run n. Figure 9 shows a departing run with flow P and with three connecting arriving runs. In the case of figure 9 the transfer waiting times from the three arriving runs to the departing run are 5 min., 20 min. and 35 min. respectively. Using the function it yields that 72% of transferring passengers will use the best connection and the remaining 28% will be dispersed on the two worst connections.

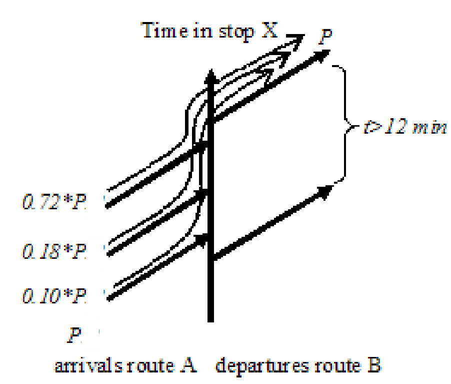


Figure 9. Illustrating redistribution on arriving runs having low frequency departures

Even though the number of transferring passengers from route to route is assumed constant, the approximation still captures to some extent the passenger route choices.

6.3. Tabu list

In its general framework TS requires that each previous incumbent solution is kept in a tabu list for a number of iterations in order to avoid cycling between solutions. The length of the tabu list (i.e. the number of iterations previous solutions remain tabu) is normally determined empirically. However, keeping entire timetable solutions in the tabu list is not practical for large scale transit systems. Each time a neighbour is examined, it must be compared to each of the previous solutions is the tabu list to check whether it is Tabu. Comparing entire solutions, i.e. comparing all the arrival and departure times, is very time consuming. Instead of keeping entire solutions in the tabu list, only the change made in each iteration is kept. Thus the only information kept in the tabu list is the number of the route changed and the number of minutes it is changed by.

By keeping only the information on the route changed and the number of minutes it is changed by, we only need to compare the change made to an incumbent solution with the previous changes kept in the tabu list. This comparison to check whether the current change undoes a previous change can be done very quickly. However, by adopting this mechanism we exclude the choice of possible non-tabu solutions. Consider a change of *n* minutes on route *r* made in the *i*'th iteration and say it is kept in the tabu list until the *k*'th iteration. Imagine that at the *j*'th iteration, $i<j<k$, a change of $-n$ minutes to route *r* is proposed. From a tabu list perspective the changes made at the *i*'th iteration are now undone and the neighbour solution will not be permitted. However, between the *i*'th iteration and the *j*'th iteration a number of other changes are made to the incumbent and thus the

changes made in the *j*'th iteration needn't undo the changes from the *i*'th iteration.

In order to allow for solutions that are registered on the tabu-list due to the limited information kept, but are not tabu, an aspiration criterion is adopted. The criterion adopted here allows for tabu solution to be the next incumbent solution if its objective value is better than the current one. Using this criterion, tabu solutions that are worse than the incumbent one are discarded, while better solutions are permitted, allowing the algorithm to always move towards a better neighbour solution, if one exists.

6.4. Stopping criteria

The algorithm is put to a stop if the improvement of the best solution is less than α % over *x* iterations. The *x* iterations will be referred to as GAP.

To estimate α and GAP we make the following observation. Consider having two routes with 20 min. frequencies and a current transfer time of 1 minute from one route to the other. If the departing run is moved one minute forward in time by two minutes, suddenly the transfer time is 19 minutes instead of 1 minute. This means that it is likely for the algorithm to propose neighbour solutions that don't improve the current best solution.

To enable the algorithm to propose poor neighbour solutions in a series of iterations the value of GAP should not be too small. Here the value of GAP is arbitrarily chosen to either 100 or 200, assuming that these figures are large enough. The higher the value of α the faster the algorithm will stop, hence this value too should not be to high to allow the algorithm to converge towards the optimal solution. We shall opt for a value of α of either 0.1% or 1%.

7. Applying the Tabu Search Algorithm to Large-Scale Data

The algorithm described in section 6 has been tested on a large scale data set originating from the Copenhagen-Ringsted model (CRM). CRM is a traffic equilibrium model made to estimate traffic in Eastern Denmark following a projected railway line from Copenhagen to Ringsted. More information on CRM can be found in [Nielsen et al. 2001]. Using CRM has the advantage that all the existing time tables for trains, metros and busses in Eastern Denmark are already assembled in one database. This provides a starting solution for the TS algorithm. Another advantage of using CRM is that the route-choice model EMME/2 in incorporated into the model. Hence it is possible to calculate passengers' route-choices based on the timetables available through CRM. The principles behind the basic model behind EMME/2 are described in [Florian 2002], and the modified version, which has been extended to find stochastic user equilibrium, used in CRM is described in [Nielsen 2003]. Using the passenger flows calculated by EMME/2, passenger transfer flows may be calculated.

The CRM-model has passengers divided in three distinct groups; 1) business passengers, 2) commuters and students, and 3) recreational passengers. Passengers in each of the three groups have different perceptions of waiting times. The value of time for each of the three passenger groups have been estimated [Nielsen, O.A. et al 2001] to 270 DKK/hour, 38 DKK/hour and 28 DKK/hour respectively. The values of time can be perceived as the amount a passenger is willing to pay to reduce transfer waiting time by one hour. Using the passenger transfer flows and the values of time, the weights for our objective function can be calculated as a multiplication of the two.

In this project we reduced the size of the data set to include the greater Copenhagen metropolitan area instead of the whole of Eastern Denmark. This is illustrated by dark area in figure 10.

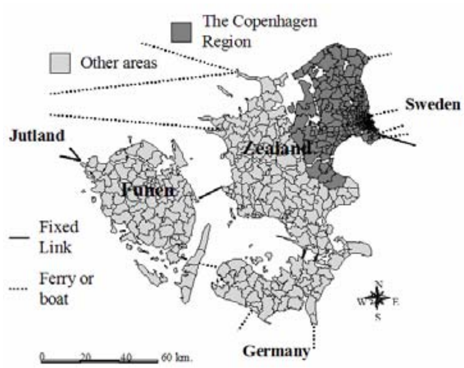


Fig. 10. Eastern Denmark and the Greater Copenhagen Area.

Furthermore in CRM the day is divided into three time periods. In this project only the time period from 16:30 to midnight is included. The size of the data set on which the TS algorithm is tested can be expressed in the following terms:

- 662 routes
- 45 fixed (train) routes
- 7.182 runs
- 1.344 stops
- 43.346 non-aggregated transfers (run connections)

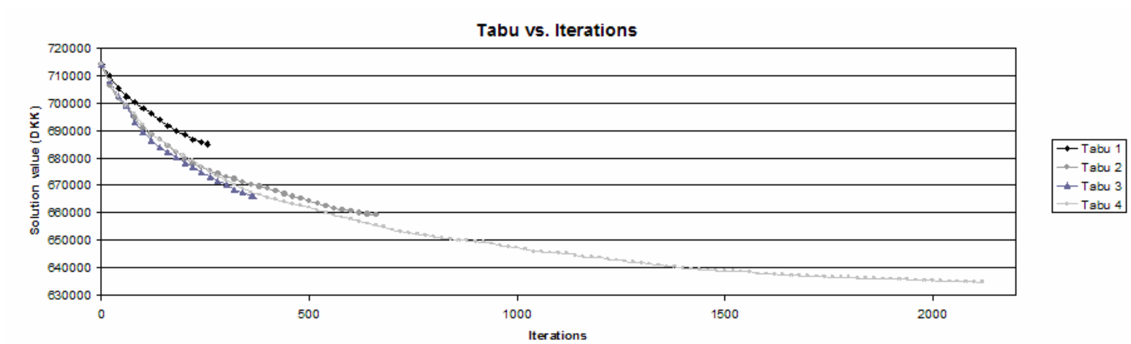
8. Results

Four computational runs with the TS algorithm where performed on the CRM-data, TS-1, TS-2, TS-3, and TS-4. The parameter settings for each run, the best obtained timetable values, and computation times are illustrated in table 1.

In figures 11 and 12 the value of the current best found solutions as a function of the number of iterations and computation times is shown respectively. TS-4 is the longest of the four computational runs and it converges horizontally both with respect to the number of iterations and computation time. TS-2 and TS-3 follow the slope of TS-4 until they are terminated. Only TS-1 diverges slightly from the other three runs. This can be explained by the difference in the size of the random neighbourhood subset examined in each iteration. TS-1 only examined a subset of 10 neighbours. Each iteration is therefore performed faster than the other runs, where 20 neighbours were examined per iteration. Let us for simplicity's sake assume that Examining 10 neighbours per iteration takes half the time of examining 20 neighbours. Each 20-neighbour iteration must then yield twice as good improvements as the 10-neighbour iterations in order for the two to decrease at the same speed. It somewhat seams reasonable that this is not the case. However, the fewer number of examined neighbour solutions means poorer best solution found in each iteration and therefore slower decrease with respect to the number of iterations as it is seen in figure 11. All functions are rather smooth which points to the proper functioning of the algorithm. Nevertheless, running times of the algorithm are considerable. TS-4 spent 131 hours before stopping. The long running times are not excessive though if compared to a planning horizon of 6 months. The reason for the extensive computation times is because of the non-linear recalculation of passenger transfer flows that need to be recalculated in each iteration. The initial disutility value on the timetable given in the CRM-data was 714.000 DKK pr day for the time period 16:30 to midnight (equivalent to 96,000 €). All four runs yielded improvements between 4% and 11%. Taking the best run, TS-4, the solution value was improved to 635.000 DKK; a 79.000 DKK improvement. This number is a measure for the improvement in waiting times for one evening

	TS-1	TS-2	TS-3	TS-4
Initial disutility value (DKK)	*714.000*			
Value of best found solution (DKK)	*685.000*	*659.000*	*666.000*	*634.000*
Improvement (%)	*4,1*	*7,7*	*6,7*	*11,1*
Time consumption (hours)	*3,0*	*33,0*	*23,1*	*130,9*
Iterations	*255*	*660*	*365*	*2120*
Parameters				
Size of random neighbourhood subset	*10*	*20*	*20*	*20*
Length of tabu list	*50*	*50*	*50*	*100*
Max. numerical change permitted on a route	*10*	*10*	*20*	*20*
GAP (number of iterations)	*100*	*200*	*100*	*200*
Stop criterion on GAP (%)	*1*	*1*	*0,1*	*0,1*

Table 1. Computational results



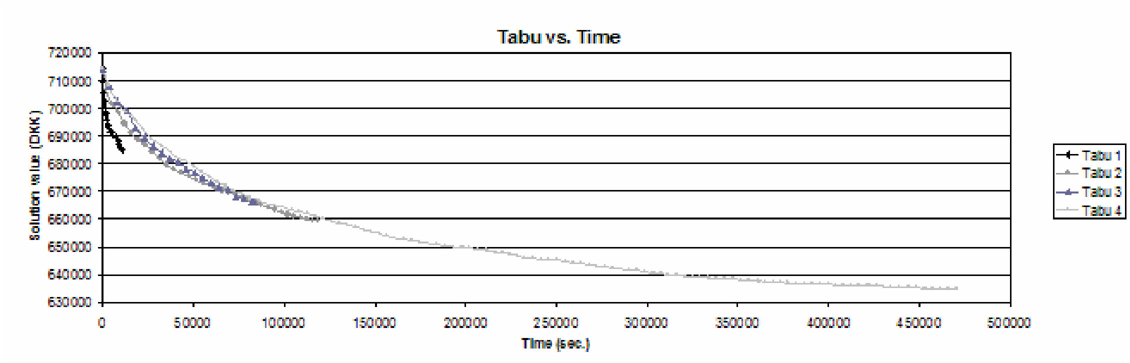


Figure 11 & 12. Current best found solution as function of iteration number and current best found solution as function of time

in the greater Copenhagen metropolitan area. For an entire year this adds up to a disutility value of approximately 29m.DKK or 4m.€. This however, is still only for the time period between 16:30 and midnight. If we assume that there is almost nothing to gain in the night hours; midnight to 6:00, and that we can achieve at least the same improvements for the time period 6:00 to 16:30 the potential savings are of more than 60m.DKK or 8m.€ a year. This number cannot be seen as a potential cost reduction for the operator but as value of the time saved by passengers using the optimized public transport network.

9. Applicability and Areas of Further Development

It is unlikely that any method for optimization of time tables will ever result in "ready-to-print" timetables. There are many soft constraints and political issues within planning public transport that are cumbersome or impossible to model. At its best a method could be used as a decision support system (DSS) providing time table scenarios that planners can revise interactively according to real-life constraints. Using such a DSS would however be useful for making scenario analysis when planning new public transport lines where no existing timetable has previously been planned.

The results shown in section 8 shows that the model can make significant improvements in passengers transfer waiting time to the existing timetable of the public transit system in the Copenhagen region. Although the results shown are promising it is reasonable to further discuss the assumptions made, possible improvements, and interesting areas of future research.

9.1. Interaction with a route choice model

The passenger transfer patterns used in this work were obtained from a modified EMME/2 route choice model run on data from the CRM model. It was assumed that the number of passengers changing between two routes would remain constant for the investigated time period. As previously stated that is a rough approximation. However, an interesting area of further research to improve on this approximation would be the possibility of constructing some interaction between a route-choice model and the time table optimization method.

It is certain that the passengers' route-choices will change if the timetable is changed using the optimization method. The method approximates this by re-distributing the passenger transfer flows as different timetables are tried out running the search method. For the final "optimal" timetable running a route-choice model will reveal the actual passengers' route-choices and thus also the real transfer flow patterns. Intuitively the sum of the new route-choices would have less disutility than the ones of the starting time-table. Thus by iteratively running the timetable optimization method and a route-choice model it could be possible to converge towards an even better time-table than by just running the method once. The question is whether the iterative procedure will converge towards an optimal timetable. This iterative procedure would be interesting to investigate.

A consideration though is the enormous amounts of computation time this procedure would require since each route-choice calculation and following timetable optimization may take several days of computation. Thus some research on how to make this procedure computationally feasible would be necessary.

9.2. Alternative modelling and solution method

The modelling assumptions presented here are very restrictive with respect to the flexibility of deciding arrival and departure times. By fixing stopping times and headways, the degrees of freedom are reduced significantly. This simplifies the model and the solution method, but supposedly also limits the potential improvements. In the current model the only decision to make is when the first run of each route departs. The remaining runs' departure time are calculated from the headway between them. The remaining arrival and departure times at the stops on each run are given because of the constant in-vehicle times and stopping time. By relaxing the headways alone this number increases to n decisions, n being the number of runs in each route. If we further relax the stopping times we will have $n \cdot (s-1)$ decisions, s being the number of stops in each route.

It is obvious that with more flexibility in planning the departure and arrival times, better connections and shorter transfer waiting times can be achieved. As mentioned the use of even-spaced headways is used in most public transit systems. However, if the headway and stopping time constraints are relaxed it would be possible to achieve better connections in a public transit system.

The problem of having variable stopping time in the current model is that only transferring passengers are considered. As long as stopping times are constant on-board passengers are unaffected by time table changes. This is not true when a run may stop indefinitely. If variable stopping times are to be included in the model on-board waiting times need to be considered in the model. E.g. it is not reasonable to allow a bus with 100 passengers on board to wait for 5 additional minutes for one transferring passenger. The number of on-board passengers can in our case be deducted from the passenger route-choices. Thus, the number is available if the model is altered to include waiting time for on-board passengers.

Relaxing either the fixed headways, the fixed stopping times or both require an alternative solution method to the one proposed here to capture the additional flexibility. The neighbourhood chosen in the tabu search method presented here is designed based on the assumptions of having fixed headways and stopping times. If the headways and stopping times are relaxed an alternative neighbourhood must be designed. Considering just the relaxation of the headways we could design a neighbourhood so that a change on one of the runs of one of the routes is a new neighbour solution. That would result in the size of the neighbourhood to increase significantly. Considering the computational time on the existing method, increasing the neighbourhood size would eventually not be computationally feasible. Hence, some alternative modelling approach, solution method or neighbourhood needs to be considered if headway constraints and stopping times are to be relaxed.

9.3. Including stochastic times in the model

Anyone using public transit systems in urban areas knows that lack of punctuality and other disruptions due to congestion are common. It is assumed in the model though that in-vehicle time is deterministic. It is therefore relevant to discuss the integration of stochastic times in our model.

It is obvious that assuming deterministic in-vehicle-times and solving the model without consideration to potential delays will yield a timetable with very tight transfers. Any minor disruption could result in missed transfers, and as result the timetable would not be good in practice. This is why buffer times for transfers were introduced in the model. Adding buffer times is not a subtle method to add robustness with respect to delays and disruptions. Nevertheless, it is common planning practice in public transit systems to assume constant in-vehicle-times in order to present legible time tables and adding some slack in the time table.

It would be interesting to see how adding stochasticity to the model that captures the possibility of late arrivals etc. would affect the timetable solutions. Instead of having fixed arrival and departure times on runs they would arrive following some distribution. The main issue is to asses the arrival and departure time distributions. In HUR empirical data information about delays (size, cause etc.) exist for about 10% of the bus runs. Hence, data to estimate the distributions empirically is very limited. It is questionable whether constructing a stochastic model and thus complicate the modelling would be reasonable based on such limited empirical data.

Nevertheless, assuming that quality data is available to estimate the distributions the following approach would be interesting to investigate. In order to limit computational complexity it is first assumed that only the mean value of the distribution for an arrival time (expected arrival time) is dependent on the departure time from the previous stop. The mean is not affected by the actual arrival time and the distributions variance is constant. This assumption holds for a homogenous time period, where congestion conditions are constant. By making this assumption we implicitly assume that the same distributions may be used for all runs in a route.

Because of the discrete nature of timetables (bus timetables are always presented in entire minutes) there are a finite number of possible arrival and departure times for a run at a stop. Assuming the arrival and departure distributions are discrete too, there are a finite number of outcomes for the arrival and departure times. There is therefore also a finite outcome of transfer waiting times. For each outcome of an arrival or departure time a probability of outcome may be calculated. Hence for each combination of arrival time of one run and departure time of another run a transfer waiting time and its outcome probability can be calculated. Based on the probabilities of each outcome it would be possible to calculate on average what the transfer waiting time for passengers will be for a given (deterministic) time table.

The advantage of using this approach would be that the distributions and hence the transfer waiting times and their outcome probability can be calculated prior to running the tabu search method. Thus for each combination of arrival time and departure time an expected transfer waiting time is used, instead of the deterministic difference between the departure time and arrival time.

9.3 Real-time optimization of time tables

As within any field, real-time adjustments to plans are necessary when coping with changes or disruptions on the day of operation. With the improvement of computational capabilities DSS are becoming more adaptable to real-time management of transportations systems. Public transit systems are in general very susceptible to delays because of congestion. Because of delays not only do passengers experience longer transit times but are also subject to missing connecting transfers, hence a reason why transfers are considered a nuisance.

[Schöbel 2002] presents a problem dubbed the delay management problem. The problem is derived from a situation where a train's arrival to a station is delayed. The busses having connections with the train at the station now face a decision on whether to wait for the train, and hence be delayed, or to depart as planned, and hence having transferring passengers missing their connection. When a delay occurs, the objective is to find a disrupted timetable that provides the least disutility given the situation. Three approaches are proposed. The first one has an objective to minimize the total number of missed connections, the second approach minimizes the total passenger delay time, and the third one has a multi-criteria objective combining the first two.

Adjusting time tables in real time provides an interesting new approach to managing public transit systems. Considering the development of mobile communication passengers may receive real-time information on departures, arrivals and delays. This makes pre-planned timetables more or less obsolete because real-time time tables will be available in real-time for the passengers. This will definitely result in more flexibility when planning frequencies, departure times and stopping time of public transit routes.

10. Conclusion

In the paper a non-linear mixed-integer programming model is presented to solve the problem of deciding departure and arrival times in a public transit system in order to achieve optimal transfers between routes. A Tabu Search algorithm to solve the model was presented. The results from applying the solution method on a case based on the Copenhagen region public transit system show that the algorithm can perform on a large-scale data set. However, computational times are considerable. Given the tactical nature of timetable planning using the algorithm on real-life systems would not prove intractable though.

The results obtained by the algorithm points to the fact that significant improvements in the timetable design in public transit systems may be obtained. The best found improvement of 11% is equivalent to yearly savings in value of time of 29 million DKK (4 million €) for the time period 16:30 to midnight in the Copenhagen region. A rough estimate indicates savings of more than 60 million DKK (8 million €) can be achieved yearly totally.

The model is generalized and an application on a real public transit network might lead to slightly different assumptions and additional constraint. In real life application we expect several additional constraints that are network specific and that need to be added for a specific transit network.

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Optimization of Intermodal Freight Train Service Schedules on Train Canals

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Abstract

This paper presents a mixed integer mathematical programming model to optimize schedules for intermodal trains networks. The model is based on a time-space representation of a service network but is essentially a capacitated network design model. The model assumes that the intermodal train services are routes on a network divided in train canals (aka. as train paths) as is becoming general practice in the European Union rail sector. The train canals represent time slots in which intermodal train services may be offered. Transit time and operating for intermodal rail services is an important service parameter in the competition with long-haul road transportation. Operating costs are a sum of the service operating cost and the terminal operation cost. Terminal operations play an important role in intermodal transportation. To capture this the model includes unloading, loading, transfer operation costs, and inventory costs and add capacity constraints on the number of handling operations and inventory. To model transit time the model introduces a value of time cost that multiplied with the transit time gives a measure of the value of time for commodities. This eventually leaves the delivery time of demand as an output of the model. To capture the trade-off between operational cost and the value of time cost the two are added and minimized. The model is applied to a generated network instance and nine different scenarios are solved using Xpress-MP's MIP-solver. Although the use of this 'brute force' approach with resulting mediocre solutions post-analysis of the results show that the model works in accordance to what is expected.

1. Introduction – Intermodality and railways

It has been estimated that the freight traffic in the European Union will increase with 50% from 1998 to 2010 [White paper 2001]. Many parts of the European transportation networks are already operating close to their capacity level. It is estimated that around 10% of the European highway network is affected on a daily level by congestion. Several parts of the rail network have been classified as bottlenecks. The European Union has in its white paper stated how it intends to promote intermodal transportation with the rail sector as the predominant strategic transportation mode in European freight transportation, and has launched a series of infrastructure projects to improve network conditions. From 1985 to 1994 the UIRR (the organisation for European rail-road intermodal operators) experienced a growth from 1.5 million TEU to 3.5 million TEU and the ICF (European in-land intercontinental container transportation) experienced a growth from 0.9 million TEU to 1.1 million TEU ([UIRR 1995]). Thus intermodal transportation is growing, but several issues need to be considered in order to make intermodal transportation able to capture the eventual growth in freight transportation.

1.1. Influencing the modal shift from road to rail

The main focus of the European Union as stated in its white paper on transportation is to shift the modal split towards rail and sea transportation and reduce the share of freight of long-haul road transportation. The reason for this is to reduce road congestion and promote environmentally friendlier modes of transportation as rail and sea transportation. The statistics presented in this and the following sub-sections are taken from [White paper 2001] unless otherwise stated.

The CO_2 emission of the transportation sector accounts for 28% of the total European Union. Thus significant overall CO_2 emission reductions can be achieved by be reducing the emission from the transportation industry. The externalities for the three main modes of freight transportation (excluding congestion costs); rail, waterborne, and road transportation measured in Euros are estimated to be 19€ per 1000 tonne-km, 17€ per 1000 tonne-km, and 88€ per 1000 tonne-km respectively. These externalities include emissions of CO_2 among other effects such as emission of other aerosols and noise, urban nuisance, and accidents. From these figures it is clear that road transportation has a significantly higher impact on the environment than rail and waterborne transportation. It is from figures like these that the idea behind attempting to shift freight from road to rail/sea originates.

Another reason for shifting the modal split in favour of rail and sea is that removing freight from the roads onto rail and water will lower the congestion on the highway system. It is estimated that the increase in road congestion will be the cause of loss in productivity amending to 1% of the Unions GDP by 2010. Hence congestion is not just a nuisance for users of the road network, but influences the competitiveness of the whole European region.

It is believed that road transportation does not pay for all of the external costs it inflicts on the environment and on congestion ([White paper 1998]). Therefore it indirectly has a competitive advantage on that account compared to rail and waterborne transportation. For this reason many European countries are introducing road taxes (tolls). Examples are Germany, Austria and Switzerland thereby favouring other modes of transportation. Although some initiative has been taken to make fairer competition between the different modes of transportation there are still other issues to take care of before rail can compete against long haul road transportation.

1.2. Status of the European rail system

Although the European Union's transport policy encourages the use of rail it only represents 8% of the total freight volume transported in Europe. Short-sea shipping has a major cut though of 41%, while road transportation has a share of 44% and inland waterways 4%. Rail freight transportation's 8% share may be put into perspective to its share in North America of 40%.

There are a number of reasons why the modal split differs between the two continents. One reason may be the geographic and demographic characteristic of the continent. The North American continent is much larger and has its population centres located at its extremities (the coasts), while Europe's are located at the centre stretching from the British midlands through the Ruhr area to the Po Valley (so-called blue banana). This means transportation distances are larger in North America than in Europe which gives rail a competitive advantage there while trucks are more efficient on the shorter transportation distances in Europe. Furthermore North America serves as a land bridge between the west coast and the east coast for intercontinental transportation from Asia to North America and Europe.

Bottlenecks and congestion also are an issue in the European rail network. 20% of the 16.000 km of rail tracks is classified as bottlenecks. Furthermore passenger rail transportation plays a dominant role in Europe which has a preventive effect on having any extensive use of freight trains. Passenger trains have traditionally been given priority over freight trains, and hence flexibility and reliability of rail freight transportation has decreased accordingly. In contradiction to this the rail networks in North America are almost fully dedicated to freight trains.

Finally the development of the Union's member states' rail systems has traditionally been marked by nationalistic protectionist tendencies. In order to prevent access to the national rail networks to foreign rail carriers very diverse network configurations have been used. This has resulted in a collective European rail network with five different electrification systems, two different gauge systems (the rail networks on the Iberian Peninsula and in Finland differing) different labour regulations, different traffic regulations, and a continental network composed of inadequately connected national networks. The improvement of interoperability between the member states' networks now presents a major challenge in achieving an integrated continental rail network.

The liberalisation of the rail industry in Europe has lead to a separation of the traditional national rail companies into infrastructure owners and operators. Rail authorities manage infrastructure and network capacity and rail operators that operate trains according to the available capacity acquired from the rail authorities. To improve the possibility of cross-border operations, collaboration between the rail authorities of the member states is being established to create an interconnected trans-European rail network for freight trains as stated in [White paper 1996], the so-called freight freeways. Projects to eliminate bottlenecks and improve interoperability have been proposed also to improve network conditions. It has already become easier to run train operations across several countries and operators do not have to procure capacity from several capacity owners due to the One-stop-shop concept adapted to the freight freeways. With the tendency continuing, the future result in having large service networks across the European continent operated by single operators or by alliances of operators, similar to those seen in the airline industry. The resulting service networks will be complex to plan and operate while having to compete or cooperate with the road transportation industry.

Significant effort has been put into research on intermodal transportation and rail transportation. We will throughout the paper include references to research relevant to the research presented here. The review is not supposed to be a complete survey of literature on intermodal transportation. Such a survey is available in [Macharis et al. 2004]. The review will focus on some of the papers included in that survey and additional ones that are relevant to the research presented in this paper.

The contribution of this paper is to present a mathematical programming model that can plan the service networks of intermodal train operators. The model introduces terminal operations and a cost of transit time for freight in order to base the service selection on these impacting factors. The remainder of this paper is divided as such. Section 2 describes intermodal train operations and with pointers to relevant previous work related to train operations. In section 3 we describe the modelling assumptions while section 4 presents the mathematical programming model based on those assumptions. Section 5 presents a generated network instance with different data scenarios and computational results obtained by using the MIP-solver from the Xpress-MP optimizing package. The paper is concluded in section 7 with pointers to future avenues of research.

2. Intermodal transportation by train

The extension of rail infrastructure is limited compared to road infrastructure. Therefore only few pairs of customers can be served solely using train transportation and it is generally impossible to provide door-to-door deliveries using rail. Drayage moves by trucks are required to move loads from their origin to a rail terminal where it is transhipped to another rail terminal before being delivered at their destination by truck. This type of intermodal transportation, where road and train transportation are combined into a transportation chain is seen as the way forward to increase the modal split for railways in Europe ([White paper 2001]). To enable a seamless transfer between truck and train, freight is containerized as opposed to conventional trains where freight is loaded and unloaded in commodity specific wagons.

Apart from the environmental and congestion preventive effects discussed in the previous section, consolidating freight on trains achieves economies of scale and thus reduces transportation costs. The trade-off however is that the flexibility of moving containers independently by truck is lost. This loss of flexibility combined with the experienced low reliability and long transit times of rail transportation seem to be major reasons why customers choose road transportation over rail. The introduction of intermodal shuttle trains in Europe is an initiative to try and improve the reliability and transit time by rail by operating freight trains like passenger trains on a tight schedule and minimizing the number of terminal operations performed.

It is arguable whether political interest and incentive regulations such as road taxes will be enough to achieve the European Union’s ambition of increasing rail’s share of the modal split from the actual 8% to 15% by 2010. It must be expected that intermodal operators need to decrease operational cost and increase service levels to take on the competition against road haulage.

2.1. Analysing the intermodal trip chain

To understand how to improve operations of intermodal transportation we first analyze the events of an intermodal trip chain and compare it to long-haul trucking. Figure 1 shows an example of four containers with different customer origins and destinations that use the same intermodal train services. The four containers are transported from the four customers to rail terminal A by drayage moves. There they are transferred to a rail service going to terminal B. At terminal B they are transferred to another rail service going to terminal C. Finally at terminal C they are transferred to the trucks for the final drayage move to their end destinations. The total transit time for each of the intermodal trip chains above is a sum of:

- The transportation time of the initial drayage move to terminal A.
- Unloading time from the trucks and storing the containers in terminal A’s storage place.
- Connection delay until the train arrives and is ready to be loaded.

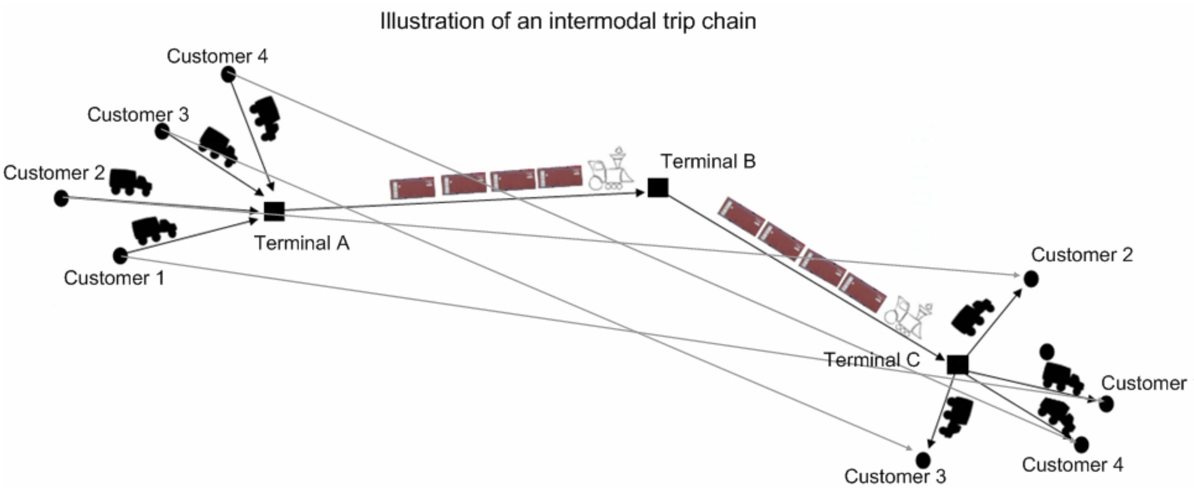

Figure 1

- Time to pluck the containers from the storage place and loading onto the train.
- Transportation time from terminal A to terminal B.
- Time to unload the containers and storing them at terminal B's storage place.
- Connection delay until the second train arrives and is ready to be loaded
- Time to pluck the containers from the storage place and loading onto the second train.
- Transportation time from terminal B to terminal C.
- Time to unload the containers and store them in terminal C's storage place.
- Connection delay for the trucks for the final drayage move to arrive.
- Time to pluck and load the containers onto the trucks.
- Transportation time of the final drayage move to the customers.

The sum of the time of the operations above has to be competitive with the direct long-haul truck moves driving directly between the points of origin and destination. The number of terminal operations and their cost are also considerable compared to having no terminal operations between the origin point and the destination point using road-haulage. In order to make intermodal trip chains competitive both the transit time and the operational cost need to be considered.

There are several possible intermodal services to offer (see [Ballis et al. 2004]), but the focus of this paper is on the intermodal shuttle trains. These are common operating practice in road-rail intermodal transportation. The characteristic of running intermodal shuttle trains is to have a fixed train make-up. That means that the train always runs with the same number of flat-bed wagons (onto which containers are loaded). The advantage of running a train with a fixed make-up means the composition of the train does not need to be changed at terminals thereby reducing handling cost and reducing the turn-around time. That enables a more efficient use of vehicle equipment. Contributions from [Turnquist et al. 1982] and [He et al 2003] propose operations research based approaches for rail yard operations. Both contributions illustrate the complexity of rail yard operations and the resulting cost and time consumption proving the reason behind running intermodal trains with a fixed train make-up.

The more efficient use of vehicle equipment in intermodal services is however subject to running trains at their capacity. There is a financial risk of providing fixed make-up trains with resulting fixed capacity if they end up running semi-empty. For intermodal operators the break-even point lies above a 90% utilization of capacity. This also poses a problem on determining the adequate train make-up. A lot of effort is put into making sure trains are operated at full capacity. Part of the process lies in marketing and sales by making sure freight demand in the service network is well balanced. In [Yan et al. 1995] an operations research based pricing method is proposed to determine optimal pricing of capacity. We will not include pricing issues in our model though, but will include a limited number of possible train make-up options.

Terminal operations are necessary to tranship containers between the different transportation modes and services. From the explanation of the events that can occur in an intermodal trip and as mentioned in [Ferreria et al. 1994] it can be deduced that terminal operations play an important role. The following events and operations may take place in a terminal:

- Arrival by train or truck, inspection
- Unloading and storage in yard
- Transhipment to other vehicle
- Stay on train for further continuation
- Loading onto train from storage

[Bostel et al. 1998] presents a model and solution method to solve the transhipment problem between two trains. The model aims to minimize the container moves between trains. [Rizzoli et al. 2002] present a simulation tool for the entire terminal process including storage operations. From the time the container arrives at the terminal by truck or train until it departs again the container does not cover any physical distance. That is why there is focus on developing technology to speed up and reduce handling cost of terminal ([Trip et al. 2002]). The unloading, transferring, and loading of containers onto trains can be done by gantry crane or by mobile crane depending on the available infrastructure at the terminal. There are only a limited number of tracks at a terminal. Thus only a limited number of trains may be present simultaneously at the terminal. The handling machinery can only perform a certain number of operations meaning that only a limited number of handling operations may occur in a given time period to avoid congestion and resulting delays. The resources available to perform terminal operations are thus limited and should to be considered when designing intermodal train services.

2.2. Characteristics of freight using intermodal train networks

The appropriate intermodal train services to offer depend largely on the demand of commodities and on the competition with road haulage. It is assumed that bulk commodities, perishable commodities, and hazardous materials are not transported by intermodal train. Due to the low value per weight unit, bulk commodities such as iron ore, coal or lumber are transported by conventional train if not by ship and are generally not accessible to intermodal transportation or long-haul road transportation. Highly perishable goods such as some dairy products are generally not transported over longer distances because of the transit time. This segment of commodities requires the flexibility and direct transportation offered by road haulage over shorter distances. Hazardous materials such as chemicals or nuclear waste have to obey certain rules and regulations and are therefore rarely transported with other commodity segments.

It is generally perceived that intermodal transportation currently is only applicable in Europe for distances over 400 km. For distances shorter than 400 km the time required to perform an intermodal trip chain makes it non-competitive compared to road transportation. For longer distance however, the transportation cost becomes a more important factor, and, assuming the train leg(s) are reliable and run at higher speeds than trucks, the additional transit time endured by terminal operations is less significant. [Nierat 1997] presents a model based on spatial theory to determine the market area of intermodal transportation. The results support the hypothesis that intermodal transportation is limited to relatively long transportation distances and to customers within reasonable distance of intermodal rail terminals and also shows that it is only for a limited region around a terminal where intermodal transportation is a cost and time efficient alternative. [Trip et al. 2002] point to the fact that the competitiveness of intermodal transportation could be improved and thus make it more attractive for shorter distances by improving terminal operations and by extending the reach of intermodal transportation networks.

What is typically seen is that intermodal train operators negotiate long term contracts with large customers such as freight forwarders or big industrial clients. With these contracts customers guarantee a certain amount of loads whilst obtaining a lower transportation price. The contracts provide stable demand for the operators and lower their financial risk. In turn the remaining capacity can be sold on the spot market. To reduce the uncertainty further Swedish operator Green Cargo for example requires customers to book in advance in order for them to be able to plan operations efficiently.

In order to compete with road transportation and attract customers we assume that intermodal operators set a transit time between origin/destination points as a strategic goal. Promising transit time sends a signal of reliability and attracts customers but also requires service standards to match the promise. A high service level achieved by running frequent trains can reduce the total transit time; however the operational cost will increase accordingly. Unless the higher service levels attract "new" demand to the system there is a significant risk of running at low utilization of capacity and thus loose the competitive edge on the operational cost. The art is to design intermodal train services that offer competitive transit times while maintaining low operational cost.

2.3. Designing intermodal network subject to infrastructure divided in train canals

Several contributions investigate modal choice and intermodal network design in a region. Such analysis can be found in [Bookbinder et al. 1998] where intermodal routing options between Canada and Mexico under NAFTA are investigated. The results of the investigation give an indication of the modal choices between pairs of 5 Canadian and 3 Mexican cities using several American cities as transhipment points. Similar analysis can be found using the STAN software package which has been applied to the São Fransisco river corridor in Brazil ([Crainic et. al. 1990]). Whether operations research methods are used or not an initial strategic analysis of a region provides an operator with a decision support which can be used to determine its network coverage area.

Given a strategic network of areas and customers to serve, the problem becomes one of choosing how often to run services. Previously, a widely adopted policy for running conventional freight trains was a “go-when-full” policy. This meant that freight trains were not scheduled and moved from their origin to their destination terminals when capacity on the rail network was available. This policy is still adopted in North-America whereas in Europe the policy is inefficient because of the large amount of passenger trains taking up the rail network capacity. The higher priority of passenger trains result in freight trains being side tracked leading to excessive transit times. For bulk commodities where low transportation costs are very important and transit time almost negligible this is not a problem. However, for time sensitive freight the long transit times are unacceptable, and it is one of the reasons for the low share of the modal split in favour of rail transportation. Contributions from [Crainic et al. 1984], [Marin et al. 1996], and [Keaton 1989] all present service network design problems with train frequencies as outputs. The competition with passenger trains for capacity on the infrastructure in the old EU15 (EU prior to expansion in 2004) means capacity is not readily available when needed. Therefore these frequency-based approaches are not appropriate for designing a service network for an European intermodal train operator.

The situation in Europe where rail business is separated into rail authorities and operators means that an intermodal train operator is not the proprietor of the infrastructure and not the sole operator using it. To overcome the issues of having several operators rail authorities have adopted a planning procedure dividing the infrastructure into so-called train paths ([Link 2005a]). The term train path is used in several operations research contributions as an actual movement of a train. However, train paths here only represent a routing possibility, which is why we will refer to them as train canals instead. Train canals are time dependent paths on the rail network. They can be compared to a time-slot or time-window within which a train must operate on the rail infrastructure. This means that there is a departure time and an arrival time associated to each of the terminals visited along the path. The division of the infrastructure into predetermined train canals prevents conflicts of trains on the network and leaves it up to the operators to acquire the train canals they need to assume their operations. Passenger trains still have priority on acquiring train canals, and passenger train operators are often involved in the process of determining train canals. However, the European national rail authorities have started to cooperate on constructing a dedicated transcontinental network of train canals for freight trains ([White paper 1996]). Although a full transcontinental network of train canals for freight is not yet implemented the main corridors have adopted the concept ([Link 2005b]) and it can be assumed that this will soon be the case for most of the European rail network. In this paper we assume that all train routing and scheduling is done according to predetermined train canals.

2.4. Service network design on train canals for intermodal trains

Several contributions can be found on train routing and scheduling and on applied service network design for train operations. A survey is presented in [Cordeau et al 1998]. [Huntley et al. 1995] and [Gorman 1998a] present service network design models with schedules for CSX transportation and Santa Fe Railways respectively. [Yano et al. 2001] present a dynamic modelling approach to schedule departures of freight and trains to and from a single terminal [Newman et al 2000] present a train routing model which includes schedules. However, freight demand is modelled to originate and is destined to rail terminals, thus drayage moves are not considered. [Nozick et al 1997] present a linear MIP-model for planning intermodal freight routing. The configuration of the train schedules is given though. [Gorman 1998b] presents a linear MIP-model for train scheduling with limited terminal operations and [Hagani 1989] proposes a linear MIP-model for scheduling trains that is similar to the one we will propose here. The MIP-models determine the optimal scheduling on a space-time representation of a network for two types of trains including the train make-ups and empty wagon repositioning problem. The models assume that trains can run within every time-period and therefore do not account for the fact that rail network capacity may be occupied by passenger trains.

The model we present includes the limitation that trains can only be routed on available train canals. Given a set of available train canals the decision on when to provide intermodal train services indirectly becomes one of selecting appropriate train canals. The notion of being constrained by routing possibilities has made us believe that schedule synchronisation is an important issue to provide fast and reliable services on a network composed of train canals. Higher frequencies of trains in a network will reduce the overall expected transit time of freight but also require higher operational costs. By synchronizing arrivals and departures of trains in terminals it is possible to transfer containers directly from train to train. This will remove connection delays and thereby reduce the transit time without having to increase frequencies and incur higher operational cost.

It is relatively easy to synchronise the two train services shown in figure 1 such that connection delays are removed. All that is required is for the two trains to be present at terminal B simultaneously and thus achieve transfer synchronisation. Transfer synchronization becomes much more complex when a

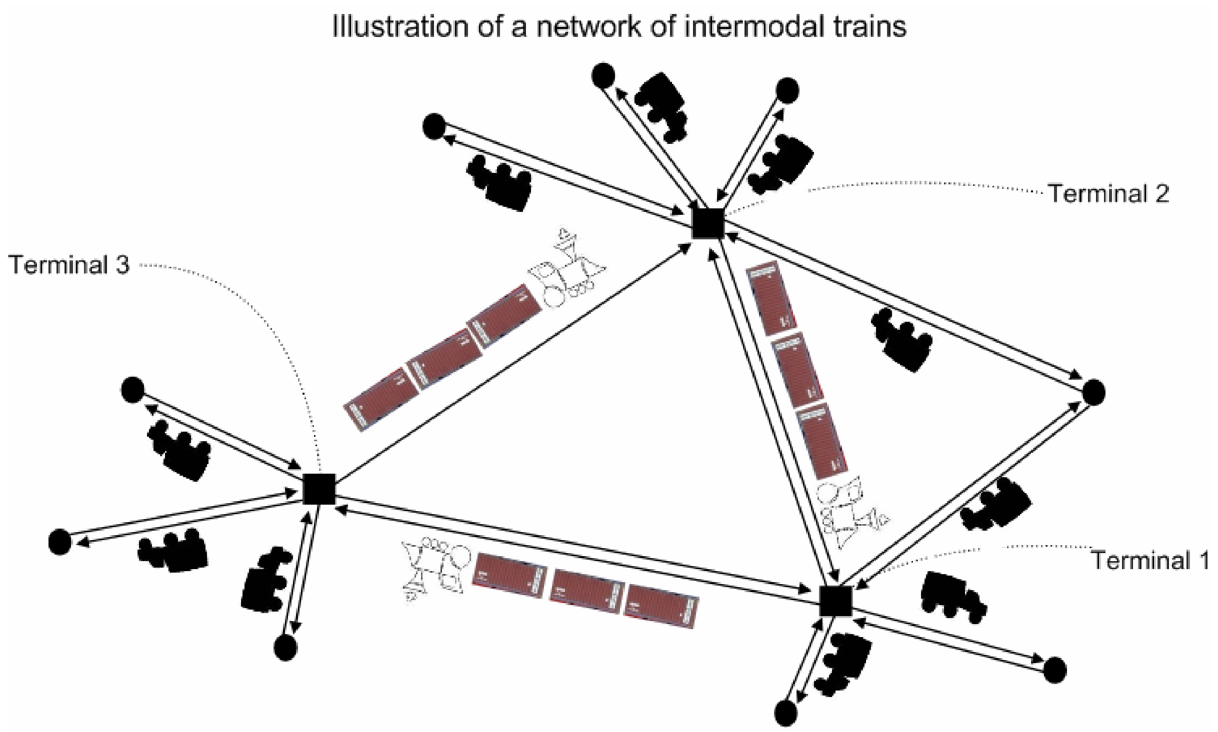

Figure 2

network structure of intermodal trains is considered. Figure 2 shows a simple network of intermodal trains. Synchronizing train service connections at one terminal may lead to deteriorating connections at other terminals. Capturing this network wide interaction is difficult if not impossible to do by manual planning. A quantitative method is needed to design a service network that proposes good synchronisations to reduce to transit time while keeping operational cost low at a global network level. However, synchronization becomes a complicated issue when only a limited number of routing possibilities are available meaning special attention has to be paid to train routing and terminal operations in order to minimize transit times for freight.

2.5. Problem description

The general problem is to determine an intermodal train service network for an intermodal train operator. The following items are included in the model:

- Train scheduling on train canals, including train make-up alternatives.
- Terminal operations and train synchronisation to minimize transit times.

We use a linear mixed integer mathematical programming model to model the problem. The objective of the model is to capture the trade-off between operational costs and the value of time cost incurred the freight transit times and minimize the sum of the two. The model needs to capture general operational constraints such as train routing possibilities, train canal availability, train mode capacities and terminal operation capacities. The output of the model is a train routing plan based on a selection of train canals and a freight routing plan. The costs incurred by operations and value of time determine what the optimal system configuration with respect to train routing, train synchronization, and freight routing is.

3. A Service network design model for intermodal trains

This section presents the formulation of the problem we intend to solve. The section gives a detailed description of the modelling assumptions made. An overview of the assumptions and the modelling can be seen in figure 10.

3.1. Representing the underlying network structure of train canals and train routing

One of the novelties in the modelling presented here is the use of the train canals to schedule trains. As described train canals are predefined time-dependent paths on the physical infrastructure. Assuming correctly that a train must operate within the boundaries of the available train canals, the underlying physical network and its capacity needn't be considered. We simply construct a network where arcs represent train canals. Only one train can run on a train canal so the routing and scheduling of intermodal trains can be interpreted as selection of train canal arcs.

We assume that the intermodal train operator operates on the same rail infrastructure as other rail carriers. This implies that not all train canals proposed by the rail authorities are available and that there is competition for the acquisition of them. Train canals are presently at a fixed price on a "first come, first serve" basis with priority to passenger trains. We assume that a given number of train canals are available e.g. through prior acquisition or non-acquired train canals. The acquisition process of train canals is therefore not included in the model. Design of a service network on train canals subject to the acquisition of train canals e.g. through a bidding mechanism is an interesting topic but is left for future research.

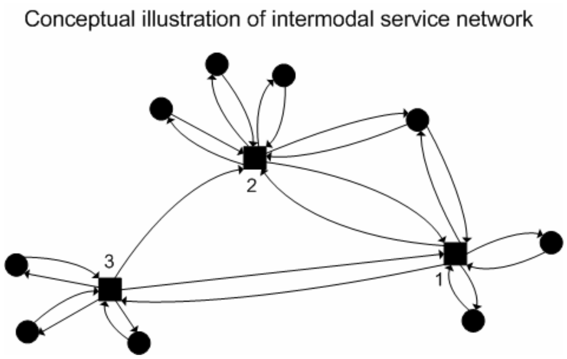

Figure 3

Figure 3 shows a conceptual view of the network in figure 2. The arcs between the terminals 1-3 (square black nodes) represent the possible train routing connections between the terminals. The arcs between the terminal nodes and the customers (round black nodes) represent the possible drayage moves between terminals and customers. To capture the time dimension of the train canals we use a space-time network representation. Figure 4 shows a space-time representation of the terminals alone from figure 3.

Each of the nodes in figure 4 represents one of the three rail terminals at a certain time interval (here days). The time periods needn't be time-wise adjacent to each other e.g. the time period could represent the opening hours of the terminal or the period of time where the majority of operations are performed. The network has a time horizon (of seven days in figure 4) and is periodic meaning it repeats itself when the time horizon is reached. It is obvious that over a long time horizon (of several years) the train schedules will change. However, passenger trains follow a repeating schedule and given their priority on the rail network intermodal trains seem to fall into that pattern too.

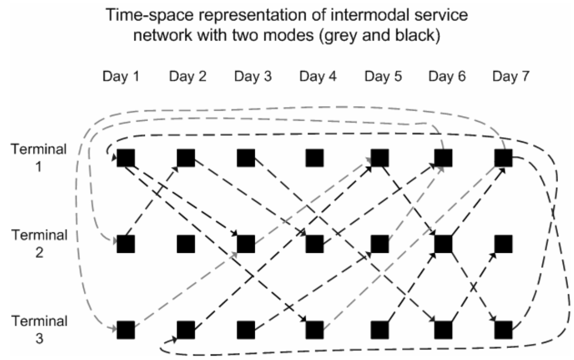

Figure 4

The time periods associated with each of the terminal nodes indicate what time periods the departure and arrival times of the train canal lie within. We simplify the representation of the arrival and departure times of by assuming that a train canal departs at the end of a node's time period and arrives at the beginning of a node's time period.

The characteristics of the train canals such as acceleration and cruising speed may set an upper bound on the number of flat-beds wagons that make up the train. To model the variability of train make-up we enumerate a number of make-up options which we shall call modes. Each mode represents a train make-up composition and has a capacity limit associated to it. If several train make-ups are possible on a train canal it can be represented by several arcs each associated to a mode. To ensure the train canal is only used once a mutual exclusion constraint may be added. We assume however that each train canal arc in the network is associated to only one mode (in figure 4 a grey and a black mode each representing different train make-ups). The capacity of the train canals arcs is inherited from the modes they are associated to.

Trains can stay at a terminal for more than one time period. This is modelled by adding train transfer arcs between succeeding terminal nodes. E.g. train transfer arcs are added for each mode between the ‘terminal 1, day 1’ node and the ‘terminal 1, day 2’ node in figure 4 etc. The arcs have been left out of figure 4 for reasons of clarity.

A fixed cost is associated to each train canal which represents the cost of train canal acquisition (if applicable) crew operating cost, maintenance and depreciation cost or leasing cost of locomotives and wagons, and fuel costs. The cost of running the train varies somewhat depending on the number of containers on the train. However, we assume that the fixed cost of is the predominant cost and thus neglect the comparatively small variable cost. The fixed cost of the transfer train arcs represents the cost of keeping the train idle at a terminal, i.e. leasing cost or deprecation and maintenance cost.

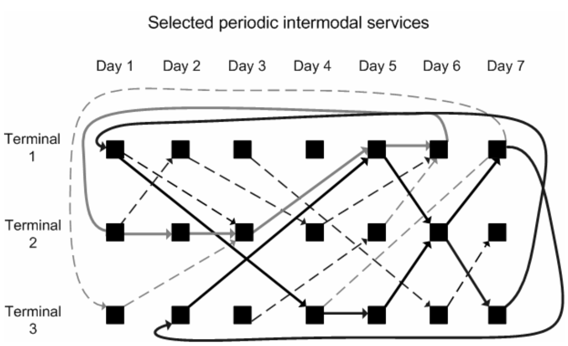

Figure 5

Figure 5 shows the train canal network from figure 3 with a selection of train canals for each mode (full lines). Notice how the nodes are balanced with respect to the number of selected train canals of each mode that enter and leave the node resulting in service cycles. The service cycles are an attribute derived from the repetitive service pattern. Since the schedule is repeated after reaching the time horizon the services must form cycles that repeat themselves. To ensure that service cycles are obeyed a constraint ensuring that trains entering a terminal in a time period must also leave it again at the end of the time period by either leaving for another terminal or to go to the terminal’s next time period is added.

3.2. Representing freight demand

Because of the acquisition process and the complex operational planning required to run intermodal trains designing a service network is considered a tactical exercise performed several months in advance of actual operations. It can not be expected to have detailed knowledge of available demand at that time and it is subject to some level of uncertainty. The service network is also repetitive (e.g. weekly schedule), which means demand levels vary between repetitions. Finally, we also need to consider that demand levels are correlated with the service offered i.e. the higher the frequency of trains, the shorter expected transit times, and thus the more attracted demand.

We assume that the customers of the operator are mainly forwarding agents or large industrial customers. These customers negotiate prices with the operator to achieve lower prices while guarantying a certain amount of loads. This means we assume that the operator has some quantitative estimate of the demand potential and is able to make reasonable forecasts for customers’ individual demand. We furthermore assume that the discrepancies in freight demand between the periodic repetitions are handled by the sales division of the operator. Given reasonable demand forecast, the potential to even out imbalances in demand and computational complexity of handling stochastic demand, we thus assume to have deterministic demand.

An important notion to respect when determining demand data is the correlation between the level of service offered and the level of demand. We assume that customers base their transportation choice on price and total transit time. This means that if the carrier provides frequent services resulting in shorter transit times while maintaining a constant price more customers will be attracted to use the services of the operator. Hence the level of demand is subject to the chosen train routings and schedules. However, it is reasonable to assume that the demand forecasts made are based on the existing service network and the attracted demand is minimal on a short term basis. Thus we can assume that the forecasted demand levels correspond with the optimized service network. Long term effects on demand could be simulated by establishing different forecast scenarios if the correlation between demand and service were specified.

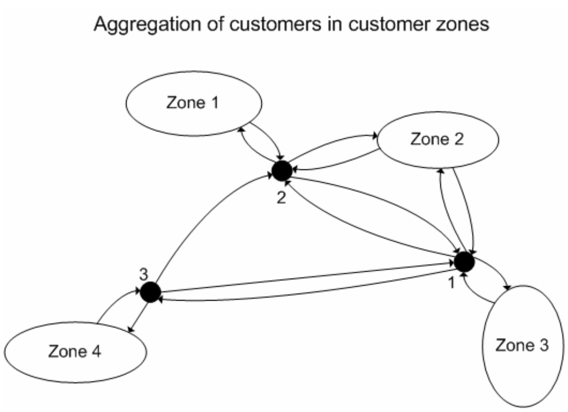

Figure 6

Although the operator is assumed to have some quantitative knowledge of the demand levels it might be on a more aggregate level. The uncertainty of data and the eventual model size makes it unreasonable to consider demand on a customer level. We believe that a realistic approach for real applications is to first aggregate customers into clusters and thus have demand based on customer zones. The demand is then forecasted as general demand potentials between each of the zones. Figure 6 represents the customers from figure 3 grouped in four customer zones. Aggregating customers into customer zones first of all reduces the size of the eventual model and also requires less detailed demand data. If the operator e.g. runs continental trains between rail hubs, customer zone data need only be forecasted on regional level.

The demand is represented as multiple commodities each with an origin customer zone and a destination customer zone. Furthermore a time of availability is associated to each commodity but we assume that commodities can be delivered to the destination customer zone at any time and thus no delivery time is associated. In the time-space representation of the network the customer zones are represented by a set of nodes that each represents a point in time (see figure 8). In the time-space representation we have multi-commodity flow problem with the peculiarity that freight has an origin node corresponding to the origin customer zone and time of availability and a set of potential destination nodes representing the destination customer zone as opposed to a single destination node.

Having no delivery time associated to the commodities means that the transit times can become very long if only operational cost are considered. Obviously that is not representative of the ambition of providing fast transit times for freight on intermodal trains. To capture the trade-off between transit times and operational cost we introduce a value of time representing the cost of the perceived transit time from a customer’s point of view. The value of time increases with the total transit time which is further accentuated if freight is delivered after a promised or expected delivery time. The value of time as a function of the delivery time could look like the exponential curve shown in figure 7. As seen in the figure the value of time rises steadily until the point of promised delivery time after which it rises faster.

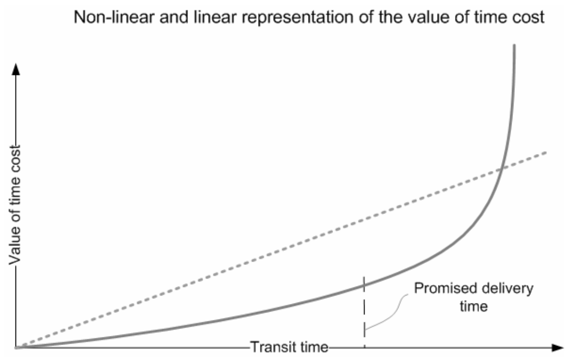

Figure 7

Freight has different values of time depending on the actual physical commodity and on the individual customers. Working on an aggregate level we assume that all commodities have the same value of time and leave further investigation on value of time for different freight commodities and heterogeneous customers to future research. Furthermore, representing the value of time by a non-linear function will add significant complexity to the model. Considering the aggregation and assumption of homogeneity of commodities it seems reasonable to neglect the non-linearity and assume a linear function for the value of time as shown in figure 7. Although the linear approximation does not give a correct representation of the cost of transit times it captures the essential difference of short transit times having low cost and low transit times having high cost. The approximation is somewhat correct for transit times that don't exceed the promised delivery time by a big margin. In figure 7 the linear approximation is an upper bound to the transit time and only diverges significantly from the "real" value of time cost after the intersection point.

It is possible to calculate a total measure of the performance of the network by adding the sum of the transit time cost for each commodity, the operating costs of running trains, and terminal operation costs. The higher the value of time the more important it will be in the measure. By adjusting the value of time the importance of fast transit versus operational cost can be controlled and thus determine the delivery time of a commodity at the customer zone.

3.3. Representing drayage moves

When grouping customers into customer zones and obtaining aggregated commodities it is important to consider the distances and costs of possible connections from the customer zones to the intermodal rail terminals. As can be seen in figure 6 customer zones can be connected to one or more terminals. These connections represent possible drayage moves by truck from the customer zones to the rail terminals. It is assumed that all customers grouped in a customer zone can reach the rail terminals they are connected to.

Figure 8 shows an expansion of the network from figure 5 where customer zone nodes have been added and non-used train canals have been omitted. The (dotted line) arcs between the customer zone nodes and the terminal nodes represent the drayage moves. The drayage arcs follow the same definition as the train canal arcs in that they are assumed to arrive at the beginning of a terminal node's time period and leave at the end of it.

To perform a drayage move it is assumed that one truck is needed for each container. We make an approximation by assuming that the transportation distances and cost are equal for all customers in a customer zone and that the transportation cost is commodity indifferent. Each drayage arc can therefore be associated with a unit transportation cost.

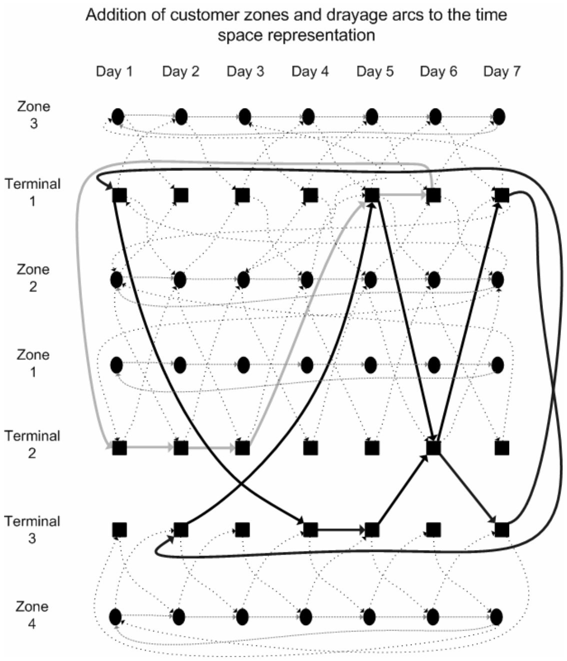

Figure 8

Given that intermodal operators are trying to achieve as seamless transportation chains as possible we assume that drayage moves are possible to perform whenever needed. That is why every terminal node is connected to a customer zone node and vice versa. The assumption is reasonable if intermodal operators plan drayage moves according to the train schedule. By assuming drayage moves are readily available at any given time the drayage arcs become un-capacitated arcs.

We assume that a commodity may be picked up any time after its time of availability. Holding arcs between the customer zone nodes are added (dashed grey lines in figure 8) to represent the possibility of commodities remaining at the customer after the time of availability until they are picked up eventually. The holding arcs have no operational cost or capacity associated to them.

3.4. Representing terminal events and operations

Making an adequate representation of terminal operations is a non-trivial task. They can not be neglected as they play an important role in the intermodal transportation chain. However, making a too detailed representation of them in a large-scale network will make the model computationally intractable. Each terminal node has a number of train canals connected to and from it representing possible train services of different modes to and from the terminal within the given time period. Furthermore a number of train transfer arcs for each mode connect from the terminal node's predecessor and to the terminal node's successor. Each mode is assumed to have a fixed train make-up, thus no operations are performed on them. However, only a limited number of trains may be present at a terminal at a given time, e.g. corresponding to the number of tracks at the terminal. Furthermore all trains that enter the terminal node must also leave it again to respect the conservation of trains.

Figure 9 shows the terminal node for terminal 1 on day 5 from figure 4. We assume that there are two available tracks at the terminal, and thus two train transfer arcs are added for each mode (grey and black horizontal full-line arrows). The remaining three train canals (inclined full line arrows) represent the train canals from figure 4 arriving from 'terminal 3, day 2' using the "black" mode, from 'terminal 2, day 3' using the "grey" mode, and leaving for 'terminal 2, day 6' using the "black" mode respectively. Using the representation in figure 9 the connection time for freight using the train canal arcs and/or train transfer arcs is not correctly represented. Both types of arcs assume that the departure time corresponds to the end of terminal nodes' time period and arrive at the beginning of them (the shaded areas in figure 9). To

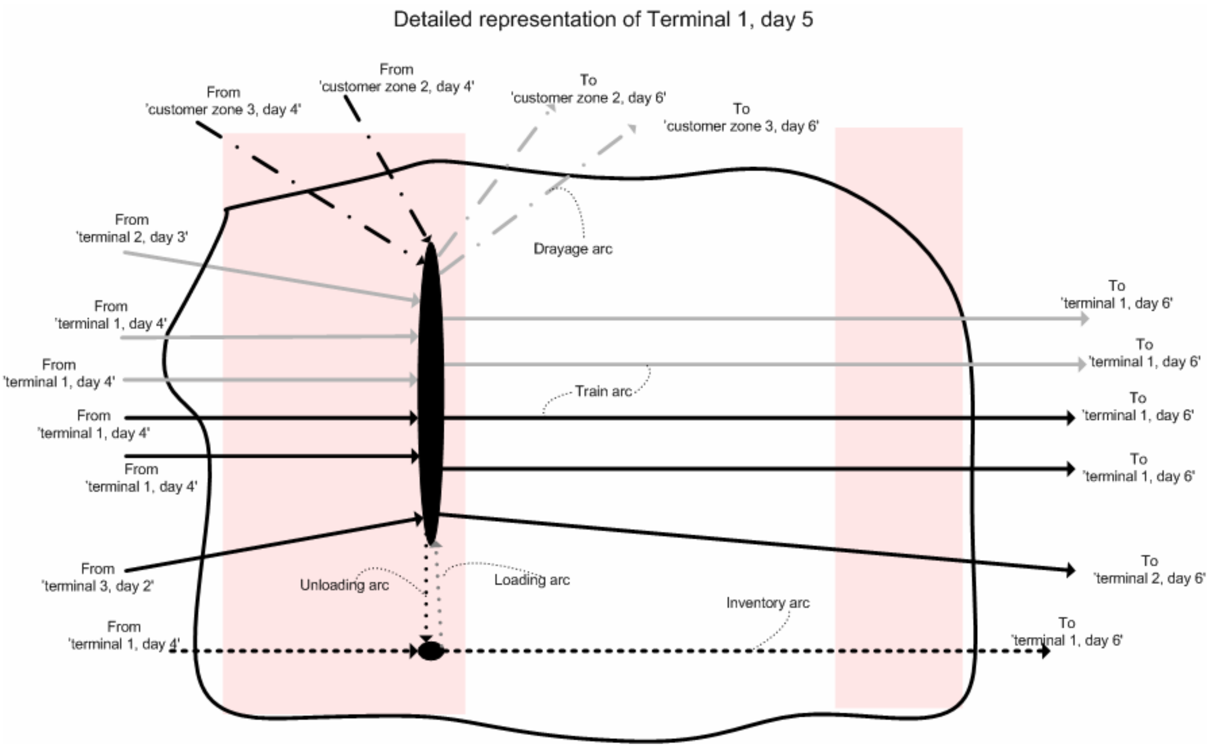

Figure 9

represent the connection time at the terminal the difference between the end time and the start time of a terminal node is added to all departing train canal arcs and departing train transfer arcs. The same procedure is done the departing drayage arcs.

Commodities can arrive to and depart from a terminal either by truck (using a drayage arc) or by train (using the selected train canals). Arriving to a terminal by train freight can either stay on-board the train, be transferred to another vehicle (truck or train), or be unloaded and put in the terminals storage place for later pick-up. Freight leaving a terminal on a train could have been plucked from the terminals storage space and loaded onto the train, transferred from a truck or another train, or simply stayed put on the train itself. The same possibilities are possible for freight arriving at a terminal except for truck/train and train/truck transfer being the only meaningful vehicle transfers.

An inventory arc (short dashed black line in figure 9) is used to represent the inventory level in the terminals storage. An inventory arc of a terminal node is connected to the succeeding terminal node to represent the transition of inventory from one time period to another. To follow the same definitions for the train canal arcs and train transfer arcs inventory arcs “depart” at the beginning of a terminal nodes time period and “arrives” at the beginning of its successors time period. The “transit” time of an inventory arc is equal to the time difference between the start times of the two terminal nodes’ time periods.

As shown in figure 9 a loading arc (dotted grey line) and an unloading (dotted black line) arc is added to each node to capture the flow to and from inventory. The unloading and loading operations are assumed to occur during the entire time period. However, since the duration is captured by the departing train canal arcs, departing train transfer arcs, departing drayage arcs, and the inventory arc, the loading and unloading operations are represented as if they happen instantaneously at the beginning of the terminal node's time period. Their "transit" times are therefore zero.

In the terminal representation shown in figure 9 it is not possible to distinguish between how the arriving and departing services are connected. Similarly it is not possible to distinguish between freight staying on a train and the vehicle transfers as there are no arcs representing the different possibilities. This means that a general assumption needs to be made on all freight arriving at a terminal. We thus assume that all freight arriving at a terminal on a service and leaving the terminal again on another service is transferred. The representation in figure 9 is thus an inaccurate representation of the possible terminal operations since staying on a train is not represented. However, a representation that could distinguish between the above mentioned operations would be much too detailed and computationally intractable. The assumption made here is an upper bound on the operational cost in a terminal and gives a better representation than assuming that no transfer operations are performed.

To capture the cost of vehicle transfer operations we add a variable vehicle transfer cost to each

Modelling assumptions			
Demand	deterministic	**Terminals**	divided into time preriods with a start time and an end time associated to them
	constant		train arcs are connected to terminal time periods according to departure and arrival times
	aggregated figures for customer zones (clusters of customers)		train transfers connect sequential time periods
	has an origin customer zone and a time of availability		capacity limits on the number of trains in a terminal within a time period
	has a destination customer zone but no fixed delivery time		all trains that enter a terminal at a time period (on a train canal or a train transfer) must leave it again
	linear value of time cost		commodities can be unloaded into or loaded from inventory
Train canals	represens a train routing possibility between two terminals		unit cost for loading and unloading operations
	has an departure time from a terminal and an arrival time to a terminal		commodities can transfer between train canals, train transfers, and drayage arcs
	limited number		commodities staying on trains are considered as being transferred
	one train may use a train canal		unit transfer cost per container
	fixed cost of use (acquisition and operating a train on it)		capacity limit on handling operations (transfer+loading+unloading)
	has a mode associated to it giving the capacity limt		capacity limit on inventory flow
Train transfers	represents trains staying at a terminal, transferring from one period to another	**Network modelling**	multicommodity demand representation
	connects sequential time periods of a terminal		a commodity has an origin ndode and multiple possible destination nodes (all belonging to the same customer zone)
	limited number determined a priori		customer zones discretized in customer zone nodes
	fixed cost representing depreciation or leasing cost of having an idle train at the terminal		terminals discretized in terminal nodes
	has a mode associated to it giving the capacity limt		train canal and train transfers represented by design arcs with a binary variable associated to them
Modes	represent a given train make-up and thus a capacity limit		design arcs connect two terminal nodes
	one mode is associated to each train canal		drayage moves represents by non-capacitated arcs with no binary variable assocaited to them
Drayage moves	connects customer zones an terminal		holding arcs added between customer zone nodes to allow commodities to stay in the customer zone after the time of availability
	unit transportation cost (one truck per container unit)		invetory arcs between terminal node model the inventory level at terminals
	unlimited capacity		cyclic network representing a repetitive network after the time horizon is reached

Figure 10

departing train canal arc, train transfer arc, and departing drayage arc. By doing this we implicitly assume that rail/rail and truck/rail transfers have the same cost. The cost of loading and unloading freight is different though as we assume some additional cost is incurred by moving a container to/from the storage place and storing/plucking it. An inventory transfer cost is added to the loading and unloading arcs. However, since all freight loaded continues on a departing train canal arc, train transfer arc, or drayage arc, the vehicle transfer cost is incurred. The vehicle transfer cost is thus subtracted from the inventory transfer cost on the loading arcs. Finally, a unit inventory cost is associated to the inventory arcs representing the storage cost of a container.

The number of possible operations in a time period at a terminal is limited. Because the same resources are used for vehicle transfers, unloading, and loading, a capacity constraint can not be added to a single arc. Previously we assumed that all freight leaving on train canal arcs, train transfer arcs, or drayage arcs went through a transfer process. Additionally freight may be loaded or unloaded into inventory. Assuming that all operations take similar time (i.e. the bottleneck is at the handling operations at the trains and not on the storage transfer transportation) and remembering that loaded freight is captured by the departing vehicle arcs, the sum of all terminal operations may be written as sum of the flow on departing train canal arcs, train transfer arcs, drayage arcs, and on unloading arcs. This sum is thus restricted by the maximum handling operations capacity. The storage places also have limited space. Thus a capacity limit is imposed on the flow on the inventory arcs.

4. Mathematical formulation of the model

In this section we present the mathematical optimization model formulation based on the modelling assumptions presented in section 3. The model is an arc flow based MIP model.

4.1. Sets

In this sub-section we present the sets used in the model. The use of the different sets in the model constraints is illustrated in figures 10 to 13 and an overview of them can be seen in appendix A. We define a set of customer zones:

$$\mathcal{Z} : \textit{set of customer zones}$$

For each customer zone $z \in \mathcal{Z}$ there is a set of customer zone nodes, and we define a union of all customer zone nodes:

$$\mathcal{N}_z : \textit{set of customer zone nodes for customer zone } z$$
$$\bigcup_{z \in \mathcal{Z}} \mathcal{N}_z : \textit{union of all customer zone nodes}$$

The customer zone node sets are indexed by $k, l \in \bigcup_{z \in \mathcal{Z}} \mathcal{N}_z$. To represent the sequence of customer zone nodes, a customer zone node k's preceding neighbour and succeeding neighbour is denoted:

$$n_z^-(k) \in \mathcal{N}_z, k \in \mathcal{N}_z : \textit{preceding customer zone node for customer zone node } k$$
$$n_z^+(k) \in \mathcal{N}_z, k \in \mathcal{N}_z : \textit{succeeding customer zone node for customer zone node } k$$

As for customer zones we determine a set of terminals

$$\mathcal{S} : \textit{set of terminals}$$

For each of the terminals in $s \in \mathcal{S}$ there is a set of terminal nodes, and we define a union of all terminal nodes:

$$\mathcal{N}_s \text{ : set of terminal nodes for terminal } s$$
$$\bigcup_{s \in \mathcal{S}} \mathcal{N}_s \text{ : union of all terminal nodes}$$

The terminal node sets are indexed by $h, i, j \in \bigcup_{s \in \mathcal{S}} \mathcal{N}_s$.

To represent the sequence of terminal nodes, terminal node *i*'s preceding and succeeding neighbour is denoted:

$$n_s^-(i) \in \mathcal{N}_s, i \in \mathcal{N}_s \text{ : preceding terminal node for temrinal node } i$$
$$n_s^+(i) \in \mathcal{N}_s, i \in \mathcal{N}_s \text{ : succeeding terminal node for terminal node } i$$

We define a set off commodities that represents the demand of freight in the network.

$$\mathcal{P} \text{ : set of commodities}$$

Each commodity $p \in \mathcal{P}$ has an origin customer zone node and a destination customer zone associated to it:

$$o(p) \in \bigcup_{z \in \mathcal{Z}} \mathcal{N}_z \text{ : origin customer zone node of commodity } p$$
$$d(p) \in \mathcal{Z} \text{ : destination customer zone of commodity } p$$

The time associated to the origin customer zone node k , t_k^γ , represents the time of availability of commodity *p*.

The different train make-up strategies are represented by a set of modes:

$$\mathcal{M} \text{ : set of modes representing a train make-up}$$

The only element that distinguishes train canal arcs and train transfer arcs of the same mode is that train transfer arcs connect two terminal nodes belonging to the same terminal. Thus we treat train canal arcs and train transfer arcs similarly in the mathematical formulation and denote them train arcs. For each mode $m \in \mathcal{M}$ there is a set of train arcs and each train arc connects terminal node *i* and terminal node *j*:

$$\mathcal{L}_m \text{ : Set of train canal arc for mode } m$$

$$\mathcal{L}_m : \{(i,j) \in \mathcal{L}_m \mid (i,j) \in \bigcup_{s \in \mathcal{S}} \mathcal{N}_s\}$$

Given the train canal arc sets we for each terminal node *i* define the inward neighbours from terminal *s*, $\mathcal{N}_{s,m}^-(i)$, and the outward neighbours to terminal *s*, $\mathcal{N}_{s,m}^+(i)$:

$$\mathcal{N}_{s,m}^-(i) : \{ j \in \mathcal{N}_{s,m}^-(i) \mid (i,j) \in \mathcal{L}_m \}$$
inward neighbours of node i from terminal s

$$\mathcal{N}_{s,m}^+(i) : \{ j \in \mathcal{N}_{s,m}^+(i) \mid (i,j) \in \mathcal{L}_m \}$$
outward neighbours of node i from terminal s

The union of all inward terminal neighbour nodes and the union of all outward terminal nodes are also defined:

$$\bigcup_{s \in \mathcal{S}} \mathcal{N}_{s,m}^-(i) \text{ : union of all inwards terminal nodes to terminal node } i$$
$$\bigcup_{s \in \mathcal{S}} \mathcal{N}_{s,m}^+(i) \text{ : union of all outwards terminal nodes from terminal node } i \quad ,$$

We define two sets of drayage arcs; a set of drayage arcs going from customer zone nodes to terminal nodes and one vice versa:

$\mathfrak{D}^{-}:\{(k,i)\in\mathfrak{D}^{-}\mid k\in\bigcup_{z\in\mathfrak{Z}}\mathfrak{N}_z, i\in\bigcup_{s\in\mathfrak{S}}\mathfrak{N}_s\}$
set of drayage arcs going from customer zone nodes to terminal nodes

$\mathfrak{D}^{+}:\{(i,k)\in\mathfrak{D}^{+}\mid i\in\bigcup_{s\in\mathfrak{S}}\mathfrak{N}_s, k\in\bigcup_{z\in\mathfrak{Z}}\mathfrak{N}_z\}$
set of drayage arcs going from terminal nodes to customer zone nodes

Given the drayage arcs sets we define $\mathfrak{N}_z^{-}(i)$ as the inward customer zone node neighbours from customer zone z of terminal node i, $\mathfrak{N}_z^{+}(i)$ as the outward customer zone node neighbours to customer zone z of terminal node i, $\mathfrak{N}_s^{+}(k)$ as the outward terminal node neighbours to terminal s from customer zone node k, and $\mathfrak{N}_s^{-}(z)$ as the outward terminal nodes from terminal s for customer zone z:

$\mathfrak{N}_z^{-}(i):\{k\in\mathfrak{N}_z^{-}(i)\mid(k,i)\in\mathfrak{D}^{-}\}$
Set of inward customer zone node neighbours from customer zone z for terminal node i

$\mathfrak{N}_z^{+}(i):\{k\in\mathfrak{N}_z^{+}(i)\mid(i,k)\in\mathfrak{D}^{+}\}$
Set of outward customer zone node neighbours from customer zone z for terminal node i

$\mathfrak{N}_s^{+}(k):\{i\in\mathfrak{N}_s^{+}(k)\mid(k,i)\in\mathfrak{D}^{-}\}$
Set of outward terminal node neighbours from terminal s for customer zone node k

$\mathfrak{N}_s^{-}(z):\{i\in\mathfrak{N}_s^{+}(z)\mid(i,k)\in\mathfrak{D}^{+}, k\in\mathfrak{N}_z\}$
Set of outward terminal node neighbours from terminal s for customer zone z

For each of the four sets defined above we define the unions as:

$\bigcup_{z\in\mathfrak{Z}}\mathfrak{N}_z^{-}(i)$: *Union of all inward customer zone node neighbours for terminal node i*

$\bigcup_{z\in\mathfrak{Z}}\mathfrak{N}_z^{+}(i)$: *Union of all outward customer zone node neighbours for terminal node i*

$\bigcup_{s\in\mathfrak{S}}\mathfrak{N}_s^{+}(k)$: *Union of all outward terminal node neighbours for customer zone node k*

$\bigcup_{s\in\mathfrak{S}}\mathfrak{N}_s^{-}(z)$: *Union of all outward terminal node neighbours for customer zone z*

4.2. Variables

This sub-section presents the variables used in the model. Appendix A includes an overview of the variables used. To represent the flow of commodities we use continuous variables. Although containers cannot be shipped in fractional numbers, the demand figures used in the model are only indications of the demand potentials and cannot be seen as actual shipment orders. There is a set of variables representing the commodity flow for holding arcs, inventory arcs, unloading arcs, loading arcs, drayage arcs, and train canal arcs:

$x_{i,p}^{\psi}$: *holding amount of commodity p at customer zone node k*

$x_{i,p}^{\mu}$: *Amount commodity p unloaded at terminal node i*

$x_{i,p}^{\nu}$: *Amount of commodity p loaded at terminal node i*

$x_{i,p}^{\omega}$: *inventory of commodity p at terminal node i*

$x_{i,k,p}^{\delta^-}$: *flow of commodity p from terminal node i to customer zone node k*

$x_{i,k,p}^{\delta^+}$: *flow of commodity p from customer zone node k to terminal node i*

$x_{i,j,m,p}^{\lambda}$: *flow of commodity p on train of mode m running on train canal arc (i, j)*

To capture the use of train arcs a binary variable is associated to each train canal arc

$$y^{\lambda}_{i,j,m} = \begin{cases} 1, \textit{if a train of mode m uses train arc (i, j)} \\ 0, \textit{else} \end{cases}$$

4.3. Parameters

This sub-section presents the parameters used in the mode. An overview is shown in appendix A. We start by recalling that the value of time is assumed have a linear relationship to the transit time. We thus define *b* to be the unit cost per time unit representing the value of time. Each commodity *p* has a parameter d_p representing the total amount of commodity *p* that needs to be shipped from its origin customer zone node $o(p)$ to its destination customer zone $d(p)$. We introduce a parameter $a_{k,p} = a^p$ if $k = o(p)$, zero else, and a parameter $a_{z,p} = d^p$ if $z = d(p)$, zero else.

$$d_p : \textit{demand of commodity } p$$

$$a_{k,p} = \begin{cases} d_p \textit{ if } k = o(p) \\ 0 \textit{ else} \end{cases}$$

$$a_{z,p} = \begin{cases} d_p \textit{ if } z = d(p) \\ 0 \textit{ else} \end{cases}$$

Each customer zone node has a time associated to it representing the time of occurrence

$$t^{\gamma}_k : \textit{time associated to customer zone node } k$$

In contrast to customer zone nodes each terminal node has a start time and an end time associated to it.

$$t^{\alpha}_i : \textit{start time associated to terminal node } i$$

$$t^{\beta}_i : \textit{end time associated to terminal node } i$$

The transit time associated to the holding arc in customer zone node *k*, t^{ψ}_k, is equal to the time difference between the time of customer zone node *k* and the time of its succeeding customer zone node's time. However, if *k* is the last node in the time horizon, and thus $n^+_z(k)$ is the first, the transit time is calculated as the time horizon, *T*, minus the time of customer zone node *k* time plus the time of customer zone node $n^+_z(k)$:

$$t^{\psi}_k = \begin{cases} t^{\gamma}_{n^+_z(k)} - t^{\gamma}_k, \textit{if } t^{\gamma}_{n^+_z(k)} \geq t^{\gamma}_k \\ (T - t^{\gamma}_k) + t^{\gamma}_{n^+_z(k)}, \textit{if } t^{\gamma}_{n^+_z(k)} < t^{\gamma}_k \end{cases}$$

$$\textit{transit time of holding arc from customer zone node } k$$

We can calculate the variable cost c^{ψ}_k associated the holding arc at customer zone node *k* as the transit time of the holding arc times the unit time cost:

$$c^{\psi}_k = b \cdot t^{\psi}_k : \textit{unit cost of holding arc from customer zone node } k$$

The transit time associated to the inventory arc in terminal node *i*, t^{ω}_i, is equal to the time difference between the start time of terminal node *i* and the time of its succeeding terminal node's start time. However, if *i* is the last node in the time horizon, and thus $n^+_s(i)$ is the first, the transit time is calculated as the time horizon, *T*, minus the start time of terminal node *i* time plus the start time of terminal node $n^+_s(i)$:

$$t^{\omega}_i = \begin{cases} t^{\alpha}_{n^+_s(i)} - t^{\alpha}_i, \textit{if } t^{\alpha}_{n^+_s(i)} \geq t^{\alpha}_i \\ (T - t^{\alpha}_i) + t^{\alpha}_{n^+_s(i)}, \textit{if } t^{\alpha}_{n^+_s(i)} < t^{\alpha}_i \end{cases}$$

$$\textit{transit time of inventory arc from terminal node } i$$

Each inventory arc has storage cost, c^e_i, associated to it. The total variable inventory cost, c^{ω}_i, associated with the inventory arc at terminal node *i* is the transit time of the holding arc times the unit time cost plus the storage cost:

$$c^{\omega}_i = c^e_i + b \cdot t^{\omega}_i : \textit{unit cost for invenotry arc from terminal node } i$$

The loading and unloading arcs of terminal node *i* have no transit time but each have an inventory transfer cost, c_i^u, associated to them. The unloading cost is equal the inventory transfer cost while the loading arc cost is subtracted the vehicle transfer cost, c_i^τ:

$$c_i^\mu = c_i^u \; : \; \textit{unit cost for unloading arc in terminal node } i$$

$$c_i^\nu = c_i^u - c_i^\tau \; : \; \textit{unit cost for loading arc in terminal node } i$$

To constrain the inventory levels each terminal node *i* has a capacity limit determining the maximum number of allowed containers in its storage place:

$$w_i \; : \textit{inventory capacity limit of terminal node } i$$

To constrain the number of transfer, unloading, and loading operations, each terminal node *i* has a handling capacity limit determining the maximum number of terminal operations in the terminal nodes time period:

$$u_i \; : \textit{handling capacity limit of terminal node } i$$

Finally the train number capacity determines the maximum number of allowed trains in the terminal node:

$$v_i \; : \textit{train capacity limit of terminal node } i$$

Each train arc *(i,j)* has a fixed cost associated to it representing the cost of routing a train on it:

$$f_{i,j,m}^\lambda \; : \; \textit{fixed cost of routing a train on train canal arc } (i,j) \textit{ of mode } m$$

The transit time of train canal arc *(i,j)*, t_{ij}^λ, is the sum of the actual transit time (from end time of departing terminal node *i* to start time of arriving terminal node *j*) plus the time period of the departing terminal node *i*. However, if the end time of terminal node *i* is larger than the start time of terminal node *j* (meaning the train runs into the following schedule repetition) the transit time is calculated as the time horizon, *T*, minus the start time of terminal node *i* time plus the start time of terminal node *j*:

$$t_{ij}^\lambda = \begin{cases} t_j^\alpha - t_i^\beta + (t_i^\beta - t_i^\alpha) = t_j^\alpha - t_i^\alpha, \textit{if } t_j^\alpha \geq t_i^\alpha \\ (T - t_i^\alpha) + t_j^\alpha, \textit{if } t_j^\alpha < t_i^\alpha \end{cases}$$

$$\textit{transit time of train canal arc } (i,j)$$

We also need to incorporate the vehicle transfer cost incurred in terminal nodes in the train arcs. Since each arc is a departing train arc the transfer cost for the origin terminal node *i*, c_i^τ, is added to each train arc *(i,j)*. The variable unit cost associated to each train arc is obtained by adding the vehicle transfer cost and the unit time cost multiplied by the transit time:

$$c_{ij}^\lambda = c_i^\tau + b \cdot t_{ij}^\lambda \; : \; \textit{unit cost for train canal arc } (i,j)$$

The flow on train arcs is limited by the make-up defined by the arcs mode. A capacity limit is associated to each mode representing the maximum number of containers transported on a train canal using mode *m*:

$$q_m^\lambda \; : \; \textit{capacity of mode } m$$

We assume that drayage arcs have the same transportation cost whether they connect terminal node *i* to customer zone node *k* or vice versa, $c_{ki}^{d+} = c_{ik}^{d-}$.The transit times differ though. Drayage arc connecting customer zone node *k* to terminal node *i* have a transit time $t_{ki}^{\delta+}$ equal to the difference between the terminal node's start time and the customer zone node's time:

$$t_{ki}^{\delta+} = \begin{cases} t_i^\alpha - t_k^\gamma \textit{ if } t_i^\alpha \geq t_k^\gamma \\ t_i^\alpha + (T - t_k^\gamma) \textit{ if } t_i^\alpha < t_k^\gamma \end{cases}$$

The variable cost of using the drayage arc between customer zone node *k* and terminal node *i* is the sum of the transportation cost and the transit time multiplied by the unit time cost:

$$c_{ki}^{\delta+} = c_{ki}^{d+} + b \cdot t_{ki}^{\delta+} : \textit{ unit cost of using drayage arcs from customer zone node } k \textit{ to terminal node } i$$

Drayage arc connecting customer zone node k to terminal node i have a transit time $t_{ki}^{\delta-}$ equal to the difference between the terminal node's end time and the customer zone node's time plus the time duration of the terminal node:

$$t_{ik}^{\delta-} = \begin{cases} t_k^{\gamma} - t_i^{\beta} + (t_i^{\beta} - t_i^{\alpha}) = t_k^{\gamma} - t_i^{\alpha} \text{ if } t_k^{\gamma} > t_i^{\alpha} \\ t_k^{\gamma} + (T - t_i^{\alpha}) \text{ if } t_k^{\gamma} < t_i^{\alpha} \end{cases}$$

The vehicle transfer cost of terminal node i, c_i^{τ}, is added to the drayage arcs departing from it. The variable cost of using the drayage arc connecting terminal node i and customer zone node k is the sum of the transportation cost, the terminal vehicle transfer cost, and the transit time multiplied by the unit value of time cost:

$$c_{ik}^{\delta-} = c_{ik}^{d-} + c_i^{\tau} + b \cdot t_{ik}^{\delta-} : \textit{ unit cost of using drayage arcs from terminal node } i \textit{ to customer zone node } k$$

4.4. Constraints

The objective is to minimize operational cost and transit time. Thus the objective function has to minimize the sum off the transportation costs, terminal operation costs, and value of time cost. The variable transportation cost, the terminal operation costs, and the value of time costs have been aggregated into unit costs associated to the flow on the respective arcs. The objective function can be written as a minimization of the sun of the fixed train canal costs multiplied by the train canal selection variable plus the sum of the unit container transit costs times the flow on the corresponding arcs:

$$\begin{aligned} \min z = & \sum_{(i,j)\in\mathcal{L}_m}\sum_{m\in\mathcal{M}} f_{i,j,m}^{\lambda} y_{i,j,m}^{\lambda} + \\ & \sum_{(i,j)\in\mathcal{L}_m}\sum_{m\in\mathcal{M}}\sum_{p\in\mathcal{P}} c_{i,j}^{\lambda} x_{i,j,p,m}^{\lambda} + \sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c_i^{\omega} x_{i,p}^{\omega} + \\ & \sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c_i^{\mu} x_{i,p}^{\mu} + \sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c_i^{\nu} x_{i,p}^{\nu} + \\ & \sum_{(k,i)\in\mathcal{D}^+}\sum_{p\in\mathcal{P}} c_{k,i}^{\delta+} x_{k,i,p}^{\delta+} + \sum_{(i,k)\in\mathcal{D}^-}\sum_{p\in\mathcal{P}} c_{i,k}^{\delta-} x_{i,k,p}^{\delta-} + \\ & \sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}_z}\sum_{p\in\mathcal{P}} c_k^{\psi} x_{k,p}^{\psi} \end{aligned} \qquad (1)$$

We introduce a number of flow balance constraints to respect the conservation of flow in the network. Commodity p originates from a customer zone node and may continue on the holding arc or on any of the departing drayage arcs. The flow balance constraint for commodities leaving customer zone nodes becomes:

$$x_{n_z^-(k),p}^{\psi} + a_{k,p} = x_{k,p}^{\psi} + \sum_{i\in\bigcup_{s\in S}\mathcal{N}_s^+(k)} x_{k,i,p}^{\delta+} \quad \forall k \in \bigcup_{z\in\mathcal{Z}}\mathcal{N}_z, \forall p \in \mathcal{P} \qquad (2)$$

The constraint is illustrated in figure 11.

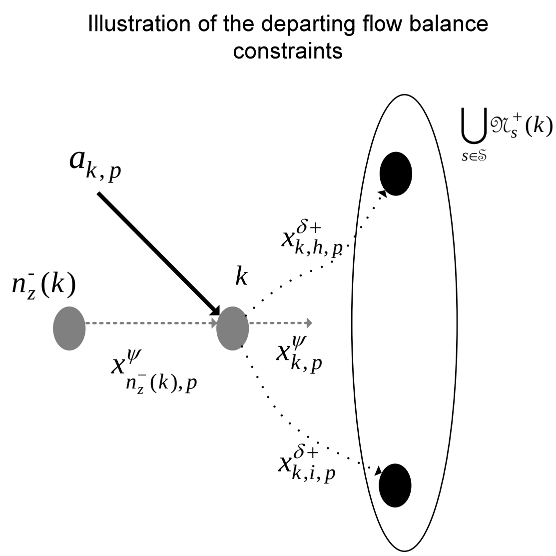

Figure 11

Since commodities have a destination customer zone, and no destination customer zone node, the flow balance constraint for commodities arriving at their destination customer zone must make sure that the sum of flow to all customer zone nodes associated to the destination customer zone must be equal to the demand of the commodity. The flow balance constraint for commodities arriving at a customer zone becomes:

$$\sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s^-(z)}\sum_{k\in\mathcal{N}_z} x^{\delta-}_{i,k,p} = a_{z,p} \quad \forall z\in\mathcal{Z}, \forall p\in\mathcal{P} \quad (3)$$

The constraint is illustrated in figure 12.

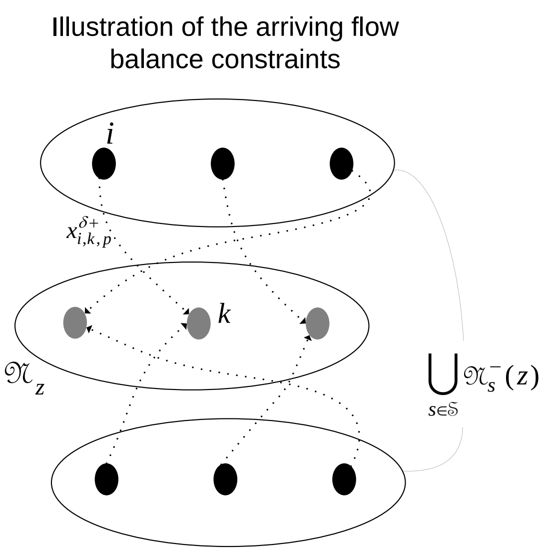

Figure 12

A commodity *p* may arrive at a terminal on a drayage arcs from customer zone nodes or on train arcs. Along with the commodities loaded from inventory onto other train canal arcs or drayage arcs and may also be stored back in inventory. For each terminal node *i* the sum of the flow of commodities arriving on arriving train arc, arriving drayage arcs, and the loading arc must be equal the sum of the flow leaving on departing train arcs, departing drayage arcs, and the unloading arc:

$$\begin{aligned}&\sum_{m\in\mathcal{M}}\sum_{h\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^+_{s,m}(i)} x^{\lambda}_{h,i,p,m} + \\ &\sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^+_z(i)} x^{\delta+}_{k,i,p} + x^{\mu}_{i,p} = \\ &\sum_{l\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^-_z(i)} x^{\delta-}_{i,l,p} + x^{\nu}_{i,p} + \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall p\in\mathcal{P} \quad (4) \\ &\sum_{m\in\mathcal{M}}\sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^-_{s,m}(i)} x^{\lambda}_{i,j,p,m}\end{aligned}$$

The constraint is illustrated in figure 13.

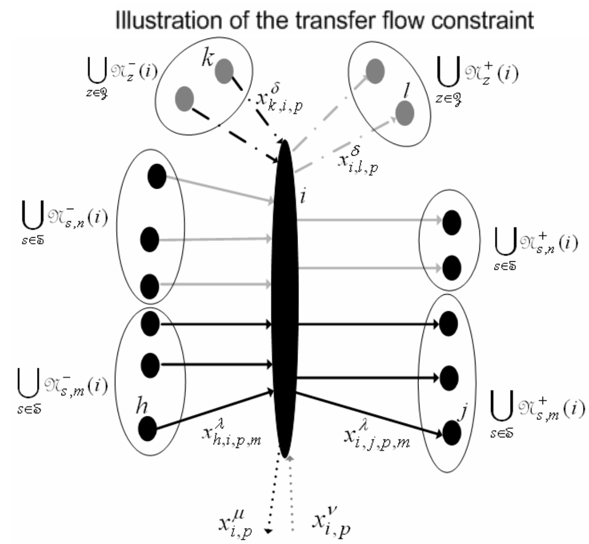

Figure 13

A flow balance constraint must also be added to ensure that there is conservation of flow in the terminals storage place. For each terminal node *i* the sum of the inventory flow from the predecessor (inventory level before the start of the time period) plus what is unloaded must be equal the sum of what is loaded plus what is left in inventory:

$$x^{\omega}_{n_s^+(i),i,p} + x^{\mu}_{i,p} = x^{\omega}_{i,p} + x^{\nu}_{i,p} \quad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall p\in\mathcal{P} \quad (5)$$

The constraint is illustrated in figure 14. Notice that there are no initial and terminal conditions on the storage level due to the cyclic, repetitive schedule.

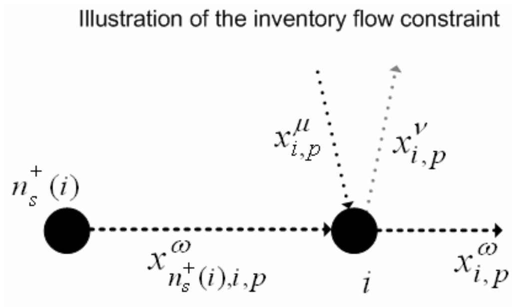

Figure 14

The capacity of terminal handlings is determined as the sum of all handling operations. All freight not remaining in inventory is handled, i.e. freight from train arcs, drayage arcs, and loading and unloading arcs. Given the balance of flow given from equation (4) the sum of all transfer operations may either be written as the sum of flow on all arriving arcs or departing arcs. We have chosen the flow on arriving arcs:

$$x^{\nu}_{i,p} + \sum_{m\in\mathcal{M}}\sum_{p\in\mathcal{P}}\sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^{-}_{s,m}(i)} x^{\lambda}_{i,j,p,m} + \sum_{p\in\mathcal{P}}\sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^{-}_{z}(i)} x^{\delta}_{i,k,p} \le u_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (6)$$

Similarly the storage place in a terminal node has limited capacity. Thus the inventory level must be lower than the terminal node storage capacity:

$$\sum_{p\in\mathcal{P}} x^{\omega}_{ip} \le w_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (7)$$

Finally we ensure the maximum number of trains that can be accommodated at terminal node *i* by setting the sum of all selected arriving train canal arcs to be less than or equal to the train number capacity

$$\sum_{m\in\mathcal{M}}\sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^{-}_{s,m}(i)} y^{\lambda}_{i,j,m} \le v_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (8)$$

The number of trains that enter a terminal node must be equal to the number of trains leaving the terminal again. The number of trains entering and leaving a terminal node is equal to the number of selected train canal arcs. Thus the number of selected train arcs entering a terminal node must equal the number leaving it:

$$\sum_{h\in\mathcal{N}^{+}_{s,m}(i)} y^{\lambda}_{h,i,m} = \sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^{-}_{s,m}(i)} y^{\lambda}_{i,j,m} \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall m\in\mathcal{M} \qquad (9)$$

The constraint is illustrated by the selection in figure 15.

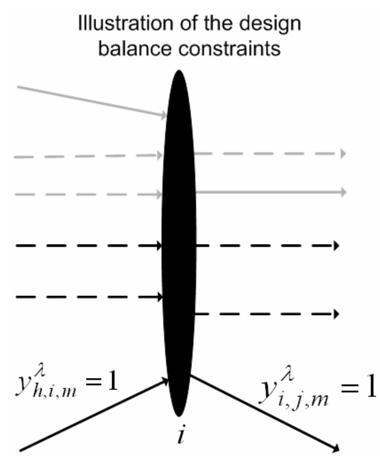

Figure 15

The maximum number of commodities that can flow on a train canal arc is constrained by the capacity of the arc's mode. By multiplying the design variable with the capacity and setting it larger or equal to the sum of the flow we ensure that the flow is less than or equal the mode capacity if the train arc is selected and zero else.

$$\sum_{p\in\mathcal{P}} x^{\lambda}_{i,j,p,m} \le q_m y^{\lambda}_{i,j,m} \qquad \forall (i,j)\in\bigcup_{m\in\mathcal{M}}\mathcal{L}_m \qquad (10)$$

The nine constraints (2)-(9) above plus the objective function (1) make up a MIP-model that designs an intermodal train schedule based on train canals considering terminal operations. An overview of the model can be found in appendix B. MIP-models are hard to solve for large instances. Even though the majority of the rail network capacity is reserved for passenger trains from a model point of view the remaining train canals still imply a large-scale instance for the model. Furthermore the multiple-destination choice for commodities provides looser bounds than for the traditional formulation with fixed delivery time.

5. Model implementation and result analysis

To get an indication of the complexity of the model we perform a series of computational experiments. These are conducted by using Xpress-MP's MIP solver to solve a generated test network. Model behaviour will be examined by simulating different scenarios with respect to value of time and commodity amounts.

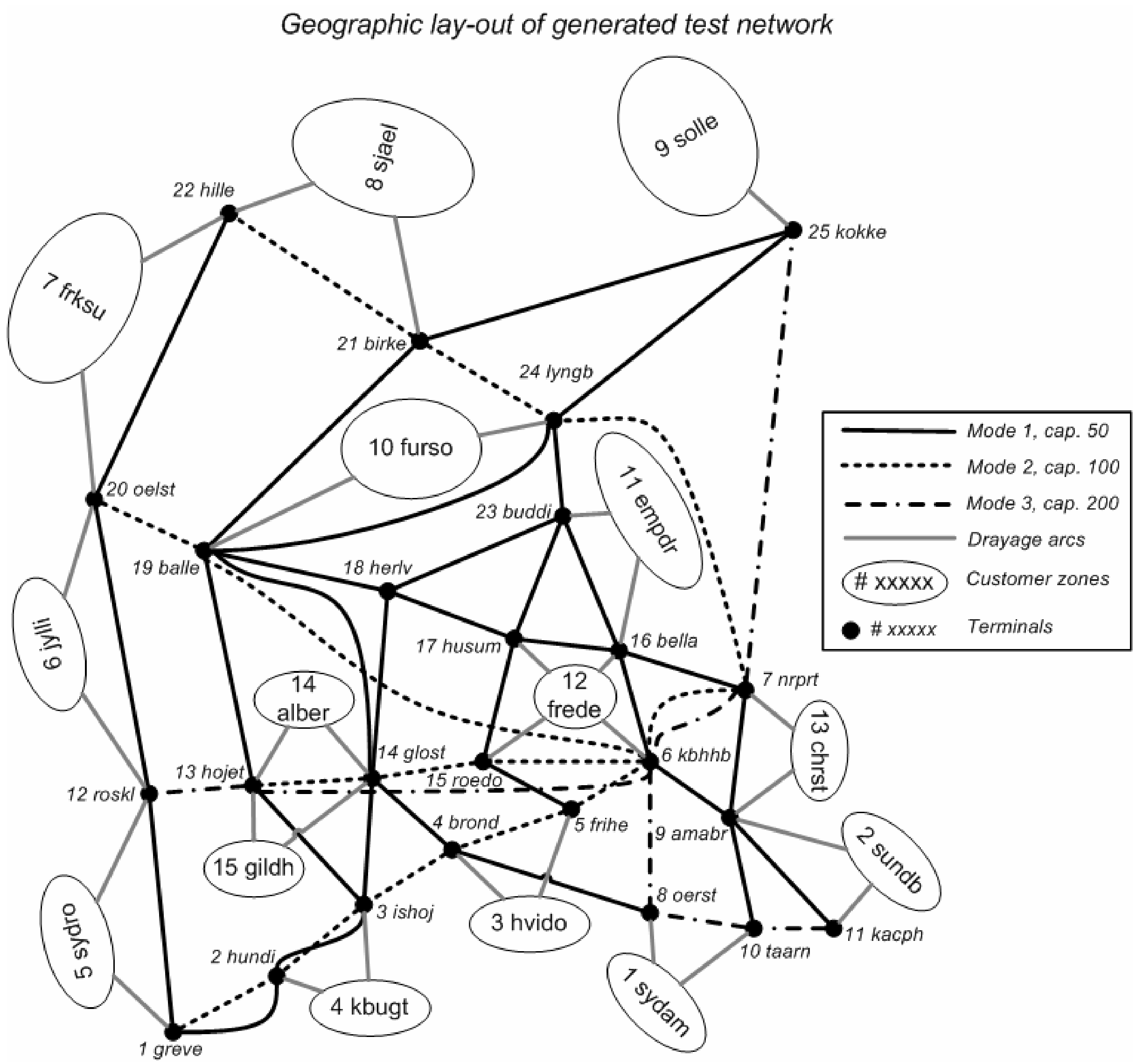

Figure 16

5.1. Constructing a test data set

To test the model a test network was constructed. The network is generated in a size which may resemble a realistically sized intermodal train service network. The network consists of 25 rail terminals and 15 customer zones. The 25 rail terminals are connected by a physical rail infrastructure and the customer zones are connected to one or more of the rail terminals. The geographic lay-out of the network is illustrated in figure 16. The connections between the terminals show which modes are applied to which connections. There are three modes with capacities of 50, 100, and 200 respectively. The planning horizon used in the instance is a 7 day period and each of the customer zones and terminals are represented by 7 nodes each representing a day of the week. There are thus 105 customer zone nodes and 175 terminal nodes. The total number of nodes is 280. All terminal nodes representing one terminal are assumed to have the same capacity of trains, transfer operations, and inventory. All instance attributes are illustrated in the summary in figure 17.

The number of available train canals between terminals for each of the three modes is 253, 112, and 62 respectively. In addition 203, 112, and 63 train transfer arcs have been added for the three modes respectively in the terminals the modes connect. The

Nodes						
Total nodes: $\mathcal{N}_z \cup \mathcal{N}_s$	280					
Terminals: $\mathcal{S}$	25					
Terminal nodes: $\mathcal{N}_s$	175					
	terminal attributes					
	Vehicle transfer cost: c_i^{τ}	Load/unloading cost: c_i^{u}	Storage cost: c_i^{e}	handling capacity: u_i	Storage capacity: w_i	train capacity: v_i
ranges	65 - 85	80 - 100	10 - 30	70 - 105	100	2 - 4
Arcs						
# of train arcs	805					
	mode 1		mode 2		mode 3	
train canal arcs $y_{i,j,m}^{\lambda}$	253		112		62	
train transfer arcs $y_{i,j,m}^{\lambda}$	203		112		63	
	Train canal cost: $f_{i,j,m}^{\lambda}$	Train transfer costs: $f_{i,j,m}^{\lambda}$	Train canal cost: $f_{i,j,m}^{\lambda}$	Train transfer costs: $f_{i,j,m}^{\lambda}$	Train canal cost: $f_{i,j,m}^{\lambda}$	Train transfer costs: $f_{i,j,m}^{\lambda}$
ranges	9585 - 13960	6000	19875 - 26780	13000	38570 - 50060	27000
# of drayage arcs: $x_{k,i,p}^{\delta+}$, $x_{i,k,p}^{\delta-}$	434					
	Unit transportation cost: c_{ki}^{d+}, c_{ik}^{d-}					
range	78 - 150					
Commodties						
# of commodities: $\mathcal{P}$	90					
	low	medium	high			
commodity amount range: d_p	3 - 6	5 - 9	6 - 12			
total amount: $\sum_{p \in \mathcal{P}} d_p$	399	618	798			
Time horizon: T	168 hours					
	low	medium	high			
value of time: b	0	5	10			
Model attributes						
binary variables	805					
continuous varaibles	168210					
constraints	44155					

Figure 17

total number of binary decision variables totals 805. In addition 434 drayage arcs have been added between the customer zone nodes and the terminal nodes. Finally 90 commodities were generated randomly each with one of the 105 customer zone nodes as their origin and one of the 15 customer zones as their destination. To examine the models behaviour 9 different scenarios have been created by varying the commodity amount values and the value of time each on three different levels. The origins and destinations of commodities are the same for all scenarios, but the amounts vary with a factor 1, 1.5, and 2 (low, medium, and high) respectively. The value of time is set to 0, 5, and 10 (low, medium, and high) respectively to simulate scenarios where the value of time has no importance, has medium importance compared the operating cost, and has high importance compared to the operating costs respectively.

5.2. Solving the problem using Xpress-MP

Considering the problem size depicted in figure 17 it is clear that the problem is not trivially solved. However, we use Xpress-MP's standard MIP solver to solve the problem in order to get an impression of the models complexity. To achieve feasible solutions 90 hours of CPU time (324.000 seconds) was allocated to solve each of the 9 scenarios on a using a PC with an Intel Pentium 4, 2.26Ghz processor. As a preliminary exercise some of the options available for the MIP-solver was tried out to see if any improvements in solution and solution time could be identified. However, no noteworthy effects were identified and the problem was solved using the MIP-solver's standard settings. The computational results achieved are illustrated in the table in figure 18.

The computational results show as expected that the problem is difficult to solve. Within the large time limit of 90 hours only 1-3 feasible solutions were found for the scenarios. The model is fundamentally an extension of a network design model. These are generally hard to solve because of the poor lower bounds provided from the LP-relaxation. The model here is no exception where the gap between the LP relaxation and the best found feasible solutions is between 38% and 58%. The cuts generated give reasonable improvements, 18% to 27%, on the LP-relaxation but the gaps to the best feasible solution still lies between 23% and 43%. Furthermore the cut generation times lie between 2 and 7 hours of computational time. The gaps between the

Computational results on 9 scenarios									
	Scenario attributes								
flow	**low**			**medium**			**high**		
value of time	**low**	**medium**	**high**	**low**	**medium**	**high**	**low**	**medium**	**high**
Time limit	324.000 sec.								
Number of feasible solutions	2	1	2	1	1	2	2	1	3
Best feasible solution time (sec.)	285,154	184,935	139,875	222,597	158,820	258,948	234,605	167,581	313,004
Best feasible solution value	1,068,860	1,746,850	2,482,350	1,444,330	2,238,650	3,206,130	1,746,030	2,736,030	3,950,940
Lower bound at time limit	617,764	1,136,761	1,620,757	905,356	1,678,198	2,405,664	1,136,908	2,113,203	3,033,931
Lower bound/best feasible solution gap	42.20%	34.93%	34.71%	37.32%	25.04%	24.97%	34.89%	22.76%	23.21%
LP solution time (sec.)	250	113	75	275	129	79	326	127	85
LP solution	455,293	838,196	1,200,815	704,272	1,296,965	1,858,225	910,586	1,676,393	2,401,627
LP/Best feasible solution gap	57.40%	52.02%	51.63%	51.24%	42.06%	42.04%	47.85%	38.73%	39.21%
Cut generation time	25,227	9,849	8,845	12,796	9,225	6,495	13,302	8,441	6,034
Solution post cut generation	617,046	1,131,995	1,618,252	895,433	1,669,894	2,401,414	1,121,190	2,103,043	3,017,793
Cut/Best feasible solution gap	42.27%	35.20%	34.81%	38.00%	25.41%	25.10%	35.79%	23.14%	23.62%

Figure 18

Key performance indicators for the 9 scenarios									
flow	low			medium			high		
value of time	low	medium	high	low	medium	high	low	medium	high
operating cost	1.068.860	1.144.690	1.402.110	1.444.330	1.389.170	1.728.810	1.746.030	1.758.810	2.051.580
operating cost increase (low time → med. time, med. time → high time)		7,09%	22,49%		-3,82%	24,45%		0,73%	16,65%
number of train services	35	44	64	52	61	64	60	56	72
train transfers	11	26	29	28	17	27	24	29	38
total service capacity	2850	2600	3900	3200	3650	5000	4150	4600	5300
total flow on services	1228	1193	1227	1915	1790	1754	2326	2109	2235
total service capacity utilization	43,09%	45,88%	31,46%	59,83%	49,04%	35,07%	56,05%	45,84%	42,17%
terminal nodes with hadling operations/at max capacity	80/1	86/3	90/0	89/10	76/5	87/6	90/19	87/12	99/12
Total number of handling operations	2315	2344	2201	3607	3202	2973	4223	3796	3950
Total inventory flow	1541	1054	784	2279	1520	1100	2463	1601	1167
Total transit time	126.474	112.698	100.290	193.215	157.404	135.360	217.500	179.832	173.700
transit time decrease (low time → med. time, med. time → high time)		10,89%	11,01%		18,53%	14,00%		17,32%	3,41%

Figure 19

lower bound achieved at the time limit of the branch-and-bound process and the best feasible solutions lie between 22% and 43% effectively only decreasing the gap by up to 1.5%. The large gaps between the bounds and the tardiness of the best found feasible solutions means that it is unreasonable to expect the best found feasible solutions to be near optimal.

Although the solutions found are not optimal or near-optimal analysis of the obtained results may still indicate whether the model works appropriately. To make the analysis of the model we have calculated a number of key-performance indicators. These are presented in the table in figure 19. The columns of the table show the performance indicators for each of the nine scenarios. The first row shows the operational cost for the best feasible solution for each of the nine scenarios. One tendency that can be seen is that the operational costs increase the higher the amount of commodities is. The other tendency that can be seen is that the operational cost increase the higher the value of time is. When the value of time increases its impact on the objective value becomes larger meaning the model chooses to include more services (resulting in higher operational costs) in order to provide faster transit times for the commodities. The second row shows the increase in operational costs from low value of time to medium value of time and from medium value of time to high value of time. Note that the operational cost actually decreases when the value of time is increased from low to medium for the medium commodity amount scenarios. An explanation to this may be that the structure of the medium/medium scenario by coincidence allows the branch-and-bound solution to find a relatively better feasible solution.

The third and fourth row show the number of chosen train canal arcs which is equivalent to the number of services offered and the number of chosen train transfers within the same terminal's terminal nodes. As expected the number of offered services increases with the value of time and the amount of commodities in order to provide more capacity and shorter transit times. Again one exception stands out when going from low value of time to medium value of time for the high commodity amount scenarios. A further analysis shows that the more of the high capacity mode train arcs are chosen in the high/medium than in the high/low scenario. Thus effectively the available capacity (row 6) and operational costs increase, but fewer services are offered. The seventh row show the overall capacity utilization of the services offered. The utilization decreases with the value of time again indicating that more services are offered to give shorter transit times the higher the value of time is. This tendency can also be seen by looking at rows eight and nine that show the total number of handling operations and total inventory flow in terminals. The higher the value of time the fewer transfer operations are performed and the less inventory flow is seen. The higher number of services means that more direct services can be offered to the commodities resulting in fewer transfers and also means that commodities have to wait for shorter time in inventory for a service departing from a terminal. Finally row ten shows the total transit time for each of the scenarios where it is clear to see that it decreases the higher the value of time cost is. By calculating and analysing the key performance indicators shown in figure 19 it is reasonable to conclude that the model captures the trade-off between value of time and operating cost. The question is now how an operator decides on the value of time. As the value of time increases the operational costs increase and the overall transit time decreases. It is then up to the operator to decide on the trade-off between increased operational costs and increased service to the customers.

6. Future research and conclusion

In this paper a mathematical model for intermodal train scheduling was presented. The main properties of the model are that it incorporates terminal operations in terminals by setting an upper limit on handling operations and inventory and by leaving the delivery time of commodities as an output of the model. The delivery times of commodities are determined by a linear cost representing the value of time. The scheduling of trains is done on train canals that are predetermined time dependent path on the rail infrastructure as is the case in the rail sector in Europe. To model the time dimension of schedules a space-time representation were the nodes represent locations within a time period and arcs represent movements in time and space between two different locations or simply a movement in time within the same location is used.

The model was applied to a generated network using nine different scenarios with varying commodity flow and value of time costs. The model was solved using Xpress-MP's MIP-solver with results, as expected, of mediocre quality. Before any practical implementation can be considered it is necessary to design better solution methods other than the "brute force" approach used here. There are several approaches one may envision to achieve better solution methods. For one, better lower bounds may help the branch-and bound process by reducing the gap between feasible solutions and the lower bound. Second, decomposition methods such as constraint generating approaches may also be an interesting approach. Finally heuristic methods can prove to be a fast and efficient way of finding feasible solutions. By combining the different approaches the gap between feasible solution and the lower bound may be reduced in order to find and prove near optimal solutions.

However, although the model has the basic structure of a network design problem (flow balance constraints and binding capacity constraints) there are a set of constraints that have not been handled before in network design models. These are the balancing constraints stating that the number of vehicles entering a node must also leave the node again. These constraints resemble vehicle routing constraints expect for there not being a depot. The constraints effectively bind the binary decision variables together as opposed to traditional network design models where opening or closing an arc can be done independently of the other design arc. We believe the next step is to research how to handle these new set of constraints for network design models before proceeding to applying such models to real instances.

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Appendix A – Sets, parameters, and variables used in the model

Overview of sets :

$\mathcal{Z}$	*set of customer zones*	$\mathcal{S}$	*set of terminals*
$\mathcal{N}_z$	*set of customer zone nodes for customer zone z*	$\mathcal{N}_s$	*set of terminal nodes for terminal s*
$\bigcup_{z\in\mathcal{Z}}\mathcal{N}_z$	*all customer zone nodes*	$\bigcup_{s\in\mathcal{S}}\mathcal{N}_s$	*all terminal nodes*
$n_z^-(k)$	*preceding neighbour customer zone node*	$n_s^-(k)$	*preceding neighbour terminal node*
$n_z^+(k)$	*succeeding neighbour customer zone node*	$n_s^+(k)$	*succeeding neighbour terminal node*
$\mathcal{M}$	*set of modes*	$\mathcal{D}^+$	*set of drayage arcs going from customer zone nodes to terminal nodes*
$\mathcal{L}_m$	*set of train canal arcs for mode m*	$\mathcal{D}^-$	*set of drayage arcs going from terminal nodes to customer zone nodes*
$\mathcal{N}_{s,m}^-(i)$	*inward terminal nodes for terminal node i of train canal arcs using mode m*	$\mathcal{N}_z^-(i)$	*inward customer zone nodes for terminal node i reached by drayage arc*
$\mathcal{N}_{s,m}^+(i)$	*outward terminal nodes for terminal node i of train canal arcs using mode m*	$\mathcal{N}_z^+(i)$	*outward customer zone nodes for terminal node i reached by drayage arc*
$\mathcal{P}$	*set of commodities*	$\mathcal{N}_s^+(k)$	*outward terminal nodes for customer zone node k reached by drayage arc*

Overview of parameters :

b *: unit value of time cost* T *: time horizon*

d_p *: demand of commodity p*

$$a_{k,p} = \begin{cases} d_p \text{ if } k = o(p) \\ 0 \text{ else} \end{cases}$$ *demand of commdity p originating from customer zone node k*

$$a_{z,p} = \begin{cases} d_p \text{ if } z = d(p) \\ 0 \text{ else} \end{cases}$$ *demand of commodity p destined to customer zone z*

t_i^α *: start time of terminal node i* t_i^β *: end time of terminal node i* t_k^γ *: time of customer zone node k*

$$t_k^\psi = \begin{cases} t^\gamma_{n_z^+(k)} - t_k^\gamma, \text{if } t^\gamma_{n_z^+(k)} \ge t_k^\gamma \\ (T - t_k^\gamma) + t^\gamma_{n_z^+(k)}, \text{if } t^\gamma_{n_z^+(k)} < t_k^\gamma \end{cases}$$ *transit time of holding arc from customer zone node k*

$$t_i^\omega = \begin{cases} t^\alpha_{n_s^+(i)} - t_i^\alpha, \text{if } t^\alpha_{n_s^+(i)} \ge t_i^\alpha \\ (T - t_i^\alpha) + t^\alpha_{n_s^+(i)}, \text{if } t^\alpha_{n_s^+(i)} < t_i^\alpha \end{cases}$$ *transit time of inventory arc from terminal node i*

$t_{ij}^{\lambda} = \begin{cases} t_j^{\alpha} - t_i^{\beta} + (t_i^{\beta} - t_i^{\alpha}) = t_j^{\alpha} - t_i^{\alpha}, if\ t_j^{\alpha} \geq t_i^{\alpha} \\ (T - t_i^{\alpha}) + t_j^{\alpha}, if\ t_j^{\alpha} < t_i^{\alpha} \end{cases}$ *transit time of train canal arc (i, j)*

$t_{ki}^{\delta+} = \begin{cases} t_i^{\alpha} - t_k^{\gamma}\ if\ t_i^{\alpha} \geq t_k^{\gamma} \\ t_i^{\alpha} + (T - t_k^{\gamma})\ if\ t_i^{\alpha} < t_k^{\gamma} \end{cases}$ *transit time for drayage arc (k,i) going from customer zone node k to terminal node k*

$t_{ik}^{\delta-} = \begin{cases} t_k^{\gamma} - t_i^{\beta} + (t_i^{\beta} - t_i^{\alpha}) = t_k^{\gamma} - t_i^{\alpha}\ if\ t_k^{\gamma} \geq t_i^{\alpha} \\ t_k^{\gamma} + (T - t_i^{\alpha})\ if\ t_k^{\gamma} < t_i^{\alpha} \end{cases}$ *transit time for drayage arc (i,k) going from terminal node k to customer zone node k*

$c_k^{\psi} = b \cdot t_k^{\psi}$: *unit cost of holding arc from customer zone node k*

c_i^{e} :*unit storage cost for terminal node i*

$c_i^{\varpi} = c_i^{e} + b \cdot t_i^{\varpi}$: *unit invenotry cost arc from terminal node i*

c_i^{u} :*loading/unloading cost in terminal node i*

c_i^{τ} :*unit vehicle transfer cost in terminal node i*

$c_i^{\mu} = c_i^{u}$: *unit cost for unloading arc in terminal node i*

$c_i^{\nu} = c_i^{u} - c_i^{\tau}$: *unit cost for loading arc in terminal node i*

$f_{i,j,m}^{\lambda}$: *fixed cost of routing a train on train canalarc (i, j) of mode m*

$c_{ij}^{\lambda} = c_i^{\tau} + b \cdot t_{ij}^{\lambda}$:*unit cost for train canal arc (i, j)*

c_{ki}^{d+} :*unit transportaion cost from node k to i*

c_{ik}^{d-} :*unit transportaion cost from node i to k*

$c_{ki}^{\delta+} = c_{ki}^{d+} + b \cdot t_{ki}^{\delta+}$: *unit cost of using drayage arcs from customer zone node k to terminal node i*

$c_{ik}^{\delta-} = c_{ik}^{d-} + c_i^{\tau} + b \cdot t_{ik}^{\delta-}$: *unit cost of using drayage arcs from terminal node i to customer zone node k*

w_i : *inventory capacity limit of terminal node i* u_i : *handling capacity limit of terminal node i*

v_i : *train capacity limit of terminal node i* q_m^{λ} : *capacity of mode m*

Overviewof variables

$x^{\psi}_{i,p}$: *holding amount of commodity p at customer zone node k*

$x^{\mu}_{i,p}$: *Amount commodity p unloaded at terminal node i*

$x^{\nu}_{i,p}$: *Amount of commodity p loaded at terminal node i*

$x^{\varpi}_{i,p}$: *inventory of commodity p at terminal node i*

$x^{\delta^-}_{i,k,p}$: *flow of commodity p from terminal node i to customer zone node k*

$x^{\delta^+}_{i,k,p}$: *flow of commodity p from customer zone node k to terminal node i*

$x^{\lambda}_{i,j,m,p}$: *flow of commodity p on train of mode m running on train canal arc (i, j)*

$$y^{\lambda}_{i,j,m} = \begin{cases} 1, \text{if a train of mode } m \text{ uses train arc } (i,j) \\ 0, \text{else} \end{cases}$$

Appendix B – Mathematical model

$$\min\ z = \sum_{(i,j)\in\mathcal{L}_m}\sum_{m\in\mathcal{M}} f^{\lambda}_{i,j,m} y^{\lambda}_{i,j,m} + \sum_{(i,j)\in\mathcal{L}_m}\sum_{m\in\mathcal{M}}\sum_{p\in\mathcal{P}} c^{\lambda}_{i,j} x^{\lambda}_{i,j,p,m} +$$

$$\sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c^{\omega}_i x^{\omega}_{i,p} + \sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c^{\mu}_i x^{\mu}_{i,p} + \sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s}\sum_{p\in\mathcal{P}} c^{\nu}_i x^{\nu}_{i,p} + \qquad (1)\ \textit{obejctive function}$$

$$\sum_{(k,i)\in\mathcal{D}^+}\sum_{p\in\mathcal{P}} c^{\delta+}_{k,i} x^{\delta+}_{k,i,p} + \sum_{(i,k)\in\mathcal{D}^-}\sum_{p\in\mathcal{P}} c^{\delta-}_{i,k} x^{\delta-}_{i,k,p} + \sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}_z}\sum_{p\in\mathcal{P}} c^{\psi}_k x^{\psi}_{k,p}$$

$$x^{\psi}_{n^-_z(k),p} + a_{k,p} = x^{\psi}_{k,p} + \sum_{i\in\bigcup_{s\in S}\mathcal{N}^+_s(k)} x^{\delta+}_{k,i,p} \qquad \forall k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}_z, \forall p\in\mathcal{P} \qquad (2)\ \textit{departing from customer zone node flow balance constraints}$$

$$\sum_{i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^-_s(z)}\sum_{k\in\mathcal{N}_z} x^{\delta-}_{i,k,p} = a_{z,p} \qquad \forall z\in\mathcal{Z}, \forall p\in\mathcal{P} \qquad (3)\ \textit{arriving to customer zone flow balance constraints}$$

$$\sum_{m\in\mathcal{M}}\sum_{h\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^+_{s,m}(i)} x^{\lambda}_{h,i,p,m} + \sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^+_z(i)} x^{\delta+}_{k,i,p} + x^{\mu}_{i,p} =$$

$$\sum_{l\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^-_z(i)} x^{\delta-}_{i,l,p} + x^{\nu}_{i,p} + \sum_{m\in\mathcal{M}}\sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^-_{s,m}(i)} x^{\lambda}_{i,j,p,m} \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall p\in\mathcal{P} \qquad (4)\ \textit{terminal node flow balance constraints}$$

$$x^{\omega}_{n^+_s(i),i,p} + x^{\mu}_{i,p} = x^{\omega}_{i,p} + x^{\nu}_{i,p} \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall p\in\mathcal{P} \qquad (5)\ \textit{inventory flow balance constraints}$$

$$x^{\nu}_{i,p} + \sum_{m\in\mathcal{M}}\sum_{p\in\mathcal{P}}\sum_{j\in\bigcup_{s\in S}\mathcal{N}^-_{s,m}(i)} x^{\lambda}_{i,j,p,m} + \sum_{p\in\mathcal{P}}\sum_{k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}^-_z(i)} x^{\delta}_{i,k,p} \le u_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (6)\ \textit{terminal handling capacity constraints}$$

$$\sum_{p\in\mathcal{P}} x^{\omega}_{ip} \le w_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (7)\ \textit{inventory capacity constraints}$$

$$\sum_{m\in\mathcal{M}}\sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^-_{s,m}(i)} y^{\lambda}_{i,j,m} \le v_i \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s \qquad (8)\ \textit{train number capacity constraints}$$

$$\sum_{h\in\mathcal{N}^+_{s,m}(i)} y^{\lambda}_{h,i,m} = \sum_{j\in\bigcup_{s\in\mathcal{S}}\mathcal{N}^-_{s,m}(i)} y^{\lambda}_{i,j,m} \qquad \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, \forall m\in\mathcal{M} \qquad (9)\ \textit{train flow balance constraints}$$

$$\sum_{p\in\mathcal{P}} x^{\lambda}_{i,j,p,m} \le q_m y^{\lambda}_{i,j,m} \qquad \forall (i,j)\in\bigcup_{m\in\mathcal{M}}\mathcal{L}_m \qquad (10)\ \textit{train capacity constraints}$$

$$y^{\lambda}_{i,j,m}\in\{0,1\} \qquad \forall (i,j)\in\bigcup_{m\in\mathcal{M}}\mathcal{L}_m, \forall m\in\mathcal{M} \qquad (11)\ \textit{binary constraints}$$

$$\left.\begin{array}{l} x^{\psi}_{i,p} \\ x^{\mu}_{i,p} \\ x^{\nu}_{i,p} \\ x^{\omega}_{i,p} \\ x^{\delta^-}_{i,k,p} \\ x^{\delta^+}_{i,k,p} \\ x^{\lambda}_{i,j,m,p} \end{array}\right\} \ge 0 \qquad \begin{array}{l} \forall (i,j)\in\bigcup_{m\in\mathcal{M}}\mathcal{L}_m, \forall m\in\mathcal{M}, \\ \forall i\in\bigcup_{s\in\mathcal{S}}\mathcal{N}_s, k\in\bigcup_{z\in\mathcal{Z}}\mathcal{N}_z, \\ \forall p\in\mathcal{P} \end{array} \qquad (12)\ \textit{non-negativity contraints}$$

Network Design with Design balance Constraints

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Abstract

In this paper we present an extension of the fixed-charge capacitated multi-commodity network design model (CMND). The extension consists of adding a new set of constraints denoted design balance constraints resulting in the design balanced capacitated multi-commodity network design model (DBCMND). The constraints require that the number of selected design arcs entering a node must be equal the number of selected design arcs leaving a node. The motivation of the extension comes from scheduling services in a transportation network. The design balance constraints can be interpreted as a conservation of flow for vehicles entering and leaving a terminal or stop. The paper presents a Tabu search heuristic framework for solving the arc-based formulation of the DBCMND. The performance of the algorithm is measured against the performance of the MIP-solver of the Xpress-MP optimization suite.

1. Introduction

Network design models represent generic models for a wide range of applications in planning transportation, logistics, telecommunication, and production systems. In these applications, multiple commodities (goods, data, people, etc.) must be routed between different points of origin and destination over a network of nodes and arcs with possibly limited capacity. Moreover, other than the routing cost proportional to the number of units of each commodity transported over a network link, a fixed cost must be paid the first time the link is used, representing its construction (opening) or improvement costs. The general network design problem consists of finding a minimum cost design i.e. a choice of arcs in the network to enable the flow of commodities such that it minimizes the sum of the fixed cost of including the arcs and the variable cost of routing the commodities on them. Presentations of different network design models and their applications can be found in [Minoux 1986], [Magnanti et al. 1984], [Ahuja et al. 1995], and [Balakrishnan et al. 1997].

Service network design is an extension where issues such as freight consolidation, service type choice, service frequency, delivery times, terminal congestion, and empty vehicle repositioning are considered. The planning scope is generally on a tactical level, as opposed to the strategic scope of network design models. The service network design problem for freight transportation is described in [Crainic 2000] and applications can be found in [Barnhart et al. 1995], [Cheung et al. 2000], and [Powell et al. 1989] for road transportation, [Joborn et al. 2004], [Marin et al. 1996], [Newman et al. 2000], and [Cordeau et al. 1998] for train transportation, [Kuby et al. 1993] for air transportation, and [Armacost et al. 2002], [Kim et al. 1999], [Nozick et al. 1997], and [Jansen et al. 2004] for various intermodal transportation problems. Although some effort has been put into vehicle balancing and repositioning ([Dejax et al. 1987] presents a survey on the issue) it is generally implicitly assumed in service network models that equipment is available when needed and that the vehicle positioning and empty repositioning problems are done at an operational planning level. However, with carriers operating with minimal fleet sizes, the problems can significantly impact the services offered. An example is the rotations that intercontinental ships perform. Each leg between calling ports can be considered as services. The individual legs are interconnected by the fact that they can not be offered unless the preceding leg on the rotation is offered. The resulting service network is a series of services following each others to perform a rotation enabling the same cyclic service pattern over a period of time. The same aspect of connected services can be seen in public transportation, airline routes, and train routes. An example of the later is the intermodal shuttle trains operated in Europe rotating to and from two or more terminals. In [Barnhart et al. 1998] and [Clarke et al. 1997] the aircraft rotation problem is presented which considers the same notion of vehicles operating in rotations but for a fixed service network. Little effort has been dedicated to designing service networks with the cyclic rotation aspect.

The contribution of this paper is twofold. First the paper presents a variant of the capacitated multi-commodity network design model, denoted CMND. A set of design balance constraints are added resulting in what we denote the design balanced capacitated multi-commodity network design model (DBCMND). The design balance constraints represent the aspect of vehicle rotations with services following each others. Second the paper proposes a tabu search heuristic framework to solve the DBCMND. The algorithm is applied on selected network design instances presented in [Crainic et al. 2000] and computational results comparing it to Xpress-MP's MIP-solver are presented.

The paper is divided as such. Section 2 gives a description of the DBCMND problem and section 3 continues by presenting the mathematical formulations of the CMND and the DBCMND formulations. Section 4 presents a Tabu search framework for solving the new formulation and specifies the algorithmic design chosen in this paper to solve the model. Section 5 presents the results obtained on network design test problems. Finally section 6 presents some general conclusions and discusses future avenues of research.

2. Problem description

In traditional network design nodes can represent a geographic location of a terminal and arcs can represent possible connections between terminals. These connections can either represent physical infrastructure such as highways or rail lines, or conceptual connections such as sailing routes or air-ways. In the CMND a set of arcs representing possible connections are each associated with a capacity limit and a binary variable modelling the choice of opening or not opening the connection. A set of commodities, each associated with an origin node, a destination node, and an amount, represent the demand that needs to be routed on the opened connections. The objective is to find a design and a routing plan that minimizes the fixed cost of opening connections and the variable costs of routing commodities on the open connections.

The traditional CMND interpretation has no time dimension associated to the connections and commodities, and can therefore not address designing service schedules. By adopting a time-space representation it is possible to address the time dimension of scheduled services. Figure 1 shows a time-space representation of a network.

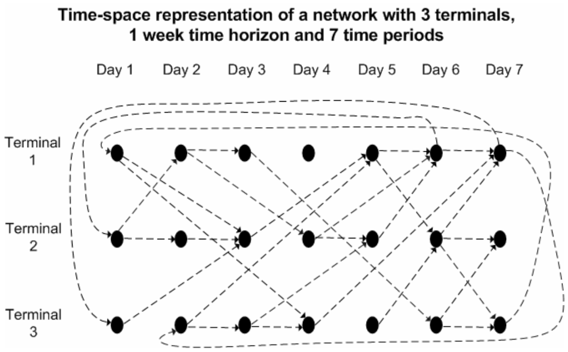

Figure 1.

In figure 1 there are three terminals, each represented by seven nodes, where each node has a time period equivalent to a day associated to it. By associating a time period to each node the arcs can be interpreted as possible scheduled service connections between terminals. For example there is a possible service from terminal 3 on day 1 (T3, TP1) that arrives at terminal 2 on day 3 (T2, TP4). The arcs going from a later time period to an earlier period represent services starting at the end of one planning time period (here one week) onto the next (the following week). The network thus represents possible services to include in a repetitive schedule for a one week time period. Considering the time period interpretation of nodes, all vehicles that arrive at a node must also leave it again at the end of its time period. A vehicle can either leave the terminal again to perform another service or stay at the terminal onto the following time period. The later is represented in figure 1 by the horizontal holding arcs. Vehicles using these arcs do not perform services. The choice of a vehicle to perform a service is from a modelling perspective similar to the choice of letting the vehicle stay at the terminal. We therefore do not distinguish between holding arcs and service arcs but just consider them as temporal connections between two terminal nodes.

The choice of performing a service is represented by the binary variables associated to each arc is now interpreted as offering a service or not, rather than opening a physical connection or not. Associating origin nodes and destination nodes to commodities is equivalent to associating a time of availability and a time of delivery. Thus the network elements are the same as for the CMND formulation, only their interpretations differ. It is therefore possible to apply the CMND-model to the scheduled service network design problem. The rotation aspect however, is not considered by the CMND-formulation. The formulation implicitly assumes that arc choices are independent of one another. Since choosing to run a service is equivalent to assigning a vehicle (train, ship bus etc.) we need to make sure that the same number of vehicles arriving at a terminal within a time period also leave the time period again. In the network representation the vehicle conservation requirement can be interpreted as the number of selected arcs (service or holding) arriving at a node must be equal to the number of selected arcs departing from it. Otherwise the balance of vehicles is disturbed. By adding a set of constraints ensuring the balance of selection of arcs in and out of nodes to the CMND-formulation we get what we denote the design balanced multi-commodity capacitated network design problem (DBCMND).

3. The Network Design model with Design Balance Constraints

We start by presenting the arc-based mathematical formulation of the CMND model. Let $\mathcal{G} = (\mathcal{N}, \mathcal{A})$ be a network with set of nodes $\mathcal{N}$ and set of directed arcs $\mathcal{A}$. Without loss of generality, we assume that all $(i, j) \in \mathcal{A}$ are design arcs. Let $\mathcal{P}$ denote the set of commodities to move using this network, where each commodity p has a single origin *o(p)*, a single destination *s(p)*, and a flow requirement of w_p units between its origin and destination nodes. The arc-based formulation of the CMND can then be written as follows:

$$\min\ z(X,Y)=\sum_{(i,j)\in\mathcal{A}} f_{ij}y_{ij}+\sum_{p\in\mathcal{P}}\sum_{(i,j)\in\mathcal{A}} c_{ij}^p x_{ij}^p \qquad (1)$$

$$\sum_{j\in\mathcal{N}^+(i)} x_{ij}^p-\sum_{j\in\mathcal{N}^-(i)} x_{ji}^p=d_i^p,\quad \forall i\in\mathcal{N},\forall p\in\mathcal{P} \qquad (2)$$

$$\sum_{p\in\mathcal{P}} x_{ij}^p\le u_{ij}y_{ij},\quad \forall (i,j)\in\mathcal{A} \qquad (3)$$

$$x_{ij}^p\ge 0,\quad \forall (i,j)\in\mathcal{A},\quad \forall p\in\mathcal{P} \qquad (4)$$

$$y_{ij}\in\{0,1\},\quad \forall (i,j)\in\mathcal{A} \qquad (5)$$

where X and Y represent the vectors of flow and design variables respectively, $y_{ij},(i,j)\in\mathcal{A}$ represent the design variables that equal 1 if arc (*i,j*) is selected (and 0 otherwise), x_{ij}^p stands for the flow distribution decision variable indicating the amount of flow of commodity $p\in\mathcal{P}$ on arc (*i,j*), and

$\mathcal{N}^+(i):\{j\in\mathcal{N}^+\mid(i,j)\in\mathcal{A}\}$,

outward neighbours of node *i*,

$\mathcal{N}^-(i):\{j\in\mathcal{N}^-\mid(j,i)\in\mathcal{A}\}$,

inward neighbours of node *i*,

u_{ij} : capacity of arc (*i,j*)

f_{ij} : fixed cost applied on arc (*i,j*),

c_{ij}^p : cost of one unit flow of commodity p on arc (*i,j*),

and

$$d_i^p=\begin{cases} w^p & if\ i=o(p)\\ -w^p & if\ i=s(p)\\ 0 & otherwise\end{cases}$$

The objective function (1) accounts for the total system cost, the fixed cost of arcs included in a given design plus the cost of routing the commodity demand, and aims to select the minimum cost design. Constraints (2) represent the network flow conservation relations for commodities, while constraints (3) state that for each arc, the total flow of all commodities cannot exceed its capacity if the arc is opened (y_{ij} = 1) and must be 0 if the arc is closed (y_{ij} = 0). Relations (4) and (5) are the usual non-negativity and integrality constraints for decision variables.

By adding the balance constraints discussed in section 2 and using the same definitions from above, the arc formulation for the DBCMND model, a-DBCMND, can be written as

$$\min\ z(X,Y)=\sum_{(i,j)\in\mathcal{A}} f_{ij}y_{ij}+\sum_{p\in\mathcal{P}}\sum_{(i,j)\in\mathcal{A}} c_{ij}^p x_{ij}^p \qquad (6)$$

$$\sum_{j\in\mathcal{N}^+(i)} x_{ij}^p-\sum_{j\in\mathcal{N}^-(i)} x_{ji}^p=d_i^p\quad \forall i\in\mathcal{N},\forall p\in\mathcal{P} \qquad (7)$$

$$\sum_{j\in\mathcal{N}^-(i)} y_{ji}-\sum_{j\in\mathcal{N}^+(i)} y_{ij}=0\quad \forall i\in\mathcal{N} \qquad (8)$$

$$\sum_{p\in\mathcal{P}} x_{ij}^p\le u_{ij}y_{ij}\quad \forall (i,j)\in\mathcal{A} \qquad (9)$$

$$x_{ij}^p\ge 0\quad \forall (i,j)\in\mathcal{A},\forall p\in\mathcal{P} \qquad (10)$$

$$y_{ij}\in\{0,1\}\quad \forall (i,j)\in\mathcal{A} \qquad (11)$$

where the set of design balance constraints (8) have been added to the original CMND model. The constraints state that the total number of open design arcs going into node i (y_{ji} = 1) must be equal to the number of open design arcs going out of node i (y_{ij} = 1), thus the name design balance constraints.

Notice that for a given design vector (feasible or infeasible), $\overline{Y}:\overline{y}_{ij}=1$, the a-DBCMND formulation becomes a capacitated multi commodity minimum cost flow problem (CMCF) just as for the CMND model:

$$\min\ z(x(\overline{Y}))=\sum_{p\in\mathcal{P}}\sum_{(i,j)\in\mathcal{A}}c_{ij}^{p}x_{ij}^{p} \tag{12}$$

$$\sum_{j\in\mathcal{N}^{+}(i)}x_{ij}^{p}-\sum_{j\in\mathcal{N}^{-}(i)}x_{ji}^{p}=d_{i}^{p}\quad\forall i\in\mathcal{N},\forall p\in\mathcal{P} \tag{13}$$

$$\sum_{p\in\mathcal{P}}x_{ij}^{p}\le u_{ij}\overline{y}_{ij}\quad\forall(i,j)\in\mathcal{A}(\overline{Y}) \tag{14}$$

$$x_{ij}^{p}\ge 0\quad\forall(i,j)\in\mathcal{A}(\overline{Y}),\forall p\in\mathcal{P} \tag{15}$$

where $\mathcal{A}(\overline{Y})$ stands for the set of arcs corresponding to the design $\overline{Y}$.

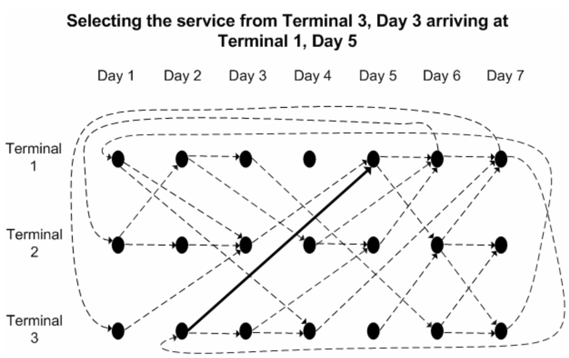

Figure 2.

The design balance constraints creates interdependency between the arc choices. This interdependency can be illustrated by the following consideration. In figure 2 a random arc in the network from figure 1 is chosen to be open. The two nodes the selected service connects (terminal 3, day 2 and terminal 1, day 5) are now out of balance. The balance can be restored if e.g. additional services as shown in figure 3 are chosen.

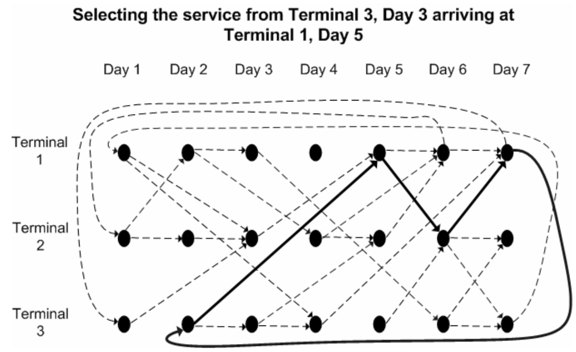

Figure 3.

The design in figure 3 is feasible with respect to the design balance constraints (8). Notice how the four selected arcs form a cycle. By reformulating the decision variables to represent cycles instead of arcs we obtain a cycle-based formulation of the DBCMND model, the c-DBCMND:

$$\min\ z(X,Y)=\sum_{(i,j)\in\mathcal{A}}\sum_{k\in\mathcal{K}}f_{ij}a_{ij}^{k}\eta^{k}+\sum_{p\in\mathcal{P}}\sum_{(i,j)\in\mathcal{A}}c_{ij}^{p}x_{ij}^{p} \tag{16}$$

$$\sum_{j\in\mathcal{N}^{+}(i)}x_{ij}^{p}-\sum_{j\in\mathcal{N}^{-}(i)}x_{ji}^{p}=d_{i}^{p}\quad\forall i\in\mathcal{N},\forall p\in\mathcal{P} \tag{17}$$

$$\sum_{p\in\mathcal{P}}x_{ij}^{p}\le u_{ij}a_{ij}^{k}\eta^{k}\quad\forall(i,j)\in\mathcal{A},k\in\mathcal{K} \tag{18}$$

$$\sum_{k\in\mathcal{K}}\eta^{k}a_{ij}^{k}\le 1\quad\forall(i,j)\in\mathcal{A} \tag{19}$$

$$x_{ij}^{p}\ge 0\quad\forall(i,j)\in\mathcal{A},\forall p\in\mathcal{P} \tag{20}$$

$$\eta^{k}\in\{0,1\}\quad\forall k\in\mathcal{K} \tag{21}$$

where η_{k}, $k\in\mathcal{K}$, represent the design variables that equal 1 if cycle *k* is included in the solution (and 0 otherwise), and a_{ij}^{k} is a parameter that is one if arc *(i,j)* is in cycle *k*. The remaining definitions for the c-DBCMND model are the same as for the CMND and a-DBCMND formulations. The binding capacity constraints (9) have been replaced by (18) that are a set of constraints binding the new cycle-based design decision variables to the arc-based flow variables. The design balance constraints (8) are captured partly by the new cycle-based decision variables and partly by

Initialize:
Solve the relaxed DBCMND model and round design variables up to obtain (infeasible) starting solution n
Local Search Phase 1 (Exploration phase):
Establish candidate list $\mathcal{C}_1^n$ *for incumbent solution n of arcs to add or drop from the design vector* Y_n
Evaluate solution value estimate $\tilde{V}_{n+1}$ *for each neighbour solution n+1 obtained from candidate list* $\mathcal{C}_1^n$
Pick neighbour solution n+1 with the smallest $\tilde{V}_{n+1}$ *to implement and solve the CMCF problem to get* V_{n+1}
Set neighbour solution n+1 to be new incumbent solution n
Update tabu list $\mathfrak{T}$
If progress in overall best solution value is less than l_g*% over the last* l_r *iterations switch to Local Search Phase 2*
Local Search Phase 2 (feasibility phase):
Establish candidate list $\mathcal{C}_2^n$ *for incumbent solution n of paths to add or drop from the design vector* Y_n
Evaluate solution value V_{n+1} *for each neighbour solution n+1 from candidate list* $\mathcal{C}_2^n$ *by solving the CMCF problem*
Pick neighbour solution n+1 with the smallest V_{n+1} *to implement*
Repeat Phase 2 until a feasible solution is found or search procedure fails and return to phase 1

Figure 4. Overall algorithmic structure

(19), which is a set-packing constraint that states that an arc may only be included in one open cycle.

The advantage of the c-DBCMND compared to the a-DBCMND formulation is that the node balance constraints are not addressed explicitly in the modelling constraints but are taken care of implicitly in the variable definition and constraints (15). The disadvantage of the c-DBCMND formulation is that the size of the set of cycles $\mathcal{K}$ is enormous and therefore the model size becomes enormous too, $|X|\cdot|\mathcal{K}|>>|X|\cdot|Y|$. It is computationally infeasible to enumerate all design variables and binding constraints for large scale instances. We will not address the c-DBCMND in this paper, but have introduced it for a more complete description of the model, and the insight the cycle-variables give of feasible solution structures.

As previously shown in [Magnanti et al. 1986] un-capacitated fixed-charge network design models are difficult to solve as they belong to the class of $\mathcal{NP}$-hard problems. The capacitated CMND model is even harder [Balakrishnan et al. 1997] due to, among other factors, the competition of commodities for the network capacity and the difficulty of representing trade-offs between arcs' fixed costs and capacities. Adding the node balance constraints adds further complexity to the problem because of the design interdependency of arc choices. We therefore assume that the DBCMND model belongs to the class of $\mathcal{NP}$-hard problems too. Thus, as for the CMND model, exact methods will not be able to solve realistically dimensioned cases; only specially tailored heuristics may prove to be of any help. The following section will present a Tabu search heuristic framework to solve the a-DBCMND formulation.

4. Tabu Search heuristic

Tabu Search (TS) belongs to the family of heuristic search known as *metaheuristics*. It was introduced by [Glover 1986] and has been widely used since (for a survey see [Glover et al. 1997]). It starts from an initial solution (generally feasible) and iteratively moves to a new (feasible) solution by selecting it from a *solution neighbourhood* of the current *incumbent* solution. The neighbourhood of an incumbent solution is a set of other solutions that can be obtained from the incumbent solution with one or a few simple changes. The transition from the incumbent solution to a neighbour solution is called a *neighbourhood move*. The best solution of the neighbourhood is selected as the new incumbent solution. The search may be divided into different *phases* each with their own distinctive neighbourhoods.

The size of a neighbourhood may be very large. It can therefore be computationally demanding to make an exhaustive search of the neighbourhood. To decrease the computational requirements for determining a neighbour move a *candidate list* of potential neighbours to be examined is determined. The candidate list contains a sub-space of potential neighbour solutions that by one or several criteria are deemed worth investigating.

To avoid the occurrence of cycling between solutions resulting from the movement back to the local optimum a *tabu list* is introduced. A tabu list is a short-term memory mechanism, which stores *attributes* identifying the moves that produced recent solutions. During examination of an incumbent solution's neighbourhood all the moves that have attributes equal to those stored in the tabu list are discarded. This prevents the search from cycling between two or more solutions.

The time required by each search iteration depends on the size of the neighbourhood that needs to be examined, of the time needed to generate each neighbour solution, and the time needed to evaluate each *neighbour solution value*. TS can be stopped after a number of iterations without notable improvements or after a predefined elapse of time.

As discussed in section 3 the node design balance constraints create interdependency between the design variables. As illustrated with the c-DBCMND formulation the design balance constraints are satisfied if cycles of arcs are considered rather than individual arcs. Thus by adding or dropping cycles of arc to the design it would be possible to move between feasible neighbour solutions. The problem with this is that the impact on the flow is not trivially determined by making what may be large-scale changes on the design vector.

The TS framework we present here is composed of two local search phases. The first phase is what could be called an exploration search phase with the intension to search the solution space by making relatively simple neighbourhood moves between possibly infeasible solutions based on an add/drop procedure. To control infeasibility a penalty value is added to each solution to estimate how far from feasibility it is. The purpose of the penalty value is to have a trade off between low cost and infeasibility. The second phase is what could be called a feasibility phase. The neighbourhood moves in the second phase are based on paths of design arcs and is intended to find feasible solutions. Both phases only search a subspace of the neighbourhood of an incumbent solution by establishing a candidate list of potential moves.

The algorithm terminates after a predefined amount of time. The overall lay-out of the algorithm can be seen in figure 4.

4.1. Initialization and starting solution and stopping criterion

In order to start the algorithm an initial neighbour solution is necessary. Since the search is performed by moving between infeasible neighbour solutions, the initial solution need not be feasible. By relaxing the binary constraints of the a-DBCMND formulation we get the r-DBCMND problem:

$$\min\ z(X,Y^0) = \sum_{(i,j)\in\mathcal{A}} f_{ij} y_{ij}^0 + \sum_{p\in\mathcal{P}} \sum_{(i,j)\in\mathcal{A}} c_{ij}^p x_{ij}^p \quad (6)$$

$$\sum_{j\in\mathcal{N}^+(i)} x_{ij}^p - \sum_{j\in\mathcal{N}^-(i)} x_{ji}^p = d_i^p, \quad \forall i\in\mathcal{N}, \forall p\in\mathcal{P} \quad (7)$$

$$\sum_{j\in\mathcal{N}^-(i)} y_{ji}^0 - \sum_{j\in\mathcal{N}^+(i)} y_{ij}^0 = 0, \quad \forall i\in\mathcal{N} \quad (8)$$

$$\sum_{p\in\mathcal{P}} x_{ij}^p \le u_{ij} y_{ij}, \quad \forall (i,j)\in\mathcal{A} \quad (9)$$

$$x_{ij}^p \ge 0, \quad \forall (i,j)\in\mathcal{A}, \forall p\in\mathcal{P} \quad (10)$$

$$y_{ij}^0 \in [0,1], \quad \forall (i,j)\in\mathcal{A} \quad (11bis)$$

Solving the r-DBCMND will result in a solution with fractional values on the design variables. By rounding op the design variables with fractional values $y_{ij} = 1 \mid y_{ij}^0 > 0\ \forall (i,j)\in\mathcal{A}$ we get an presumably infeasible starting solution that is used as a starting solution for the neighbourhood search.

The algorithm is stopped after a given amount of elapsed time, $\tau_{\max}$.

4.2. Neighbourhood structure of phase 1

An intuitive scheme to adopt as a move between neighbour solutions is the add/drop procedure. Neighbour solutions are obtained by either adding or dropping an arc from the design vector. This approach was adopted in [Powell 1986], [Koskosidis et al. 1992] and [Crainic et al. 1993]. The add/drop procedure has proven to be only little effective in solving these problems. This is due to the fact that a single arc is only one of many in a path from an origin to a destination of a commodity and its impact is generally limited. One may often reroute traffic and obtain an almost equivalent solution. Or, as for arc *(a,b)* in Figure 6, it may not even be connected to the other currently open arcs. Introducing such an arc into the network has no influence whatsoever or very little on the flow of the current solution but adds the fixed cost of it to the total system cost. Alternatively, removing an arc may result in an infeasible solution, because connectivity is removed. If e.g. ac *(d,c)* is removed from the solution in the network in figure 5 the commodities with destination node *c* cannot attain their destination, thus rendering the solution infeasible.

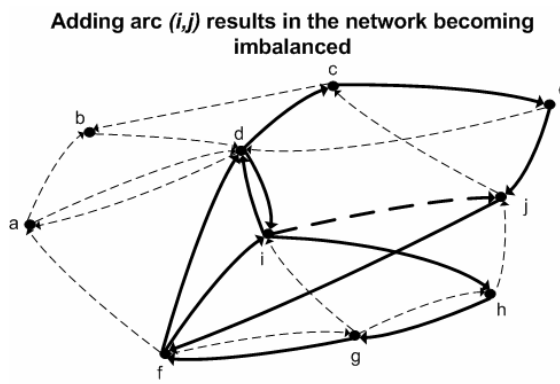

Figure 5.

For the DBCMND model however, adding or dropping an arc has more impact on the solution. E.g. simply adding or dropping one arc from a design feasible solution for the DBCMND problem will in every case result in an infeasible solution with respect to the design balance constraints. If arc *(i,j)* is added to the design vector for the network in figure 5 the design balance in nodes *i* and *j* become imbalanced, i.e. the number of arcs entering and leaving the node are not equal. However, if instead arc *(i,j)* in figure 5 is already part of the incumbent design, dropping it will achieve feasibility. Because of the interconnection between the decision variables we believe the add/drop procedure provides an interesting possibility for a move in the TS search framework for the a-DBCMND formulation. We thus adopt the add/drop procedure as a template for a neighbour move in phase 1. We will limit the number of add/drop moves to one per iteration. Thus the total number of potential neighbour solution we can examine is the size of the set of arcs, $|\mathcal{A}|$, as each arcs can be closed if open, and opened if closed.

To determine when to stop phase 1 and proceed to phase 2 two empirical parameters, the *improvement range, l_i,* and the *improvement gap, l_g* are introduced. The improvement range is the number of iterations over which the improvement on the best total solution value is registered. The improvement gap is the percentage by which the best total solution value will be required to improve over the improvement range in order to qualify as a significant improvement. Thus if the best solution value has not improved with l_g% over the last l_i iterations the algorithm switches to phase 2.

4.3. Controlling infeasibility in phase 1 by using a penalty value

To enable the algorithm to search for feasible neighbour solutions, or neighbours close to feasible solutions, it is necessary to implement a scheme to monitor the infeasibility. To guide the search, a *penalty value, P_n,* for solution n is introduced. The penalty value is a pseudo cost that represents an estimate of what it takes to make an infeasible solution feasible. The penalty value is added to the total system cost, Z_n, giving a *solution value, V_n,* for neighbour solution n:

$$V_n = Z_n + P_n$$

The solution value is the measure by which neighbour solutions are compared. A solution with a relatively high total system cost that is close to being feasible may be better than one with a lower total system cost that is further from being feasible.

The penalty value adopted in this implantation to measure the infeasibility of a given solution uses two parameters, the *total system imbalance* and the *maximum absolute imbalance*. Both parameters are calculated from the *node imbalances* in the network. The node imbalance of node i for solution n, ψ_n^i, is calculated as the difference between the number of open outgoing arcs and open ingoing arcs in node i.

$$\psi_n^i = \sum_j y_{ji} - \sum_j y_{ij}$$

Hence the node imbalance is negative if there are more outgoing arcs than ingoing arcs and vice versa. Figure 6 shows two nodes, one with negative imbalance, and one with positive imbalance.

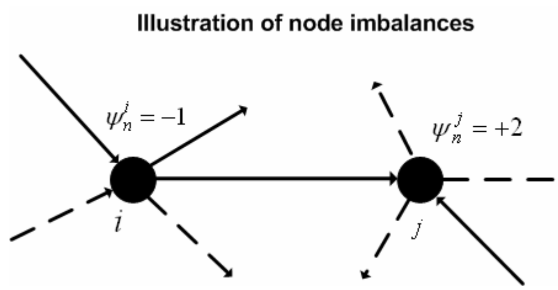

Figure 6

The total system imbalance for solution n, ψ_n^{N}, is calculated as the sum over all absolute node imbalances, whilst the maximum absolute imbalance for solution n, $\psi_n^{\max}$, is the largest absolute value of all node imbalances:

$$\psi_n^{\mathfrak{N}} = \sum_i \left|\psi_n^i\right|$$

$$\psi_n^{\max} = \max\left(\left|\psi_n^i\right|\right)$$

The total node imbalance gives an indication of the infeasibility of the total system by representing the total number of imbalances that need to be fixed. The maximum node imbalance gives an indication of the difficulty of achieving feasibility in a single node.

Using the analogy of scheduled train networks a node imbalance can be compared to adding $|\psi_n^i|$ empty trains in or out of node *i* in order to eliminate the imbalance. Thus it is reasonable to scale the imbalances with a value that represents the cost of adding an empty arc. The cost $\tilde{f}$ is calculated as the product of the average of the network arcs' fixed cost, $\bar{f}$, and an empirical scaling parameter, ψ^p. The empirical parameter is used to externally control the importance of the penalty value in the solution value of a neighbour solution.

By multiplying the cost with the total system imbalance and the maximum node imbalance an estimated value for making a solution feasible eliminating all imbalances is obtained. The penalty value is thus computed as:

$$P = \tilde{f} \cdot \psi^{\mathfrak{N}} \cdot \psi^{\max}, \quad \tilde{f} = \bar{f} \cdot \psi^p$$

It the current implementation the scaling parameter ψ^p is a fixed value that does not change during the progress of the algorithm. A dynamic scheme could be adopted to set the value of the parameter according to the infeasibility of the solutions found in the search. This however is left to future research.

4.4. Neighbourhood move and total system cost evaluation for phase 1

Changing the design by adding or dropping an arc results in a new design vector Y_{n+1} which eventually may lead to a new flow vector X_{n+1}.

Recall that given a design vector the flow vector can be computed by solving the capacitated minimum cost flow problem (CMCF). However, even if the CMCF problem is a LP problem, solving an instance for each potential neighbour solution is not computationally feasible. Recall also that closing an arc may lead to losing connectivity and an infeasible solution to the CMCF problem.

To permit fast evaluation and guarantee feasible flow solutions when changing the design we propose a hybrid of the simple add/drop procedure and a procedure resembling the cycle-based neighbourhoods proposed by [Ghamlouche et al. 2003]. Cycle-based neighbourhood moves redirect flow around cycles by closing and opening design arcs accordingly. The idea behind the move comes from the acknowledgement that commodities move on paths and thus require that several arcs open and close simultaneously. The following two sub-sections describe the neighbour solution evaluation when closing and opening an arc respectively.

4.4.1. Neighbour move and total system cost estimate when closing an arc

Closing arc *(i,j)* means changing the design vector for an incumbent solution, Y_{n-1}. The incumbent solution's flow vector, X_{n-1}, is no longer feasible, if arc *(i,j)* has positive flow, because the commodities traversing arc *(i,j)*, $\mathcal{P}_{ij}$:$\{p \in \mathcal{P} \mid x_{ij}^p > 0\}$, no longer have feasible flow paths. Figure 7 shows a network with flow of two commodities. If arc *(i,j)* is closed, the dark grey commodity no longer has a feasible flow path.

In order to maintain flow feasibility its flow of commodities must be redirected onto other arcs. The commodities may be redirected on open arcs using the arcs residual capacity, $r_{ij} = u_{ij} - \sum_{p \in \mathcal{P}} x_{ij}^p$. To enable the restoration of broken connectivity, the redirection is also permitted on closed arc that in turn are opened.

In the local search phase in [Ghamlouche et al. 2003] the flow of commodities $\mathcal{P}_{ij}$ on arc *(i,j)* is aggregated and redirected as an entity. As shown that may result in a design with an infeasible flow solution. In this paper we redirect commodities individually in local search phase 1 to guarantee flow-feasibility. A further advantage of redirecting commodities individually, rather than aggregating them, is enabling a more efficient use of residual capacity on open arcs as the flow entities are smaller for individual commodities.

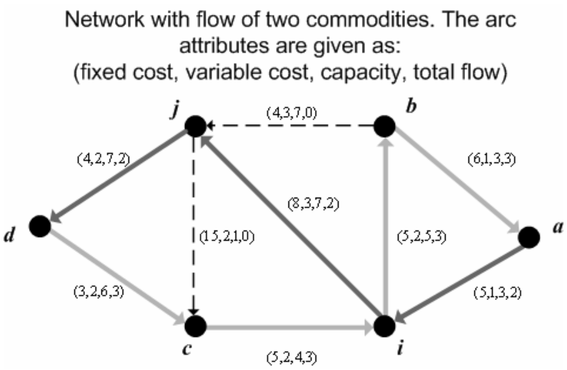

Figure 7

The idea behind the redirection method is to construct a Γ^p-residual graph, $\mathcal{G}_p^\Gamma = (\mathcal{N}, \mathcal{A}_p^\Gamma)$, Γ^p being is the total amount of commodity p, for all commodities $\mathcal{P}_{ij}$ on arc *(i,j)*. All arcs, except arc *(i,j)*, are included in the residual graph if their capacity u_{kl} is larger than Γ^p if they are closed or if their residual capacity is larger than Γ^p if they are open:

$$\mathcal{A}^{\Gamma,closed} = \{(k,l) \in \mathcal{A} \,|\, y_{kl} = 0 \wedge u_{kl} \geq \Gamma^p\}$$

$$\mathcal{A}^{\Gamma,open} = \{(k,l) \in \mathcal{A} \,|\, y_{kl} = 1 \wedge u_{kl} - \sum_{p \notin \mathcal{P}_{ij}} x_{kl}^p \geq \Gamma^p\}$$

The union of the two sets makes up the arcs in the residual graph, $\mathcal{A}_p^\Gamma = \mathcal{A}_p^{\Gamma,open} \cap \mathcal{A}_p^{\Gamma,closed}$ for commodity p. Notice that the residual capacity on an arc is calculated without flows of the commodities in $\mathcal{P}_{ij}$. This means that the commodities in $\mathcal{P}_{ij}$ are removed entirely from the network, and new path must be found from their origin nodes to their destination nodes. To limit computational complexity only one path is determined for a commodity by solving the shortest path on its residual graph. The residual graph arc costs are:

$$c_{kl}^\Gamma = \begin{cases} f_{kl} + c_{kl} \cdot \Gamma^p & if\ (k,l) \in \mathcal{A}^{\Gamma,closed} \\ c_{kl} \cdot \Gamma^p & if\ (k,l) \in \mathcal{A}^{\Gamma,open} \end{cases}$$

The cost of using a closed arc represents the cost of opening the arc and routing the entire commodity amount on it. The cost of using an open arc is the cost of routing the entire commodity amount on it. Solving the shortest path for a commodity $p \in \mathcal{P}_{ij}$ results in path with the set of arcs, $\mathcal{A}_p^\Gamma(\pi)$, and has the cost:

$$\Delta Z_p^\Gamma = \sum_{(i,j) \in \mathcal{A}_p^\Gamma(\pi)} c_{ij}^\Gamma$$

Figure 8 shows the residual graph for the dark grey commodity from figure 7. Note e.g. that arc (j,c) is not included in the residual graph, as its capacity (=1) is less than the required redirection flow (=2). Similarly arc *(b,a)* is not included because its residual capacity is zero. The shortest path in the residual network is *(a,i)*, *(i,b)*, *(b,j)*, and *(j,d)* and requires the opening of arc *(b,j)* in the original network.

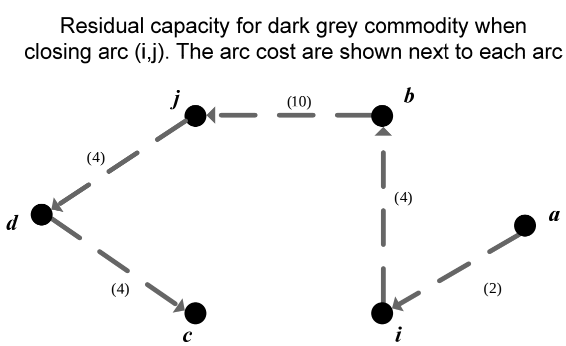

Figure 8

Because the design changes if a closed arc is used in the path, and because the commodities cannot use the same residual capacity on other open arcs, the flow on the original network needs to be updated after redirecting each commodity $p \in \mathcal{P}_{ij}$. Figure 9 shows the updated network from figure 7 where arc (i,j) has been closed.

The redirection needs to be done sequentially for each commodity. The sequence in which commodities are redirected is here done according to the enumeration of the commodities. To calculate the total system cost of the potential neighbour solution after closing arc *(i,j)* the following procedure is used:

$$Initialize: \begin{cases} \tilde{Z}_{n+1} = Z_n - f_{ij} - \sum_{p \in \mathcal{P}_{ij}} \sum_{(i,j) \in \mathcal{A}} c_{ij}^p x_{ij}^p \\ \tilde{Y}_{n+1} = Y_n \\ \tilde{X}_{n+1} = X_n - \sum_{p \in \mathcal{P}_{ij}} x_{ij}^p \end{cases}$$

$For\ all\ p \in \mathcal{P}_{ij}$

$Construct\ residual\ graph\ for\ commodity\ p$

$Solve\ shortest\ path\ \pi\ to\ determine\ \Delta Z_p^{\Gamma}\ and\ \Delta Y_p^{\pi}$

$$Update: \begin{cases} \tilde{Z}_{n+1} = \tilde{Z}_{n+1} + \Delta Z_p^{\Gamma} \\ \tilde{Y}_{n+1} = \tilde{Y}_{n+1} + \Delta Y_p^{\pi} \\ \tilde{X}_{n+1} = \tilde{X}_{n+1} + \sum_{(i,j) \in \mathcal{A}_p^{\Gamma}(\pi)} \Gamma^p \end{cases}$$

The total system cost is initialized to be equal that of the incumbent solution minus the fixed cost of arc *(i,j)* (that is to be closed) minus the routing cost on all arcs of commodities $p \in \mathcal{P}_{ij}$ traversing arc *(i,j)*. For each redirection of commodities $p \in \mathcal{P}_{ij}$ the neighbour solution's total system cost is updated by adding the new path cost, the design vector is updated with the arcs opened solving the shortest path, and the flow vector is updated with the flow of the new commodity path.

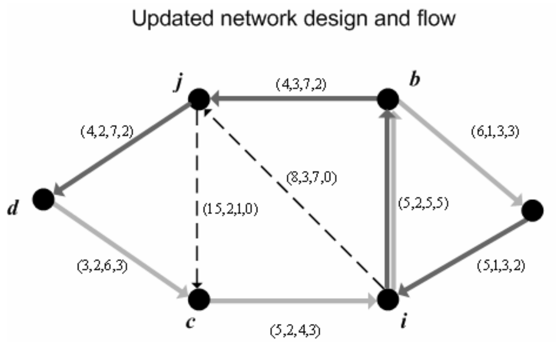

Figure 9

Repeating the update of the flow and design vectors results in an approximation for the neighbour solution $(\tilde{Y}_{n+1}, \tilde{X}_{n+1})$ and in an estimated neighbour total system cost $\tilde{Z}_{n+1}$.

4.4.2. Neighbour move and total system cost estimate when opening an arc

Opening an arc may result in new routing possibilities for commodities and thus change the solution of the CMCF formulation. However, as stated previously, it may also have little or no impact on the flow vector. Assuming the flow is unaffected by opening the arc, the solution value will increase with the value of the arc's fixed cost. Opening an arc can improve node imbalances of an incumbent solution and thereby move the search towards a feasible neighbour solution. We assume that the gain of moving towards a feasible solution outweighs the fixed cost incurred by opening the arc. Therefore it is advantageous to include a move that opens an arc in the neighbourhood structure.

To precisely evaluate a potential neighbour solution's total system cost when opening an arc it is necessary to solve the CMCF problem for the neighbour design. However, we assume that the gain of opening an arc to improve node imbalances outweighs the impact from the change in the flow vector. If an arc is opened and added to the design the incumbent solution's flow vector, X_n, is a feasible flow vector, $\tilde{X}_{n+1}$, for the neighbour solution. We therefore approximate the neighbour solution's flow vector and design vector by setting the flow vector equal to that of the incumbent solution and the design vector equal to that of the incumbent solution including the opened arc *(i,j)*:

$$\tilde{X}_{n+1} = X_n,\ \tilde{Y}_{n+1} = Y_n \cup (i,j)$$

The estimated neighbour total system cost is easily calculated by adding the fixed cost of arc *(i,j)*:

$$\tilde{Z}_{n+1} = Z_n + f_{ij}$$

By ignoring the potential lower variable cost a reasonable approximation of and upper bound on the total system cost, $\tilde{Z}_{n+1} \geq Z_{n+1}$, is achieved.

4.5. Determining a candidate list for phase 1

The basic add/drop moves results in $|\mathcal{A}|$ potential neighbour solutions for an exhaustive search of the neighbourhood. However, an exhaustive search of all potential neighbours may require an examination of uninteresting potential moves resulting in a waste of computational time. It is deemed more effective to consider only a limited number of "good" potential solutions in each iteration. Thus a list of candidate arcs that is a subset of the network arcs, $\mathcal{C}_1^n \subseteq \mathcal{A}$, is composed for incumbent solution *n*.

In the implementation proposed here we have opted to determine the candidate list from four sub-candidate lists each selecting arcs according to different criteria. The four sub-lists are

1. $\mathcal{C}_f$, open arcs with the highest fixed cost
2. $\mathcal{C}_v$, open arcs with the highest variable cost
3. $\mathcal{C}_r^n$, open arcs with highest residual capacity
4. $\mathcal{C}_p^n$, Arcs with the lowest estimated penalty value $\tilde{P}_n$

The length of each sub-list is determined by the empirical parameters l_f, l_v, l_r, and l_p. In the implementation these are given externally and remain constant throughout the progress of the algorithm.

Each of the criteria of the four sub-list have a motivation. Closing an open arc *(i,j)* high fixed cost can reduce the total system cost. Similarly closing an open arc *(i,j)* with high variable cost can decrease the total system cost. Arcs with high residual capacity (Capacity minus total flow) do not use their capacity to its full extent and may therefore have a high fixed cost per unit flow. Closing an open arc *(i,j)* with large residual capacity can thus remove the fixed cost incurred by the arc while only having to redirect a small amount of flow onto other paths not including arc *(i,j)*. Choosing arc *(i,j)* that may be either open or closed with a low expected penalty value will decrease the solution value and thus move the search towards a more feasible solution.

The fixed cost sub-list $\mathcal{C}_f$ and the variable cost sub-list $\mathcal{C}_v$ do not change over the course of the iterations and can be initialized at the start of the algorithm. The residual capacity sub-list $\mathcal{C}_r^n$ needs to be updated after every iteration. The penalty sub-list $\mathcal{C}_p^n$ also needs to be updated every time a new design is adopted. As we shall show the impact of closing an arc may involve opening other arcs and because of the interdependency between opening and closing arcs on the node imbalances it is thus not possible to determine the exact penalty value of a potential neighbour solution prior to performing the candidate list.

An estimate of the penalty value is used to determine the arcs in the penalty sub-list. The estimate is based on the simplifying assumption that the design only changes by adding or dropping the candidate arcs. Based on this approximation the estimated resulting system imbalance, $\tilde{\psi}_{n+1}^{\mathfrak{N}}$, is easily computed for each arc from the incumbent solution's system imbalance, $\psi_n^{\mathfrak{N}}$, by updating the imbalance changes:

$$\begin{aligned}&\tilde{\psi}_{n+1}^{\mathfrak{N}} = \psi_n^{\mathfrak{N}} + \Delta(\psi_{n+1}^i) + \Delta(\psi_{n+1}^j),\\ &\quad \textit{where } \Delta(\psi_{n+1}^i) = \left|\psi_{n+1}^i - \psi_n^i\right|\\ &\quad \textit{and } \Delta(\psi_{n+1}^j) = \left|\psi_{n+1}^j - \psi_n^j\right|\end{aligned}$$

Finding the potential neighbour solution's estimated maximal node imbalance, $\tilde{\psi}_n^{\max}$, is more complicated. In order to have a correct value for the maximal imbalance it is not sufficient to consider the changes in the candidate arcs' two nodes as is the case with the total system imbalance. Lets assume that arc *(i,j)* is dropped, and node *i* has the maximal node imbalance in the incumbent solution, $\left|\psi_{n-1}^i\right| = \psi_{n-1}^{\max}$. Let us further assume that the node imbalance in node *i* is smaller in the potential neighbour solution than in the incumbent solution, $\left|\psi_n^i\right| < \left|\psi_{n-1}^i\right|$. There is no guarantee that the maximal node imbalance is equal to the node imbalance in node *i* for the potential neighbour solution, as there might be another node *k* with the same maximal imbalance in the incumbent solution, $\left|\psi_{n-1}^k\right| = \left|\psi_n^k\right| = \left|\psi_{n-1}^i\right| = \psi_n^{\max}$. The maximal imbalance will in that case not change for the potential solution even though the imbalance in node *i* is smaller. To determine the real value of the maximal node imbalance all the nodes in the network would need to be examined for a potential neighbour solution. To limit computational complexity, $\tilde{\psi}_n^{\max}$ is estimated using the following approximation:

$$\tilde{\psi}_{n+1}^{\max} = \begin{cases} \psi_n^{\max} & \textit{if } \left|\psi_n^i\right|, \left|\psi_n^j\right| < \psi_n^{\max} \\ \max(\psi_{n+1}^i, \psi_{n+1}^j) & \textit{otherwise} \end{cases}$$

The approximation assumes (correctly) that the maximal node imbalance does not change if the node imbalances in node *i* and *j* in the incumbent solution are both smaller than the maximal node imbalance. If however, the imbalance in node *i* or *j* in the incumbent solution is equal to the maximal node imbalance, $\psi_{n-1}^{\max}$, its value might change. If the maximal node imbalance increases the new maximal node imbalance calculated by the approximation is correct. If the node imbalance decreases there is as explained no guarantee that there is not another node in the network with the maximal node imbalance. However, to reward the decrease of a (large) node imbalance the estimated penalty cost is calculated as if the maximal node imbalance for the network has decreased.

The estimated penalty value of a potential neighbour solution based on the potential system imbalance and the estimated potential maximal imbalance is calculated as:

$$\tilde{P}_n = \tilde{f} \cdot \tilde{\psi}_n^{\mathfrak{N}} \cdot \tilde{\psi}_n^{\max}$$

4.6. Tabu list composition for phase 1

The purpose of the Tabu list is to avoid cycling between the same neighbour solutions as the algorithm iterates. The tabu list contains information of the previous l_t neighbour solutions. As the name indicates, solutions on the tabu list may not be considered as a potential neighbour solution.

It is not practical to save all the attributes (design and flow vectors) for a solution and thus an alternative is considered. Since the basic neighbour move is based on flipping the value of the design variable of arc *(i,j)* a tabu move is defined as choosing the same arc directly to be flipped back for the following l_t iterations. The tabu list is thus a list of the previous l_t chosen candidate arcs.

Keeping only the chosen candidate arcs in the tabu list may result in banning neighbour non-tabu solutions. If an arc is added to the tabu-list at iteration n it will stay there until iteration $n+l_t$ and thus may not be considered as a candidate arc. However, at iteration m, $n<m<n+l_t$, adding the chosen candidate arc from iteration n does not necessarily result in the same neighbour solution, because of the changes made to the solution between iteration n and m. In order not to strictly exclude arcs from good potential solutions they are only tabu'ed from the candidate list. That means that if arc *(i,j)* is closed and thus is tabu it can still re-enter into the solution if it is chosen on the redirection path of a commodity.

The Tabu list is initialized as an empty list, $\mathfrak{I} = \{\emptyset\}$. For iterations $n \le l_t$ the chosen candidate arc in iteration n, $c_n \in \mathcal{C}^n$, is added to the Tabu list $\mathfrak{I} = \mathfrak{I} \cap c_n$. For iterations $n > l_t$ the first element of the Tabu list, the candidate arc of iteration $n > l_t$, c_{n-l_t}, is removed and replaced by the candidate arc of current iteration n, $c_n \in \mathcal{C}^n$ to get $\mathfrak{I} = \{\mathfrak{I} \setminus c_{n-l_t}\} \cap c_n$.

4.7. Neighbourhood structure for phase 2

The neighbourhood structure of the local search in phase 1 allows moves between infeasible solutions with respect to the design balance constraints. There is therefore no guarantee that the exploration of the solution space in phase 1 will result in feasible solutions. The local search in phase 2 is designed specifically to find good feasible solutions.

The termination of phase 1 results in a given infeasible incumbent solution. In this solution there are a number of nodes that are imbalanced. Consider once more the network design in figure 5. Assuming arc *(i,j)* is not included in the design vector the solution is feasible with respect to the design balance constraints. If arc *(i,j)* is added the solution is now infeasible because there are imbalances in node i and j. More specifically the imbalance of node i is -1 and the imbalance of node j is +1. It is easily seen that for any imbalanced solution the sum of the absolute negative imbalances is always equal to the sum of the positive imbalances.

The idea behind the neighbourhood structure for phase 2 is to eliminate pairs of oppositely imbalanced nodes by closing or opening paths of arcs between them. Closing a path of arcs from a node with negative imbalance to a node with a positive imbalance will reduce the imbalance in each of the nodes. Similarly, opening a path of arcs from a node with a positive imbalance to a node with negative imbalance will also reduce the imbalance in both nodes. The imbalances of nodes lying on the path in between are unaffected because both an ingoing and an outgoing arc will either be removed or added to the node. Figure 10a & b show an example of connecting two nodes *i* and *j* by either opening or closing a path of arcs respectively.

A feasible solution with respect to design can be achieved by closing the arcs on path *(i,d)*, *(d,a)* and *(a,j)* as shown with the grey arcs in figure 10a, or by opening the arcs on path *(j,h)*, *(h,g)*, *(g,f)* and *(f,i)* as shown in figure 10b. Iteratively matching imbalanced nodes and closing or opening paths of arcs between them eventually eliminates the imbalances and generates a feasible solution. The overall procedure for phase 2 can be seen in figure 4.

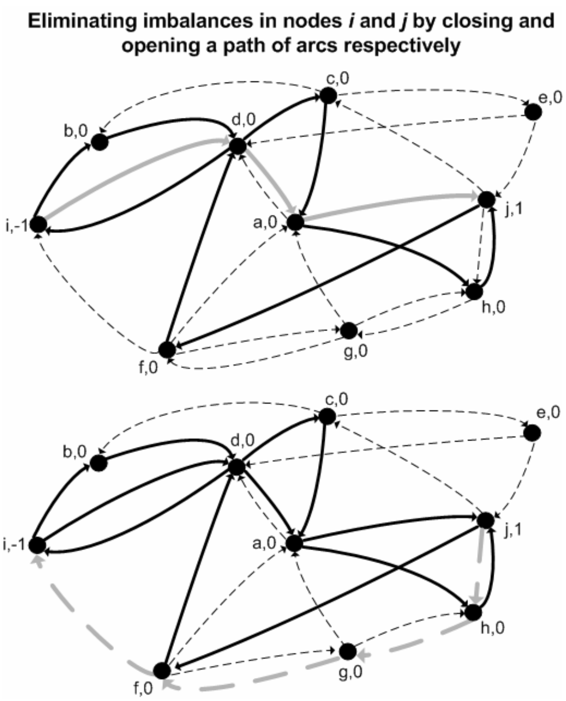

Figure 10a & b.

4.8. Neighbourhood move and neighbour solution evaluation for phase 2

The template for the neighbourhood moves for phase 2 is the add/drop procedure. Instead of adding or dropping an arc as in phase 1, the add/drop procedure in phase 2 is done on paths of arcs. To achieve a feasible solution we iteratively eliminate pairs of imbalances by connecting oppositely signed nodes with paths to close or open. If the procedure is successful $\psi_n^{\mathcal{N}}/2$ iterations are performed, equivalent to eliminating imbalances in pairs of two (one negative and one positive for each iteration).

In the implementation proposed here the node with the maximum imbalance is first identified, $i:\{|\psi_{n-1}^i| = \psi_{n-1}^{\max}\}$. Secondly the set of nodes with oppositely signed imbalances are identified, $\mathcal{N}^c:\{j \in \mathcal{N}^c | \psi_{n-1}^i \cdot \psi_{n-1}^j < 0\}$. A candidate set, $\mathcal{C}_2^n$, of path (to open or close) is identified between node *i* and any of the nodes in $\mathcal{N}^c$.

Opening or closing a path of arcs in the design may have a big impact on the flow solution. If a path is closed many commodities may have to be redirected using the residual capacity of other open arcs. Opening a path may result in better routing possibilities for commodities. Thus to get a reasonable evaluation of the impact the CMCF problem is solved for each candidate path. The path resulting in the smallest total system cost is implemented resulting in a new incumbent solution.

4.9. Determining a candidate list for phase 2

For a single pair of imbalanced nodes there can be several possible paths that can be opened or closed between them. E.g. in figure 10a & b other than closing path *(i,d)*, *(d,a)* and *(a,j)* or opening path *(j,h)*, *(h,g)*, *(g,f)* and *(f,i)*, paths *(i,b)*, *(b,d)*, *(d,c)*, *(c,a)* and *(a,h)* or *(i,d)*, *(d,a)*, *(a,h)* and *(h,j)* could be closed and result in a solution feasible with respect to the design balance constraints. If there are several imbalanced nodes the number of possible paths between positive and negative imbalanced nodes is very large. Furthermore the evaluation of each potential path is done by solving the CMCF problem. Thus we restrict the number of candidate paths examined to a few interesting ones.

We propose a candidate list containing four candidate paths. The four paths are determined by solving the shortest path problem on four constructed graphs with alternating arc costs. Each shortest path problem is solved with node *i*, $i{:}\{|\psi_{n-1}^{i}| = \psi_{n-1}^{\max}\}$, as the source node. The paths may use any of the nodes in $\mathcal{N}^{c}{:}\{j \in \mathcal{N}^{c} | \psi_{n-1}^{i} \cdot \psi_{n-1}^{j} < 0\}$ as the sink node. For paths that need to be opened node *i* is actually the sink node. However, this can be encountered by reversing the direction of the arcs in the constructed network. For each of the constructed graphs a pseudo node *k* is added and a set of arcs with zero cost is added from the nodes in $\mathcal{N}^{c}$ to pseudo node *k*, $\mathcal{A}^{p}: \{(j,k) \in \mathcal{A}^{p} \mid j \in \mathcal{N}^{c}\},\ c_{ij}^{x} = 0 \quad \forall (j,k) \in \mathcal{A}^{p}$. The four graphs are determined as $\mathcal{G}^{c} = (\mathcal{N}, \mathcal{A}^{c} \cap \mathcal{A}^{p})$, where $\mathcal{A}^{c} \subseteq \mathcal{A},\ c = \{1,2,3,4\}$ is the set of arcs included in the constructed graph. The four sets of arcs and the cost associated to each arc in the sets is determined as:

1. $\mathcal{A}^{1}: \{(i,j) \in \mathcal{A}^{1} \mid (i,j) \in \mathcal{A} \wedge y_{ij} = 1\}$,
   $c_{ij}^{1} = \sum_{p \in \mathcal{P}} x_{ij}^{p} \quad \forall (i,j) \in \mathcal{A}^{1}$
2. $\mathcal{A}^{2}: \{(i,j) \in \mathcal{A}^{2} \mid (i,j) \in \mathcal{A} \wedge y_{ij} = 1\}$,
   $c_{ij}^{2} = \max_{(i,j) \in \mathcal{A}} (f_{ij}) - f_{ij} \quad \forall (i,j) \in \mathcal{A}^{2}$,
3. $\mathcal{A}^{3}: \{(i,j) \in \mathcal{A}^{3} \mid (j,i) \in \mathcal{A} \wedge y_{ij} = 0\}$,
   $c_{ij}^{3} = c_{ij} \quad \forall (i,j) \in \mathcal{A}^{3}$,
4. $\mathcal{A}^{4}: \{(i,j) \in \mathcal{A}^{4} \mid (j,i) \in \mathcal{A} \wedge y_{ij} = 0\}$,
   $c_{ij}^{4} = f_{ij} \quad \forall (i,j) \in \mathcal{A}^{4}$,

The arc set of graph 1, $\mathcal{A}^{1}$, includes all arcs that are open and assigns each arc $(i,j) \in \mathcal{A}^{1}$ a cost equal to the total flow on the arc. Solving the shortest path on graph 1 will result a path of arcs π^{1} with little flow on them. Closing this path will only lead to a relatively small amount of commodity flow to be redirected onto other open arcs and thus may have a good chance of success.

The arc set of graph 2, $\mathcal{A}^{2}$, includes all arcs that are open and assigns each arc $(i,j) \in \mathcal{A}^{2}$ a cost equal to the largest fixed cost of the arcs in the network minus the fixed cost of arc *(i,j)*. Solving the shortest path on graph 2 will result in a path of arcs π^{2} with high fixed costs. Closing the arcs on this path will remove arcs with high fixed costs which will reduce the total system cost.

The arc set of graph 3, $\mathcal{A}^{3}$, includes all arcs that are closed and assigns each arc $(i,j) \in \mathcal{A}^{3}$ a cost equal to the variable cost of arc $(j,i) \in \mathcal{A}$. Solving the shortest path on graph 3 will result in a path of arcs π^{3} with small variable costs. Opening this path may enable some cheaper routing alternatives for commodities and thereby reduce the total solution value although fixed costs are incurred by opening the path

The arc set of graph 4, $\mathcal{A}^{4}$, includes all arcs that are closed and assigns each arc $(i,j) \in \mathcal{A}^{4}$ a cost equal to the fixed cost of arc $(j,i) \in \mathcal{A}$. Solving the shortest path on graph 4 will result in a path of arcs π^{4} with low fixed cost. Opening this path will reduce the absolute imbalances by opening cheapest possible path and thereby limiting the increase of the total solution value.

There could be other graphs with other cost structures or alternative path finding methods that would be interesting to investigate to determine candidate paths. This is left to future research.

Given that the candidate list only examines a subset of paths, there is no guarantee that it is possible to determine a new incumbent solution from one of the four paths found by solving the shortest path problem on the constructed graphs.

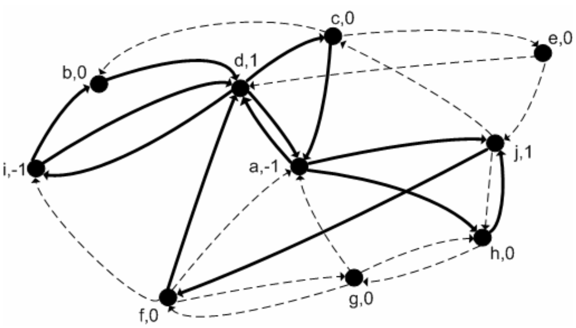

Figure 11.

Take for example figure 11 where node *d* has an imbalance of +1 and node *i* has an imbalance of -1. To eliminate the imbalance a path of closed arcs could be opened from node *d* to node *i* or a path of open arcs from node *i* could be closed. However, as it can be seen there are no closed arcs emanating from node *d*, and therefore it is not possible to find a path using constructed graphs 3 and 4. Furthermore there is no guarantee that the two paths calculated using graphs 1 and 2, closing arcs between node *i* and node *d*, produce a design that has a feasible CMCF-solution. If such a situation occurs where none of the four proposed paths can be found, phase 2 is terminated and passes over the current (infeasible) incumbent solution obtained to phase 1 where the search algorithm continues.

5. Results

To test the algorithm selected network design instances used in [Crainic et al 2000] and [Ghamlouche et al 2003] have been used. There are two sets of instances, R and C, out of which only the most difficult ones have been selected for the final experimentation. Each of the network design instances have varying capacities on arcs although it is presumed that in a service scheduling application the capacities would be more homogenous. It must however intuitively be assumed that it is more difficult to solve the DBCMND on networks with varying capacities. Thus we assume the results presented here are not an over estimation of the performance of an eventual application of the algorithm on for a scheduled service design network. The shortest path used in the TS algorithm is a ML-Thresh-X2 [Jørgensen et al 2004] and the CMCF problems are solved using Xpress-MP's LP-solver. The algorithm was implemented in C++ using Microsoft Visual Studio .NET 2003 using the Xpress-BCL builder component library to interact with Xpress-MP's MIP-solver. The algorithm's performance is compared to solutions obtained with Xpress-MP's MIP-solver.

5.1. Initial parameter tuning

In order to find the most effective configuration of parameters some initial experimentation is conducted. Ten different instances have been picked out from both the R and C data sets on which to carry out the parameter tuning experimentation. The ten instances are presented in figure 12. The data sets have been picked in different sizes and with different characteristic. The 'capacity ratio' is a ratio of commodity demand over total network capacity. The 'cost ratio' is a ratio of the fixed cost over the variable cost of arcs. The 'Opt.' solution column indicates whether an optimal solution was found for the instance solving it using Xpress-MP's MIP solver on a PC with a 2.26 GHz Intel Pentium 4 processor within a 3600s time limit.

There are eight parameters defined in the implementation of the Tabu Search framework we have presented. To determine appropriate values for these eight parameters we apply a 2-level 2^8 factorial experimentation plan [Montgomery 2000] where each of the eight parameters is evaluated on two levels, a low level and a high level. The two levels chosen for each of the eight parameters are:

- l_i, an iteration range of 10 and 30
- l_g, a percentage gap 0.5% and 5%
- ψ^p, a penalty scaling factor of 0.5 and 2
- l_t, a length of the Tabu list of 5 and 25
- l_f, a number of fixed cost candidates of 5 and 15
- l_v, a number of variable cost candidates of 5 and 15
- l_r, a number of residual capacity candidates of 5 and 15
- l_p, number of penalty value candidates of 5 and 15

The two levels of each parameter are determined from intuitive considerations. All of the levels have been determined at two extremities from the consideration that their effects would be best tested with extreme values. However the extremities are chosen with moderation as each of the parameters intuitively will have no effect if set to 0 and either produce poor results or have no effect at very high levels. The total length of the candidate list is determined from the size of each of the four candidate sub-lists. It is estimated that no less that 20 candidates should be tested considering the network sizes of the network instances. Accrediting each sub-list equal importance the low level for each of the sub-list parameters l_f, l_v, l_r, and l_p is set to 5. The high level of 15 is chosen as an estimated significant difference. The tabu list was set at a low level of 5 in comparison to the minimum size of the candidate list of 20. The high level of 25 is estimated to be a reasonable high extremity. The iteration range levels were chosen just above the Tabu list length levels but the low level staying below the high level of the Tabu tenure. This means that the Tabu tenure is saved from one phase 1 search to another for a low/high combination of iterations range/tabu tenure. The improvement gap percentage was chosen with a high level of 5% and a low tight level of 0.5%. Finally the penalty scale factor is chosen to test the importance of the penalty value at half or double value as extremities.

Size and characteristics of selected network instances for paramter tuning

instance name	network size			Network characteristic		
	nodes	arcs	commodities	capacity ratio	cost ratio	Opt. Solution
R10,F05,C2	20	120	40	medium	medium	yes
R12,F10,C2	20	120	200	medium	high	yes
R13,F01,C8	20	220	40	tight	low	yes
R15,F10,C8	20	220	200	tight	high	yes
C20,230,200,F,L	20	230	200	loose	high	no
R16,F10,C1	20	314	40	loose	high	no
R17,F01,C1	20	318	100	loose	low	yes
R18,F05,C2	20	315	200	loose	medium	no
C30,520,100,V,T	30	519	100	tight	low	no
C100,400,30,F,L,10	100	400	30	loose	high	no

Figure 12

Aggregated computational results for the 32 runs (600s.) on selected instances for parameter tuning								
instance name	Xp. Sol	Bound	Sol. Gap	Time (s)	TS. Avg. TS. Best	Avg. Xp. GAP Best Xp. Gap	Avg. Bound Gap Best Bound Gap	Spread (% of Avg.)
R10,F05,C2	443.149	443.149	0,00%	1198	449.705 443.547	1,46% 0,09%	1,46% 0,09%	1,02%
R12,F10,C2	7.408.996	7.408.996	0,00%	1055	7.760.968 7.530.870	4,54% 1,62%	4,54% 1,62%	1,66%
R13,F01,C8	218.787	218.787	0,00%	2332	226.181 223.231	3,27% 1,99%	3,27% 1,99%	0,76%
R15,F10,C8	9.105.014	9.105.014	0,00%	1131	9.745.193 9.366.760	6,57% 2,79%	6,57% 2,79%	2,64%
C20,230,200,F,L	160.923	128.014	20,45%	(t)	150.180 146.643	-7,15% -9,74%	14,76% 12,70%	1,90%
R16,F10,C1	379.910	309.383	18,56%	(t)	362.252 352.681	-4,87% -7,72%	14,59% 12,28%	2,17%
R17,F01,C1	364.784	364.784	0,00%	1895	369.441 365.801	1,26% 0,28%	1,26% 0,28%	1,05%
R18,F05,C1	1.986.164	1.362.596	31,40%	(t)	1.673.958 1.597.610	-18,65% -24,32%	18,60% 14,71%	2,25%
C30,520,100,V,T	53.219	52.662	1,05%	(t)	54.569 53.972	2,47% 1,40%	3,49% 2,43%	0,56%
C100,400,30,F,L	81.638	58.316	28,57%	(t)	75.941 67.603	-7,50% -20,76%	23,21% 13,74%	5,18%

Figure 13

Testing all the combinations of parameters at both levels require 2^8 experiments for each of the ten instances. To get a reasonable estimate of the search process for a parameter configuration we allow the algorithm to run for 600 seconds. To conduct the $10 \cdot 2^8$ experiments 1.5 million seconds would be required. To limit computational requirements we reduce the experimentation plan to a fractional 2^5 factorial design by confounding 3 of the parameters with higher degree interactions. This is reasonable to do if it is assumed that parameter interaction is limited. A total of 32 experimentation runs are performed using the TS algorithm for the selected instances for the parameter tuning.

The results from the parameter tuning experiments are presented in figure 13. The first four columns show the instance name, the best found solution using Xpress-MP's MIP solver within a time limit of 3600s., the lower bound obtained from the Xpress-MP solution, and the relative gap between the best obtained solution and the lower bound. The fifth column show the solution time to find the optimal solution or a (t) if the solver was stopped after 3600s. The following column shows in pairs the average solution values of all 32 runs and the best solution value using the TS-algorithm, the following one the relative gap between the best Xpress-MP solution and the average solution and best solution found with the TS-algorithm, and the following one the gap between the lower bound obtained from the MIP-solver and the average solution and best solution found with the TS-algorithm. The last column shows the spread relative to the average solution value found with the TS-algorithm.

Notice that for the 4 instances Xpress-MP solved to optimality, excluding instance R15,F10,C8, the average solutions lies within 5% of the optimal solution and the best solutions within 2%. This has to be seen in relation to the algorithm run times were limited to 600 seconds compared to the 3600 seconds allocated to Xpress-MP. The relatively poorer results for instance R15,F10,C8 is due its computationally demanding CMCF-problem and its imbalanced nature requiring much computation time during phase 2. The 600 seconds of run time was not sufficient for more than 1-2 runs of phase 2 and therefore only 1-2 feasible solutions where found per experiment. For all instances that Xpress-MP did not find the optimal solution for our TS- algorithm finds better results except for instance C30,520,100,V,T. The solution found by Xpress-MP is 1.05% from the lower bound and therefore too close to it for the algorithm to do better.

An interesting observation is the spread of the results. For all instances, except instance C100,400,30,F,L, the spread of the solution values is less than 3% from the best average solution. This indicates that the algorithm is somewhat robust to parameter choice, which is an important attribute if the algorithm was to be applied to real applications. The reason behind instance C100,400,30,F,L having a higher spread than the other instances can be explained from two observations. First, some cycling was experienced for some configurations. The changes made in phase 1 sometimes resulted in path choices in phase 2 that would result in the same feasible solution as for the previous instance of phase 2. Thus achieving feasible solutions and thereby eventually finding good solutions seems to be more a matter of coincidence when searching the neighbourhoods. Second, the network is sparse which led to a high degree of failure on phase 2 because feasible path were harder to find, and thus resulting in fewer obtained feasible solutions. We believe however, that the tuning of parameters has little influence on whether cycling is avoided or not, but that a diversification procedure or another memory mechanism to avoid it would be advantageous.

The effects of the eight parameters in the 2^5 experiments are calculated using Yates' algorithm. The results from using Yates' are only used to get an indication of the best parameter setting. The evaluation of the effects has not been subject to statistical analysis to investigate their significance. Figure 14 shows a subjectively interpreted optimal configuration of the parameter values for each of the ten instances based on the 32 runs performed with the TS-algorithm. When the table reads *"low"* it indicates that the best results are achieved with the parameter at its low level, while *"high"* indicates the opposite. The words put in parenthesis indicate that only a relatively small effect is registered from the effect of the parameter. Where nothing is written we expect that the value of the

Best paramter selection from initial computational runs								
instance name	**Paramter**							
	# f. cost	**# p. cost**	**# residual**	**# v. cost**	**tabu ten.**	**p. scale**	**imp. gap**	**it. range**
R10,F05,C2	low	low	high			low	high	low
R12,F10,C2		low						low
R13,F01,C8				(low)		(low)		(low)
R15,F10,C8		(low)				(low)		low
C20,230,200,F,L				(high)		(low)		
R16,F10,C1	low		high	(high)	high	low		low
R17,F01,C1	high		high	high	high		(high)	
R18,F05,C2								
C30,520,100,V,T								
C100,400,30,F,L,10	high	low	high		high			low
	Aggregated paramter selection indication							
		low	high	high	high	low	high	low

Figure 14

Paramter configuration for 8 computational runs										
Run	Parameter								Score	Rank
	# f. cost	# p. cost	# residual	# v. cost	tabu ten.	p. scale	imp. gap	it. range		
1	5	5	15	15	25	0.5	5	10	3,74	2
2	5	5	5	5	25	0.5	5	10	4,26	3
3	10	10	10	10	25	2	5	20	6,24	8
4	8	7	5	5	20	2	5	10	4,91	6
5	5	5	10	10	20	2	5	10	4,94	7
6	5	5	10	10	20	0.5	5	20	4,47	5
7	10	10	10	10	10	2	5	10	4,44	4
8	5	5	15	15	10	0.5	5	10	2,83	1

Figure 15

parameter has no effect in the tested range. If all the effects from each of the ten instances are aggregated into one "optimal" parameter configuration we achieve the configuration illustrated at the bottom of the table in figure 14. The setting of the fixed cost sub-list length parameter is somewhat inconclusive. The apparent optimal configuration indicates that high values should be applied for the improvement gap, the tabu list length, the variable cost sub-list length and the residual capacity sub-list length while low values should be applied to the penalty value sub-list length, the penalty scaling factor and the iteration range. An intuitive reason for having a high level for the improvement gap combined with a low level for the iteration range is that phase 2 is initiated more often and thus more feasible solutions are obtained. The reason for the high length of the tabu list could be accredited to the fact that keeping arcs in tabu tenure for longer diversifies the search more. Furthermore the combination between having longer tabu tenure than iteration range allows the exclusion of arc to be carried over from one phase 1 search to another and prevent direct cycling between the solutions obtained in the two phases.

5.2. Algorithm tests on network instances

The TS-algorithm is tested on instances from the R and C data sets. 24 of the most difficult instances have been selected from the C data set and the 54 most difficult ones from the R data set. Each of the individual runs has been allocated 3600 seconds of CPU-time using a PC with an Intel Pentium 4, 2.26Ghz processor. The performances are compared to solutions obtained Xpress-MP's MIP solver by allowing the same amount of CPU-time. The 78 selected instances have been solved using eight different parameter settings inspired by the results from the initial parameter tunings. The different parameter settings for each of the eight runs are shown in figure 15. To further investigate the effect of different parameter settings we rank each of the settings (1 to 8) according to the best achieved results on each of the 78 instances and average the total score by the number of instances. These results are shown in the 'score' column in figure 15. Two runs stand out. Run number 8 is significantly better than the others and run 3 is significantly worse. For run 3 the parameter settings for the iteration range and penalty scaling factor where set to high contradicting the recommendation of the parameter tuning exercise. It is reasonable to conclude that these two parameters should be set at relatively low values to achieve the best results. This is the case for run 8, although the tabu tenure here is set to low, contradicting the recommendation from the parameter

Computational results (3600s.) selected C-problems						
Instance	**XP**	**Bound**	**Avg TS Best TS**	**Spread**	**Avg Gap Bound Best Gap Bount**	**Avp Gap XP Best Gap XP**
C20,230,200,V,L	101112	86.180	103.340 (8) 101.345	1,12%	16,60% 14,96%	2,15% 0,23%
C20,230,200,F,L	153534	122.311	151.220 (8) 148.384	1,09%	19,11% 17,57%	-1,54% -3,47%
C20,230,200,V,T	105840	92.608	106.187 (1) 103.371	1,94%	12,76% 10,41%	0,29% -2,39%
C20,230,200,F,T	154026	124.358	148.177 (4) 144.766	1,46%	16,06% 14,10%	-3,97% -6,40%
C20,300,200,V,L	81183,5	73.894	80.999 (6) 80.143	1,12%	8,76% 7,80%	-0,24% -1,30%
C20,300,200,F,L	131876	110.533	128.017 (8) 126.258	1,11%	13,65% 12,45%	-3,03% -4,45%
C20,300,200,V,T	78675	74.583	80.054 (8) 78.444	1,48%	6,82% 4,92%	1,70% -0,29%
C20,300,200,F,T	127412	106.628	119.218 (1) 116.338	1,75%	10,54% 8,35%	-6,90% -9,52%
C30,520,100,V,L	55138	54.160	56.386 (5) 55.786	0,67%	3,94% 2,91%	2,21% 1,16%
C30,520,100,F,L	n/a	92.636	103.922 (2) 101.612	1,04%	10,85% 8,83%	n/a n/a
C30,520,100,V,T	53125	52.681	54.329 (5) 54.092	0,29%	3,03% 2,61%	2,21% 1,79%
C30,520,100,F,T	106761	97.653	106.551 (8) 104.702	1,21%	8,34% 6,73%	-0,21% -1,97%
C30,520,400,V,L	n/a	111.054	119.649 (5) 118.071	0,91%	7,18% 5,94%	n/a n/a
C30,520,400,F,L	n/a	143.335	163.106 (7) 160.979	1,00%	12,11% 10,96%	n/a n/a
C30,520,400,V,T	n/a	114.725	121.380 (1) 120.421	0,59%	5,48% 4,73%	n/a n/a
C30,520,400,F,T	n/a	148.210	164.799 (1) 161.978	1,01%	10,06% 8,50%	n/a n/a
C30,700,100,V,L	48849	48.400	49.834 (1) 49.429	0,69%	2,87% 2,08%	1,97% 1,17%
C30,700,100,F,L	65516	59.483	63.795 (4) 63.292	0,93%	6,75% 6,02%	-2,71% -3,51%
C30,700,100,V,T	47052	46.260	48.020 (8) 47.487	0,51%	3,66% 2,58%	2,01% 0,92%
C30,700,100,F,T	57447	55.123	58.481 (8) 57.187	1,19%	5,73% 3,61%	1,76% -0,45%
C30,700,400,V,L	n/a	94.725	105.874 (1) 103.932	1,51%	10,51% 8,86%	n/a n/a
C30,700,400,F,L	n/a	128.950	161.498 (5) 148.114	6,16%	19,89% 12,94%	n/a n/a
C30,700,400,V,T	n/a	95.183	103.705 (1) 103.085	0,63%	8,21% 7,67%	n/a n/a
C30,700,400,F,T	n/a	128.441	141.686 (8) 138.609	1,08%	9,34% 7,34%	n/a n/a

Figure 16

Relative spread distribution for instances in the R ad C data sets						
Data set	Spread as relative persentage					
	[0.0%]-[0.5%]	[0.5%]-[0.1%]	[1.0%]-[1.5%]	[1.5%]-[2.0%]	>[0.2%]	Average
C	1	8	11	3	1	1,27%
R	2	16	12	12	12	1,48%
C & R	3	24	23	15	13	1,41%

Figure 17

tuning. Since this is the only parameter that differs run 8 from run 1 this may point to the fact that the tabu tenure either was wrongly estimated or has a different impact when allocating more CPU-time to solve the instances. Nevertheless, the remaining 6 runs all have relatively similar scores indicating once more that the algorithm is somewhat robust with respect to the parameter settings. This claim is further supported by the computational results for the selected C instances shown in figure 16. The table is composed as such. The 'XP' column shows the best results obtained with Xpress-MP's MIP solver in 3600 seconds of computational time. The 'Bound' column shows the lower bound of the instance found by Xpress-MP too. The third column shows the average solution ('Avg TS') of all eight parameter settings and the best achieved solution ('Best TS') over the eight runs. The number in parenthesis in front of the best result indicates the run number that found the best solution. The 'Spread' shows the spread relative to the average solution. The last two columns show the relative gap between the solution and the lower bound found with the MIP-solver and the average and best found solution with the TS-algorithm. A similar figure for the R-instances is shown in appendix A. Appendix B shows the computational results for each of the 78 instances for each of the 8 parameter settings.

As can be seen the biggest spread is 6.16% for instance C30,700,400,F,L. Figure 17 shows the distribution of the spreads for each instance from the C and R data sets. The distribution shows that most spreads lie within 2% of the average solution value, and that the average spread is less than 1.5%. Considering the very different characteristics of the 78 instances the algorithm's robustness claim is strongly supported.

Figure 16 also shows that the algorithm, apart from being robust, also performs well compared to the MIP-solver. For 16 of the 24 C-instances the average solutions obtained with the TS-algorithm are better

Distribution of relative gap between TS solution values and XpressMP spolution values								
Data set	Average solution vs.XpressMP solution gap distribution							Average gap
	n/a	<[-5%]	[-5%]-[-2.5%]	[-2.5%]-[0%]	[0%]-[2.5%]	[2.5%]-[5%]	>[5%]	
C	9	1	3	3	8	0	0	-0,29%
R	2	5	1	6	20	14	6	1,40%
C+R	11	6	4	9	28	14	6	1,03%
	Best solution vs.XpressMP solution gap distribution							
	n/a	<[-5%]	[-5%]-[-2.5%]	[-2.5%]-[0%]	[0%]-[2.5%]	[2.5%]-[5%]	>[5%]	
C	9	2	3	5	5	0	0	-1,90%
R	2	7	4	11	20	7	3	-0,61%
C+R	11	9	7	16	25	7	3	-0,90%

Figure 18

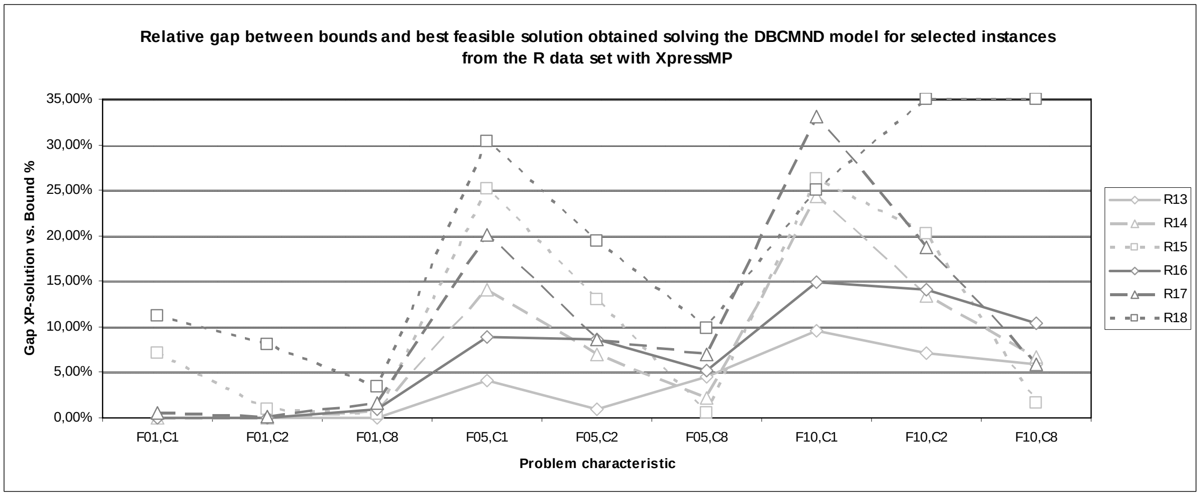

Figure 19

than the solutions obtained with the MIP-solver. For 19 of the 24 cases the best solution found is better than the MIP-solver. In 9 of cases the MIP-solver failed to find a feasible solution within the time limit, whereas the TS-algorithm in all cases managed to find a feasible solution. In appendix A it can be seen that for 14 and 23 out of 54 R instances the average solution value and the best solution value obtained with the TS algorithm respectively is better than the one found with the MIP solver. The relatively less impressive performance on the R-instances has to be compared to the fact that the selected R-instances are generally smaller than the selected C-problems and thus easier problems for the MIP-solver. For the nine R18-instances (most difficult R- instances) the algorithm outperformed the MIP-solver in 6 and 7 out of 9 cases for the average and best solution values respectively.

Figure 18 shows the distribution of the relative gap between the MIP-solver solutions and that average and best solutions obtained with the TS -algorithm. In 30 out of the 78 instances the algorithm's average solution was better than the MIP-solver's solution. In 43 out of

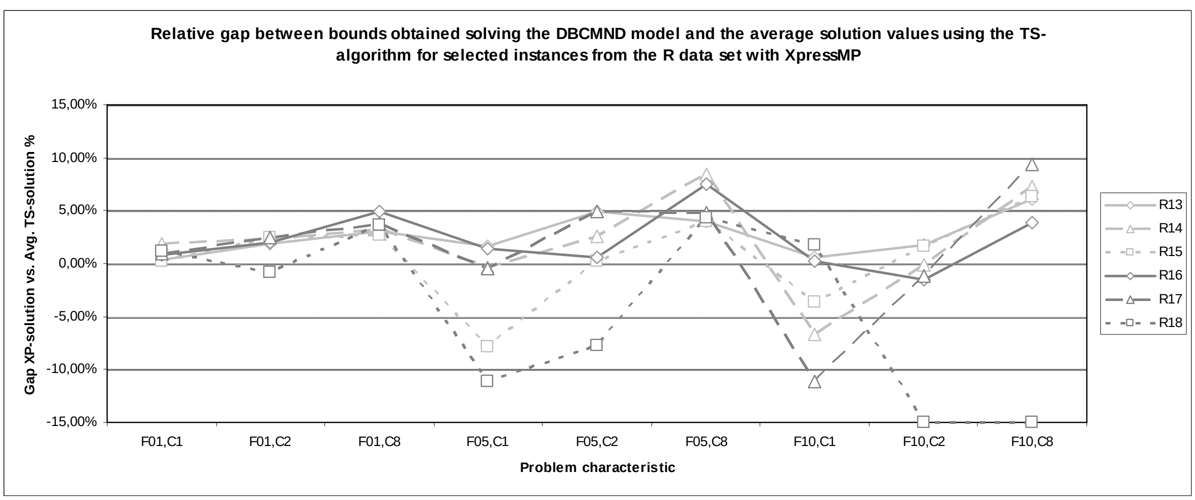

Figure 20

the 78 instances the algorithm's best solution was better than the MIP-solver's solution. The column furthest to the right shows the average gap for each of the data sets and aggregated data sets. It must be noted that the 11 instances where no gap can be calculated due to the lack of a MIP-solution do not enter in these averages. Thus the figures are based on the remaining 15 instances from the C data set and the 52 remaining instances from the R data set. Thus the average figures indicate a poorer performance of the algorithm than is the case. On average though the algorithm's average solutions are better than the MIP-solver on the C instances and only 1% worse on the C+R set. The algorithm's best solutions on average outperform the MIP-solver.

There is a slight pattern in the results indicating that networks with high fixed cost and loose capacity are the most difficult to solve for the DBCMND-formulation. Figure 19 shows a graph of the relative gaps between the best feasible solution and the lower bound obtained with the MIP-solver for each of the 6 R-instance groupings (R13-R18). For the instances where no feasible solution gaps of 35% have been assimilated. Not surprisingly the tendency is that the higher the fixed cost/variable cost ratio the larger the gap thus signifying the more difficult the instances become. Surprisingly though the gaps tend to peak for the loose capacity instances and fall the tighter capacity is, indicating that tight capacity problems are easier to solve. This tendency may be related to the design balance constraint. Even if the integrality constraints are relaxed the design balance constraints may constrain the solution space for tightly capacitated networks meaning better lower bounds are found for the LP-relaxation. To support this claim however further investigation would be required. Figure 20 shows the gap between the average TS-algorithm solution and the MIP-solver solutions for each of the 6 groups of R instances according to the problem characteristics. The tendency from figure 19 repeats itself in that lowest peaks are seen for the problems with high fixed cost and loose capacity. This indicates that the algorithm is somewhat indifferent to the problem characteristics. Considering the initial motivation from solving the DBCMND this is an important characteristic of the algorithm. When applying the DBCMND model to service scheduling problems intuitively there are a large number of possible services to select out oh which only a few are selected. Furthermore all costs of running a service are in the network representation captured in the fixed cost of arcs and the variable cost reflecting the cost from routing an amount of commodities (passengers or freight) is negligible. This means the networks for scheduling problems can be assumed to have the high fixed cost, loose capacity characteristics. Therefore the TS-algorithm seems to be the best alternative to solve the DBCMND problem applied to scheduling problems.

Candidate selection for Phase 1 local search				
	f. cost	p. cost	residual	v. cost
Run 1	33,20%	21,70%	31,80%	13,29%
Run 2	39,95%	17,98%	27,76%	14,31%
Run 3	48,25%	12,92%	24,17%	14,66%
Run 4	47,12%	15,32%	22,94%	14,62%
Run 5	30,99%	16,25%	32,03%	20,73%
Run 6	36,70%	11,39%	35,90%	16,01%
Run 7	38,84%	9,60%	31,10%	20,45%
Run 8	25,43%	8,91%	45,80%	19,86%
Average all runs	37,56%	14,26%	31,44%	16,74%

Figure 21

5.3. Analysis of algorithmic behaviour

The candidate list for the TS-algorithm is composed of candidates from the four different sub-list, whose numbers are determined by the parameters l_f, l_v, l_r, and l_p. However, the nature of these sub-lists where determined a priori and it is therefore interesting to investigate if all four sub-list contribute in the algorithm. Figure 21 shows a table with the distribution of the sub-list of origin of the selected neighbour solutions for phase 1 in the algorithm. The figures are average percentage rates for all 78 instances for each parameter setting. As can be seen from the figure, all four sub-lists contribute to the selection of best neighbour solution and therefore all are on average legitimate to use. The fixed cost candidates tend to dominate the selection which intuitively is not surprising considering the best results obtained where for the fixed cost, loose capacity instances. The figures are averages though and the sub-list selection varies greatly from instance to instance and on the parameter settings. Especially the penalty sub-list has a tendency of not providing any best neighbour solutions for some parameter settings and instances. Appendix C shows an individual selection distribution for each of the 78 instances for each parameter setting.

The four path-types described in section 4.9 are also determined a priori. We present the same selection analysis for the path selection as we did for the candidate selection in phase 1. Figure 22 shows a table with the average path selections for each of the eight parameter settings. Once again it can be seen that all paths on average are used. Thus investigating all four paths under phase 2 is reasonable. However, as for the candidate selection in phase 1, the selection in phase 2 depends largely on the individual instances. Thus, depending on the instance some computational resources are spent on non-contributing computations.

Path selection for Phase 2 local search				
	f. cost	p. cost	residual	v. cost
Run 1	58,03%	12,16%	15,26%	14,55%
Run 2	57,47%	12,16%	14,15%	16,22%
Run 3	58,22%	11,63%	14,64%	15,51%
Run 4	58,52%	11,88%	13,86%	15,74%
Run 5	59,81%	11,48%	13,71%	15,00%
Run 6	55,72%	12,28%	14,31%	17,70%
Run 7	57,99%	12,95%	11,95%	17,11%
Run 8	53,87%	14,48%	12,04%	19,61%
Average all runs	57,45%	12,38%	13,74%	16,43%

Figure 22

We also investigate the interaction between phases 1 and 2. Figure 23 shows the development of the solution value for instance C20,200,300,F,L using

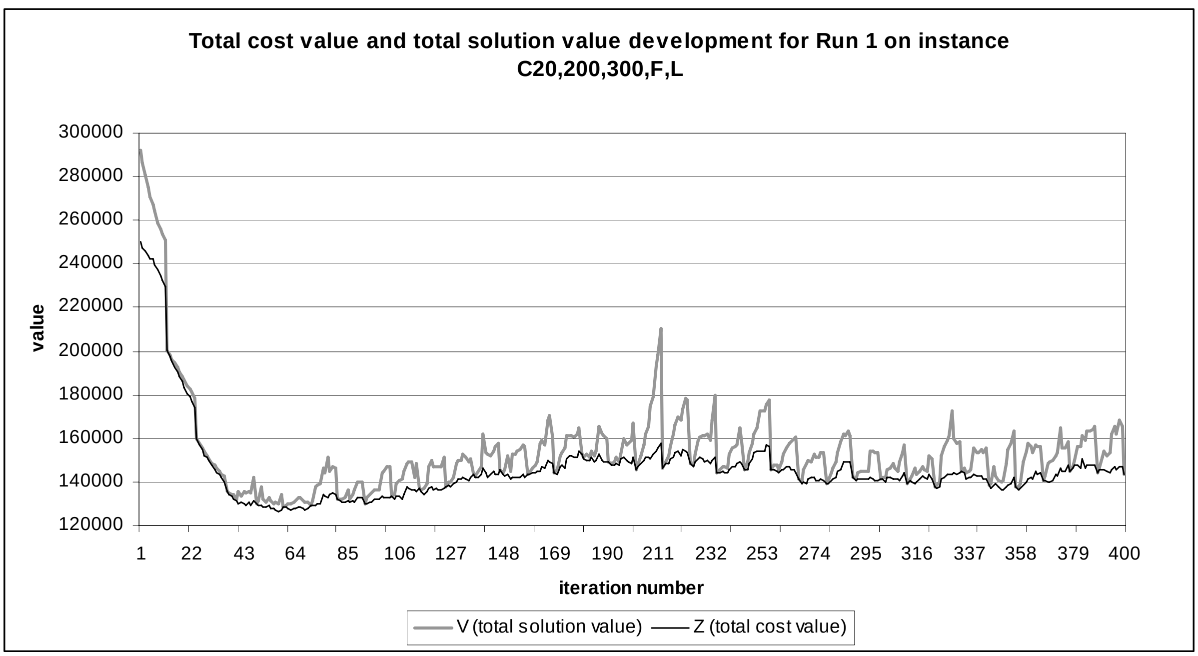

Figure 23

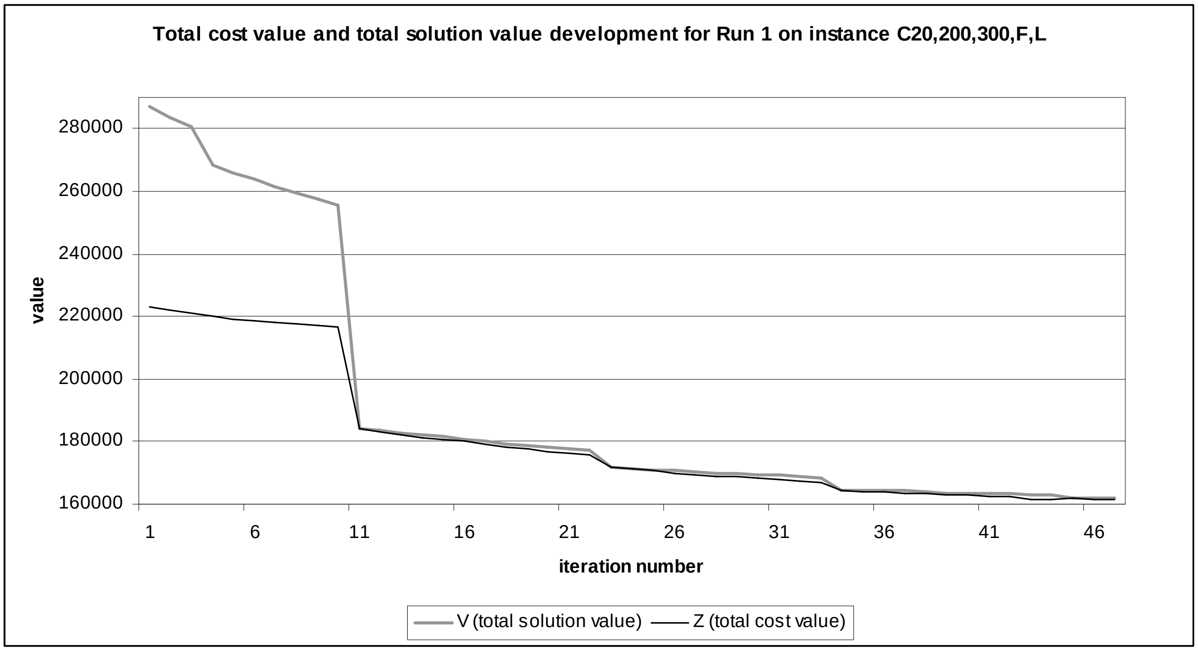

Figure 24

parameter setting 1. The two curves represent the development in the solution cost and the solution value (solution cost + penalty value) over the iterations in phase 1. The initial solution r-DBCMND and rounding heuristic yields a solution with high cost and penalty values. The algorithm starts off with phase 1 for eleven iterations. Although the improvements are significant the improvement gap is set to 5% and the iteration range to 10, thus iterations phase 2 sets in after the eleven iterations. Every ten iterations Phase 2 sets in which can be seen as the points where the two curves meet (penalty value=0). An interesting development is that the best solution is found after 55 iterations with phase 1 and 5 initiations of phase 2. For the remaining time the search oscillates above the best found solution. This could signify that the algorithm for this particular instance produces near-optimal solutions. However, this hypothesis is a subjective interpretation. For the most complex instances the search is stopped before the improvement in feasible solutions smoothes out. Figure 24 shows the development of the solution value for instance C30,520,400,F,T. The drops in the curves show where phase 2 was initiated. The solution value improves for every phase 2 initiation but the search is stopped when the time limit is reached indicating that further improvements may be achieved. The few iterations performed for this instance indicates that phase 2, where several CMCF problems are solved, is very computationally demanding. For example between 500 and 1000 seconds where used for the C30,520,400,F,T instance per initiation of phase 2 depending on the level of imbalance. This raises the question of whether an alternative evaluation method should be applied for phase 2 or if fewer paths should be investigated (i.e. fewer CMCF problems solved).

6. Conclusion and Future research

In this paper we proposed an extension to the fixed-charge capacitated multi-commodity network design model, where a set of design balance constraints have been added, resulting in what we denoted the design balanced capacitated multi-commodity network design model (DBCMND). The design balance constraints impose a restriction on the arc selection by requiring an equal number of selected arcs entering and leaving each node in the network. The motivation behind the DBCMND formulation arises from transportation service scheduling. Interpreting nodes in a network as terminals with a time period associated to them, the arcs can be interpreted as possible services to offer between terminals where the temporal dimension is captured by the time associated to the nodes they connect. Assuming each service is operated by a vehicle, the number of vehicles arriving at a terminal is equal to the number of services arriving. To maintain vehicle conservation all vehicles that enter a node must also leave it again given the time period associated to it. This attribute is what lead to the addition of the design balance constraints.

Network design models are generally hard to solve. Adding the design balance constraints interconnects the binary decision variables possibly making them even harder. We propose a tabu search heuristic framework to solve the DBCMND. The algorithm is based on two local search phases. The first phase is based on a hybrid of a simple add/drop procedure and cycle based neighbourhoods. The phase searches a neighbourhood of infeasible solutions. The second phase is added to explicitly search for feasible solutions. It connects nodes where the design balance are not obeyed by paths of arcs. Computational results show that the interaction between these two local phases performed well on the 78 generated network design instances. Comparing the results obtained with the algorithm to the MIP-solver of the Xpress-MP optimization package showed that the algorithm performed better for the largest selected network instances. For the very largest instances where the MIP-solver did not find a solution within a 3600s time limit the algorithm managed to find feasible solutions in all cases within the same time limit. The low spread of the results for different parameter settings and network instances with varying network characteristics supports evidence that the algorithm is robust with respect to both parameter settings and network characteristics.

Although the algorithm performed well alternative candidate arcs for phase 1 and candidate paths for phase 2 could be considered. It would be interesting to investigate relation between the candidate selection and the network characteristics. If some relation can be found, the information can be used prior to during running the algorithm and dynamically adjust the number of sub-list candidates in the candidate lists.

Furthermore there is still no guarantee that feasible solutions are found for any network instance. Especially for sparse networks, where the initial solution obtained by relaxing the integrality constraints and using a rounding heuristic results in a high network imbalance, the algorithm may fail in producing feasible solutions. We envision several ways to address this problem. First, alternative neighbourhoods for the local search phases could be adopted. E.g. the 2-phased approach could be replaced by a single local search phase moving between feasible solutions. This could be achieved by considering the cycle-based variables instead of the arc based ones. The difficulty in adopting this approach of more complex neighbourhood moves is the estimation of potential neighbour solutions without having to solve the CMCF problem. Second, a third local search phase could be implemented for particularly imbalances instances. The problem encountered in phase 2 was the inability to find paths of arcs eliminating the imbalanced nodes. A potential 3^{rd} phase could, instead of using neighbourhood moves with full paths, use partial paths. This approach would shuffle the imbalance in the network until eventually a feasible solution can be found using phase 2. Adopting a phase 3 could also limit the computational requirements for phase 2, and thus speeding up the search process. Considering the computational results achieved combined with the potential areas of further investigation described above we believe the tabu search heuristic framework presented proves to be an apt approach to solve DBCMND problems.

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Appendix A – Computational results for selected instances

Computational Results (3600s.) selected R-problems (1)									
Instances	**nodes**	**arcs**	**com.**	**Opt (time)**	**Bound**	**Avg TS Best TS**	**Spread**	**Avg Gap Bound Best Gap Bound**	**Avg Gap Opt Best Gap Opt**
R13,F01,C1	20	220	40	147.349 1	147.349	147.797 147.349	0,23%	0,30% 0,00%	0,30% 0,00%
R13,F05,C1	20	220	40	281.283 (t)	269.793	285.965 281.668	1,19%	5,64% 4,22%	1,63% 0,14%
R13,F10,C1	20	220	40	404.045 (t)	365.588	406.589 400.656	1,00%	10,08% 8,75%	0,62% -0,85%
R13,F01,C2	20	220	40	155.887 56	155.887	158.862 156.585	0,84%	1,87% 0,45%	1,87% 0,45%
R13,F05,C2	20	220	40	295.180 (t)	292.249	310.459 304.672	1,25%	5,85% 4,08%	4,91% 3,12%
R13,F10,C2	20	220	40	443.831 (t)	411.984	451.818 437.396	2,76%	8,76% 5,81%	1,70% -1,47%
R13,F01,C8	20	220	40	218.787 2.935	218.787	225.545 223.541	0,62%	2,99% 2,13%	2,99% 2,13%
R13,F05,C8	20	220	40	502.811 (t)	480.366	524.068 510.887	1,73%	8,31% 5,97%	4,03% 1,58%
R13,F10,C8	20	220	40	812.606 (t)	764.751	866.442 823.314	2,93%	11,67% 7,11%	6,14% 1,30%
R14,F01,C1	20	220	100	422.709 855	422.709	430.837 427.872	0,55%	1,88% 1,21%	1,88% 1,21%
R14,F05,C1	20	220	100	835.597 (t)	717.432	832.516 811.102	1,54%	13,81% 11,55%	-0,39% -3,02%
R14,F10,C1	20	220	100	1.259.890 (t)	954.048	1.181.860 1.157.500	1,63%	19,26% 17,58%	-6,63% -8,85%
R14,F01,C2	20	220	100	452.591 498	452.591	463.445 458.240	0,66%	2,34% 1,23%	2,34% 1,23%
R14,F05,C2	20	220	100	912.189 (t)	848.873	936.969 917.832	1,49%	9,38% 7,51%	2,63% 0,61%
R14,F10,C2	20	220	100	1.397.100 (t)	1.210.230	1.395.741 1.356.910	1,94%	13,26% 10,81%	-0,13% -2,96%
R14,F01,C8	20	220	100	704.719 (t)	699.947	729.123 720.494	0,99%	3,99% 2,85%	3,34% 2,19%
R14,F05,C8	20	220	100	1.696.780 (t)	1.659.720	1.853.000 1.795.650	2,31%	10,39% 7,57%	8,39% 5,51%
R14,F10,C8	20	220	100	2.874.660 (t)	2.681.490	3.100.885 2.997.290	2,35%	13,48% 10,54%	7,25% 4,09%
R15,F01,C1	20	220	200	1.042.790 (t)	969.165	1.044.935 1.032.640	0,89%	7,24% 6,15%	0,20% -0,98%
R15,F05,C1	20	220	200	2.297.560 (t)	1.718.650	2.130.235 2.082.990	1,25%	19,31% 17,49%	-7,87% -10,30%
R15,F10,C1	20	220	200	3.304.180 (t)	2.436.030	3.188.733 3.116.770	1,25%	23,59% 21,84%	-3,63% -6,01%
R15,F01,C2	20	220	200	1.176.860 (t)	1.164.850	1.206.376 1.191.440	0,74%	3,44% 2,23%	2,44% 1,22%
R15,F05,C2	20	220	200	2.723.740 (t)	2.368.130	2.731.536 2.698.680	1,02%	13,30% 12,25%	0,28% -0,93%
R15,F10,C2	20	220	200	4.349.910 (t)	3.467.490	4.421.580 4.310.340	1,64%	21,56% 19,55%	1,60% -0,92%
R15,F01,C8	20	220	200	2.402.800 (t)	2.392.650	2.469.571 2.441.630	0,59%	3,11% 2,01%	2,70% 1,59%
R15,F05,C8	20	220	200	5.807.050 (t)	5.774.260	6.045.045 5.969.370	1,12%	4,47% 3,27%	3,93% 2,72%
R15,F10,C8	20	220	200	9.169.890 (t)	9.025.170	9.805.603 9.304.650	4,16%	7,82% 3,00%	6,34% 1,45%

Computational Results (3600s.) selected R-problems (2)

Instances	nodes	arcs	com.	Opt (time)	Bound	Avg TS Best TS	Spread	Avg Gap Bound Best Gap Bound	Avg Gap Opt Best Gap Opt
R16,F01,C1	20	314	40	140.082 15	140.082	141.233 140.149	0,71%	0,81% 0,05%	0,81% 0,05%
R16,F05,C1	20	314	40	259.840 (t)	236.810	263.457 261.503	0,89%	10,11% 9,44%	1,37% 0,64%
R16,F10,C1	20	314	40	364.786 (t)	310.584	365.568 358.550	1,55%	15,02% 13,38%	0,19% -1,74%
R16,F01,C2	20	314	40	142.381 101	142.381	145.354 143.921	0,80%	2,04% 1,07%	2,04% 1,07%
R16,F05,C2	20	314	40	275.626 (t)	251.711	277.158 273.024	1,05%	9,17% 7,81%	0,54% -0,95%
R16,F10,C2	20	314	40	396.966 (t)	341.107	391.089 375.041	2,04%	12,75% 9,05%	-1,54% -5,85%
R16,F01,C8	20	314	40	180.199 (t)	178.497	189.646 185.397	1,57%	5,86% 3,72%	4,96% 2,80%
R16,F05,C8	20	314	40	396.721 (t)	376.351	428.840 419.945	1,62%	12,22% 10,38%	7,47% 5,53%
R16,F10,C8	20	314	40	637.944 (t)	571.578	663.428 647.212	1,92%	13,82% 11,69%	3,81% 1,43%
R17,F01,C1	20	318	100	364.784 (t)	362.602	368.401 365.913	0,72%	1,57% 0,90%	0,98% 0,31%
R17,F05,C1	20	318	100	730.195 (t)	583.094	727.378 702.957	2,85%	19,78% 17,05%	-0,46% -3,87%
R17,F10,C1	20	318	100	1.150.630 (t)	769.660	1.035.443 1.002.660	1,67%	25,65% 23,24%	-11,15% -14,76%
R17,F01,C2	20	318	100	382.593 (t)	382.315	392.178 389.249	0,50%	2,51% 1,78%	2,44% 1,71%
R17,F05,C2	20	318	100	761.041 (t)	695.446	800.201 786.198	1,04%	13,08% 11,54%	4,88% 3,20%
R17,F10,C2	20	318	100	1.195.710 (t)	971.426	1.181.778 1.159.440	1,90%	17,77% 16,22%	-1,21% -3,13%
R17,F01,C8	20	318	100	531.791 (t)	523.185	552.346 539.817	1,49%	5,26% 3,08%	3,70% 1,49%
R17,F05,C8	20	318	100	1.284.720 (t)	1.195.670	1.349.095 1.323.330	1,01%	11,36% 9,65%	4,76% 2,92%
R17,F10,C8	20	318	100	2.047.390 (t)	1.927.200	2.259.330 2.207.590	2,03%	14,67% 12,70%	9,35% 7,26%
R18,F01,C1	20	315	200	869.263 (t)	772.151	880.082 864.425	0,77%	12,26% 10,67%	1,22% -0,56%
R18,F05,C1	20	315	200	1.869.230 (t)	1.302.720	1.682.318 1.627.700	2,20%	22,53% 19,97%	-11,16% -14,84%
R18,F10,C1	20	315	200	2.390.740 (t)	1.793.780	2.435.599 2.366.280	2,80%	26,30% 24,19%	1,78% -1,03%
R18,F01,C2	20	315	200	980.178 (t)	900.627	972.295 962.402	0,79%	7,37% 6,42%	-0,82% -1,85%
R18,F05,C2	20	315	200	2.146.670 (t)	1.730.640	1.992.019 1.958.160	1,58%	13,10% 11,62%	-7,79% -9,63%
R18,F10,C2	20	315	200	n/a (t)	2.478.890	3.017.943 2.986.000	0,83%	17,86% 16,98%	n/a n/a
R18,F01,C8	20	315	200	1.560.790 (t)	1.507.840	1.618.999 1.608.600	0,41%	6,86% 6,26%	3,59% 2,97%
R18,F05,C8	20	315	200	4.230.970 (t)	3.817.170	4.425.091 4.268.580	2,38%	13,70% 10,58%	4,34% 0,88%
R18,F10,C8	20	315	200	n/a (t)	6.180.620	7.666.431 7.194.120	4,05%	19,27% 14,09%	n/a n/a

Appendix B – Computational results on instances for each parameter setting

Computational results for paramter setting 1									
Data set	**nodes**	**arcs**	**com.**	**Opt.**	**Bound**	**TS sol**	**TS Time**	**Gap Bound**	**Gap Opt.**
C20,230,200,V,L	20	228	200	101112	86180	102919	468	16,26%	1,76%
C20,230,200,F,L	20	230	200	153534	122311	150764	507	18,87%	-1,84%
C20,230,200,V,T	20	229	200	105840	92608	103371	80	10,41%	-2,39%
C20,230,200,F,T	20	228	200	154026	124358	149942	1817	17,06%	-2,72%
C20,300,200,V,L	20	294	200	81184	73894	82533	228	10,47%	1,63%
C20,300,200,F,L	20	292	200	131876	110533	128757	180	14,15%	-2,42%
C20,300,200,V,T	20	291	200	78675	74583	78571	2014	5,08%	-0,13%
C20,300,200,F,T	20	291	200	127412	106628	116338	3079	8,35%	-9,52%
C30,520,100,V,L	30	518	100	55138	54160	55981	23	3,25%	1,51%
C30,520,100,F,L	30	516	100	n/a	92636	104533	156	11,38%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54493	3141	3,33%	2,51%
C30,520,100,F,T	30	517	100	106761	97653	105167	2927	7,14%	-1,52%
C30,520,400,V,L	30	520	400	n/a	111054	119735	3029	7,25%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	162360	3106	11,72%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	120421	3064	4,73%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	161978	3569	8,50%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49429	64	2,08%	1,17%
C30,700,100,F,L	30	680	100	65516	59483	63889	52	6,90%	-2,55%
C30,700,100,V,T	30	687	100	47052	46260	48202	83	4,03%	2,39%
C30,700,100,F,T	30	686	100	57447	55123	58204	147	5,29%	1,30%
C30,700,400,V,L	30	685	400	n/a	94725	103932	3213	8,86%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	157043	3510	17,89%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103085	3067	7,67%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	141917	2807	9,50%	n/a
R13,F01,C1	20	220	40	147349	147349	147837	3037	0,33%	0,33%
R13,F05,C1	20	220	40	281283	269793	281668	1074	4,22%	0,14%
R13,F10,C1	20	220	40	404045	365588	404434	1714	9,61%	0,10%
R13,F01,C2	20	220	40	155887	155887	159852	1088	2,48%	2,48%
R13,F05,C2	20	220	40	295180	292249	311209	2837	6,09%	5,15%
R13,F10,C2	20	220	40	443831	411984	470034	941	12,35%	5,57%
R13,F01,C8	20	220	40	218787	218787	225339	440	2,91%	2,91%
R13,F05,C8	20	220	40	502811	480366	512027	4	6,18%	1,80%
R13,F10,C8	20	220	40	812606	764751	875984	540	12,70%	7,24%
R14,F01,C1	20	220	100	422709	422709	431562	2513	2,05%	2,05%
R14,F05,C1	20	220	100	835597	717432	811102	20	11,55%	-3,02%
R14,F10,C1	20	220	100	1259890	954048	1193950	11	20,09%	-5,52%
R14,F01,C2	20	220	100	452591	452591	465762	2972	2,83%	2,83%
R14,F05,C2	20	220	100	912189	848873	942678	13	9,95%	3,23%
R14,F10,C2	20	220	100	1397100	1210230	1401880	59	13,67%	0,34%
R14,F01,C8	20	220	100	704719	699947	720882	17	2,90%	2,24%
R14,F05,C8	20	220	100	1696780	1659720	1795650	192	7,57%	5,51%
R14,F10,C8	20	220	100	2874660	2681490	2997290	50	10,54%	4,09%
R15,F01,C1	20	220	200	1042790	969165	1039440	36	6,76%	-0,32%
R15,F05,C1	20	220	200	2297560	1718650	2170310	207	20,81%	-5,86%
R15,F10,C1	20	220	200	3304180	2436030	3194270	107	23,74%	-3,44%
R15,F01,C2	20	220	200	1176860	1164850	1205790	1099	3,40%	2,40%
R15,F05,C2	20	220	200	2723740	2368130	2698680	335	12,25%	-0,93%
R15,F10,C2	20	220	200	4349910	3467490	4447950	265	22,04%	2,20%
R15,F01,C8	20	220	200	2402800	2392650	2472860	641	3,24%	2,83%
R15,F05,C8	20	220	200	5807050	5774260	6067350	456	4,83%	4,29%
R15,F10,C8	20	220	200	9169890	9025170	10263600	361	12,07%	10,66%
R16,F01,C1	20	314	40	140082	140082	142692	2178	1,83%	1,83%
R16,F05,C1	20	314	40	259840	236810	261775	2407	9,54%	0,74%
R16,F10,C1	20	314	40	364786	310584	374819	11	17,14%	2,68%
R16,F01,C2	20	314	40	142381	142381	145266	3110	1,99%	1,99%
R16,F05,C2	20	314	40	275626	251711	277307	13	9,23%	0,61%
R16,F10,C2	20	314	40	396966	341107	391386	2778	12,85%	-1,43%
R16,F01,C8	20	314	40	180199	178497	187176	20	4,64%	3,73%
R16,F05,C8	20	314	40	396721	376351	423320	13	11,10%	6,28%
R16,F10,C8	20	314	40	637944	571578	649121	40	11,95%	1,72%
R17,F01,C1	20	318	100	364784	362602	374016	25	3,05%	2,47%
R17,F05,C1	20	318	100	730195	583094	718135	17	18,80%	-1,68%
R17,F10,C1	20	318	100	1150630	769660	1041450	11	26,10%	-10,48%
R17,F01,C2	20	318	100	382593	382315	393608	15	2,87%	2,80%
R17,F05,C2	20	318	100	761041	695446	786198	27	11,54%	3,20%
R17,F10,C2	20	318	100	1195710	971426	1162290	83	16,42%	-2,88%
R17,F01,C8	20	318	100	531791	523185	539817	114	3,08%	1,49%
R17,F05,C8	20	318	100	1284720	1195670	1348750	93	11,35%	4,75%
R17,F10,C8	20	318	100	2047390	1927200	2227780	72	13,49%	8,10%
R18,F01,C1	20	315	200	869263	772151	864425	42	10,67%	-0,56%
R18,F05,C1	20	315	200	1869230	1302720	1640200	2514	20,58%	-13,96%
R18,F10,C1	20	315	200	2390740	1793780	2399230	53	25,24%	0,35%
R18,F01,C2	20	315	200	980178	900627	962402	196	6,42%	-1,85%
R18,F05,C2	20	315	200	2146670	1730640	1958160	223	11,62%	-9,63%
R18,F10,C2	20	315	200	n/a	2478890	2986000	172	16,98%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1617320	368	6,77%	3,50%
R18,F05,C8	20	315	200	4230970	3817170	4268580	719	10,58%	0,88%
R18,F10,C8	20	315	200	n/a	6180620	7440780	390	16,94%	n/a

Computational results for paramter setting 2									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	103190	400	16,48%	2,01%
C20,230,200,F,L	20	230	200	153534	122311	151973	2785	19,52%	-1,03%
C20,230,200,V,T	20	229	200	105840	92608	105312	989	12,06%	-0,50%
C20,230,200,F,T	20	228	200	154026	124358	148180	163	16,08%	-3,95%
C20,300,200,V,L	20	294	200	81184	73894	80368	278	8,06%	-1,01%
C20,300,200,F,L	20	292	200	131876	110533	127909	109	13,58%	-3,10%
C20,300,200,V,T	20	291	200	78675	74583	80519	452	7,37%	2,29%
C20,300,200,F,T	20	291	200	127412	106628	118632	157	10,12%	-7,40%
C30,520,100,V,L	30	518	100	55138	54160	56653	805	4,40%	2,67%
C30,520,100,F,L	30	516	100	n/a	92636	101612	2491	8,83%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54368	1232	3,10%	2,29%
C30,520,100,F,T	30	517	100	106761	97653	106503	1421	8,31%	-0,24%
C30,520,400,V,L	30	520	400	n/a	111054	119615	3432	7,16%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	163436	3520	12,30%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	122482	2173	6,33%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	165395	2604	10,39%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49797	130	2,81%	1,90%
C30,700,100,F,L	30	680	100	65516	59483	64130	179	7,25%	-2,16%
C30,700,100,V,T	30	687	100	47052	46260	48017	74	3,66%	2,01%
C30,700,100,F,T	30	686	100	57447	55123	58691	450	6,08%	2,12%
C30,700,400,V,L	30	685	400	n/a	94725	105261	2355	10,01%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	176720	3073	27,03%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	104727	2832	9,11%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	141735	3509	9,38%	n/a
R13,F01,C1	20	220	40	147349	147349	147349	1634	0,00%	0,00%
R13,F05,C1	20	220	40	281283	269793	288773	737	6,57%	2,59%
R13,F10,C1	20	220	40	404045	365588	406813	1134	10,13%	0,68%
R13,F01,C2	20	220	40	155887	155887	159791	2534	2,44%	2,44%
R13,F05,C2	20	220	40	295180	292249	311338	2071	6,13%	5,19%
R13,F10,C2	20	220	40	443831	411984	466235	9	11,64%	4,81%
R13,F01,C8	20	220	40	218787	218787	223816	2138	2,25%	2,25%
R13,F05,C8	20	220	40	502811	480366	522598	245	8,08%	3,79%
R13,F10,C8	20	220	40	812606	764751	839174	20	8,87%	3,17%
R14,F01,C1	20	220	100	422709	422709	429785	1803	1,65%	1,65%
R14,F05,C1	20	220	100	835597	717432	840330	3015	14,62%	0,56%
R14,F10,C1	20	220	100	1259890	954048	1210970	117	21,22%	-4,04%
R14,F01,C2	20	220	100	452591	452591	465997	1638	2,88%	2,88%
R14,F05,C2	20	220	100	912189	848873	948150	101	10,47%	3,79%
R14,F10,C2	20	220	100	1397100	1210230	1389470	3575	12,90%	-0,55%
R14,F01,C8	20	220	100	704719	699947	720494	62	2,85%	2,19%
R14,F05,C8	20	220	100	1696780	1659720	1838210	32	9,71%	7,69%
R14,F10,C8	20	220	100	2874660	2681490	3128040	2069	14,28%	8,10%
R15,F01,C1	20	220	200	1042790	969165	1053500	39	8,01%	1,02%
R15,F05,C1	20	220	200	2297560	1718650	2110140	48	18,55%	-8,88%
R15,F10,C1	20	220	200	3304180	2436030	3219500	55	24,34%	-2,63%
R15,F01,C2	20	220	200	1176860	1164850	1191440	201	2,23%	1,22%
R15,F05,C2	20	220	200	2723740	2368130	2698750	424	12,25%	-0,93%
R15,F10,C2	20	220	200	4349910	3467490	4310340	3082	19,55%	-0,92%
R15,F01,C8	20	220	200	2402800	2392650	2468420	3288	3,07%	2,66%
R15,F05,C8	20	220	200	5807050	5774260	5969370	736	3,27%	2,72%
R15,F10,C8	20	220	200	9169890	9025170	9318770	457	3,15%	1,60%
R16,F01,C1	20	314	40	140082	140082	140149	1991	0,05%	0,05%
R16,F05,C1	20	314	40	259840	236810	264930	2354	10,61%	1,92%
R16,F10,C1	20	314	40	364786	310584	360884	702	13,94%	-1,08%
R16,F01,C2	20	314	40	142381	142381	145029	3	1,83%	1,83%
R16,F05,C2	20	314	40	275626	251711	273024	7	7,81%	-0,95%
R16,F10,C2	20	314	40	396966	341107	394252	17	13,48%	-0,69%
R16,F01,C8	20	314	40	180199	178497	187858	3587	4,98%	4,08%
R16,F05,C8	20	314	40	396721	376351	419945	611	10,38%	5,53%
R16,F10,C8	20	314	40	637944	571578	647212	2929	11,69%	1,43%
R17,F01,C1	20	318	100	364784	362602	367117	156	1,23%	0,64%
R17,F05,C1	20	318	100	730195	583094	734129	11	20,57%	0,54%
R17,F10,C1	20	318	100	1150630	769660	1044530	29	26,32%	-10,16%
R17,F01,C2	20	318	100	382593	382315	393077	30	2,74%	2,67%
R17,F05,C2	20	318	100	761041	695446	792427	44	12,24%	3,96%
R17,F10,C2	20	318	100	1195710	971426	1159440	44	16,22%	-3,13%
R17,F01,C8	20	318	100	531791	523185	551127	50	5,07%	3,51%
R17,F05,C8	20	318	100	1284720	1195670	1338930	3210	10,70%	4,05%
R17,F10,C8	20	318	100	2047390	1927200	2207590	165	12,70%	7,26%
R18,F01,C1	20	315	200	869263	772151	878574	1587	12,11%	1,06%
R18,F05,C1	20	315	200	1869230	1302720	1668160	171	21,91%	-12,05%
R18,F10,C1	20	315	200	2390740	1793780	2446350	57	26,68%	2,27%
R18,F01,C2	20	315	200	980178	900627	974067	34	7,54%	-0,63%
R18,F05,C2	20	315	200	2146670	1730640	1977190	89	12,47%	-8,57%
R18,F10,C2	20	315	200	n/a	2478890	3004980	820	17,51%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1621030	651	6,98%	3,72%
R18,F05,C8	20	315	200	4230970	3817170	4389030	391	13,03%	3,60%
R18,F10,C8	20	315	200	n/a	6180620	8212610	581	24,74%	n/a

Computational results for paramter setting 3									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	104863	1882	17,82%	3,58%
C20,230,200,F,L	20	230	200	153534	122311	150367	65	18,66%	-2,11%
C20,230,200,V,T	20	229	200	105840	92608	108868	92	14,94%	2,78%
C20,230,200,F,T	20	228	200	154026	124358	148173	1420	16,07%	-3,95%
C20,300,200,V,L	20	294	200	81184	73894	82144	755	10,04%	1,17%
C20,300,200,F,L	20	292	200	131876	110533	126782	47	12,82%	-4,02%
C20,300,200,V,T	20	291	200	78675	74583	82101	49	9,16%	4,17%
C20,300,200,F,T	20	291	200	127412	106628	123406	241	13,60%	-3,25%
C30,520,100,V,L	30	518	100	55138	54160	56974	103	4,94%	3,22%
C30,520,100,F,L	30	516	100	n/a	92636	104476	564	11,33%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54570	2160	3,46%	2,65%
C30,520,100,F,T	30	517	100	106761	97653	106157	3349	8,01%	-0,57%
C30,520,400,V,L	30	520	400	n/a	111054	118656	3233	6,41%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	161274	2253	11,12%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	121376	2179	5,48%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	166028	2769	10,73%	n/a
C30,700,100,V,L	30	680	100	48849	48400	50533	38	4,22%	3,33%
C30,700,100,F,L	30	680	100	65516	59483	65091	47	8,62%	-0,65%
C30,700,100,V,T	30	687	100	47052	46260	48344	102	4,31%	2,67%
C30,700,100,F,T	30	686	100	57447	55123	59389	148	7,18%	3,27%
C30,700,400,V,L	30	685	400	n/a	94725	106424	693	10,99%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	159991	1871	19,40%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103693	3022	8,21%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	140424	2596	8,53%	n/a
R13,F01,C1	20	220	40	147349	147349	148415	2833	0,72%	0,72%
R13,F05,C1	20	220	40	281283	269793	291843	1776	7,56%	3,62%
R13,F10,C1	20	220	40	404045	365588	414616	1494	11,82%	2,55%
R13,F01,C2	20	220	40	155887	155887	160478	1364	2,86%	2,86%
R13,F05,C2	20	220	40	295180	292249	304672	2191	4,08%	3,12%
R13,F10,C2	20	220	40	443831	411984	449258	1286	8,30%	1,21%
R13,F01,C8	20	220	40	218787	218787	227697	1967	3,91%	3,91%
R13,F05,C8	20	220	40	502811	480366	534706	19	10,16%	5,96%
R13,F10,C8	20	220	40	812606	764751	883946	3	13,48%	8,07%
R14,F01,C1	20	220	100	422709	422709	434311	644	2,67%	2,67%
R14,F05,C1	20	220	100	835597	717432	853315	2809	15,92%	2,08%
R14,F10,C1	20	220	100	1259890	954048	1199730	3009	20,48%	-5,01%
R14,F01,C2	20	220	100	452591	452591	461998	3080	2,04%	2,04%
R14,F05,C2	20	220	100	912189	848873	932506	33	8,97%	2,18%
R14,F10,C2	20	220	100	1397100	1210230	1413910	2579	14,41%	1,19%
R14,F01,C8	20	220	100	704719	699947	740421	17	5,47%	4,82%
R14,F05,C8	20	220	100	1696780	1659720	1929690	46	13,99%	12,07%
R14,F10,C8	20	220	100	2874660	2681490	3146390	100	14,78%	8,64%
R15,F01,C1	20	220	200	1042790	969165	1053830	185	8,03%	1,05%
R15,F05,C1	20	220	200	2297560	1718650	2144620	1390	19,86%	-7,13%
R15,F10,C1	20	220	200	3304180	2436030	3239740	582	24,81%	-1,99%
R15,F01,C2	20	220	200	1176860	1164850	1219400	120	4,47%	3,49%
R15,F05,C2	20	220	200	2723740	2368130	2768280	1092	14,45%	1,61%
R15,F10,C2	20	220	200	4349910	3467490	4556610	1466	23,90%	4,54%
R15,F01,C8	20	220	200	2402800	2392650	2441630	1201	2,01%	1,59%
R15,F05,C8	20	220	200	5807050	5774260	6121440	1040	5,67%	5,14%
R15,F10,C8	20	220	200	9169890	9025170	9469220	735	4,69%	3,16%
R16,F01,C1	20	314	40	140082	140082	140526	1027	0,32%	0,32%
R16,F05,C1	20	314	40	259840	236810	262899	2786	9,92%	1,16%
R16,F10,C1	20	314	40	364786	310584	366735	1108	15,31%	0,53%
R16,F01,C2	20	314	40	142381	142381	145852	315	2,38%	2,38%
R16,F05,C2	20	314	40	275626	251711	278745	2573	9,70%	1,12%
R16,F10,C2	20	314	40	396966	341107	402460	526	15,24%	1,37%
R16,F01,C8	20	314	40	180199	178497	189815	2177	5,96%	5,07%
R16,F05,C8	20	314	40	396721	376351	433189	4	13,12%	8,42%
R16,F10,C8	20	314	40	637944	571578	676461	6	15,50%	5,69%
R17,F01,C1	20	318	100	364784	362602	369255	938	1,80%	1,21%
R17,F05,C1	20	318	100	730195	583094	768602	1037	24,14%	5,00%
R17,F10,C1	20	318	100	1150630	769660	1062300	15	27,55%	-8,31%
R17,F01,C2	20	318	100	382593	382315	394748	2055	3,15%	3,08%
R17,F05,C2	20	318	100	761041	695446	801708	34	13,25%	5,07%
R17,F10,C2	20	318	100	1195710	971426	1228630	45	20,93%	2,68%
R17,F01,C8	20	318	100	531791	523185	566267	2851	7,61%	6,09%
R17,F05,C8	20	318	100	1284720	1195670	1366370	91	12,49%	5,98%
R17,F10,C8	20	318	100	2047390	1927200	2291750	2701	15,91%	10,66%
R18,F01,C1	20	315	200	869263	772151	880241	876	12,28%	1,25%
R18,F05,C1	20	315	200	1869230	1302720	1745410	3171	25,36%	-7,09%
R18,F10,C1	20	315	200	2390740	1793780	2513120	1236	28,62%	4,87%
R18,F01,C2	20	315	200	980178	900627	981885	174	8,28%	0,17%
R18,F05,C2	20	315	200	2146670	1730640	1981420	36	12,66%	-8,34%
R18,F10,C2	20	315	200	n/a	2478890	3032070	246	18,24%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1624740	671	7,19%	3,94%
R18,F05,C8	20	315	200	4230970	3817170	4479780	321	14,79%	5,55%
R18,F10,C8	20	315	200	n/a	6180620	7891480	513	21,68%	n/a

Computational results for paramter setting 4									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	104966	1813	17,90%	3,67%
C20,230,200,F,L	20	230	200	153534	122311	153990	1693	20,57%	0,30%
C20,230,200,V,T	20	229	200	105840	92608	107728	3069	14,04%	1,75%
C20,230,200,F,T	20	228	200	154026	124358	144766	154	14,10%	-6,40%
C20,300,200,V,L	20	294	200	81184	73894	81354	211	9,17%	0,21%
C20,300,200,F,L	20	292	200	131876	110533	130733	84	15,45%	-0,87%
C20,300,200,V,T	20	291	200	78675	74583	80215	145	7,02%	1,92%
C20,300,200,F,T	20	291	200	127412	106628	118689	460	10,16%	-7,35%
C30,520,100,V,L	30	518	100	55138	54160	56413	1558	3,99%	2,26%
C30,520,100,F,L	30	516	100	n/a	92636	104099	104	11,01%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54176	2636	2,76%	1,94%
C30,520,100,F,T	30	517	100	106761	97653	108008	3593	9,59%	1,15%
C30,520,400,V,L	30	520	400	n/a	111054	121420	3069	8,54%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	165951	2141	13,63%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	120527	3394	4,81%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	166434	3478	10,95%	n/a
C30,700,100,V,L	30	680	100	48849	48400	50047	1371	3,29%	2,39%
C30,700,100,F,L	30	680	100	65516	59483	63292	786	6,02%	-3,51%
C30,700,100,V,T	30	687	100	47052	46260	47987	3481	3,60%	1,95%
C30,700,100,F,T	30	686	100	57447	55123	59246	31	6,96%	3,04%
C30,700,400,V,L	30	685	400	n/a	94725	108827	3104	12,96%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	175098	2509	26,36%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	104532	3171	8,94%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	142033	3517	9,57%	n/a
R13,F01,C1	20	220	40	147349	147349	147837	3598	0,33%	0,33%
R13,F05,C1	20	220	40	281283	269793	285307	1731	5,44%	1,41%
R13,F10,C1	20	220	40	404045	365588	409200	1512	10,66%	1,26%
R13,F01,C2	20	220	40	155887	155887	156585	3409	0,45%	0,45%
R13,F05,C2	20	220	40	295180	292249	311263	1542	6,11%	5,17%
R13,F10,C2	20	220	40	443831	411984	444370	654	7,29%	0,12%
R13,F01,C8	20	220	40	218787	218787	223541	2902	2,13%	2,13%
R13,F05,C8	20	220	40	502811	480366	522387	2552	8,04%	3,75%
R13,F10,C8	20	220	40	812606	764751	882302	554	13,32%	7,90%
R14,F01,C1	20	220	100	422709	422709	431303	782	1,99%	1,99%
R14,F05,C1	20	220	100	835597	717432	842371	12	14,83%	0,80%
R14,F10,C1	20	220	100	1259890	954048	1185410	121	19,52%	-6,28%
R14,F01,C2	20	220	100	452591	452591	461404	1782	1,91%	1,91%
R14,F05,C2	20	220	100	912189	848873	933582	138	9,07%	2,29%
R14,F10,C2	20	220	100	1397100	1210230	1403610	1755	13,78%	0,46%
R14,F01,C8	20	220	100	704719	699947	728077	16	3,86%	3,21%
R14,F05,C8	20	220	100	1696780	1659720	1855350	57	10,54%	8,55%
R14,F10,C8	20	220	100	2874660	2681490	3122070	80	14,11%	7,92%
R15,F01,C1	20	220	200	1042790	969165	1057710	2976	8,37%	1,41%
R15,F05,C1	20	220	200	2297560	1718650	2144670	48	19,86%	-7,13%
R15,F10,C1	20	220	200	3304180	2436030	3219210	58	24,33%	-2,64%
R15,F01,C2	20	220	200	1176860	1164850	1210270	799	3,75%	2,76%
R15,F05,C2	20	220	200	2723740	2368130	2765850	84	14,38%	1,52%
R15,F10,C2	20	220	200	4349910	3467490	4407810	219	21,33%	1,31%
R15,F01,C8	20	220	200	2402800	2392650	2494970	3598	4,10%	3,69%
R15,F05,C8	20	220	200	5807050	5774260	5969370	582	3,27%	2,72%
R15,F10,C8	20	220	200	9169890	9025170	9304650	591	3,00%	1,45%
R16,F01,C1	20	314	40	140082	140082	140514	1212	0,31%	0,31%
R16,F05,C1	20	314	40	259840	236810	261925	1772	9,59%	0,80%
R16,F10,C1	20	314	40	364786	310584	362096	832	14,23%	-0,74%
R16,F01,C2	20	314	40	142381	142381	145417	1698	2,09%	2,09%
R16,F05,C2	20	314	40	275626	251711	274116	2956	8,17%	-0,55%
R16,F10,C2	20	314	40	396966	341107	389169	2486	12,35%	-2,00%
R16,F01,C8	20	314	40	180199	178497	191781	7	6,93%	6,04%
R16,F05,C8	20	314	40	396721	376351	428409	7	12,15%	7,40%
R16,F10,C8	20	314	40	637944	571578	671002	12	14,82%	4,93%
R17,F01,C1	20	318	100	364784	362602	369874	2878	1,97%	1,38%
R17,F05,C1	20	318	100	730195	583094	702957	19	17,05%	-3,87%
R17,F10,C1	20	318	100	1150630	769660	1030640	2966	25,32%	-11,64%
R17,F01,C2	20	318	100	382593	382315	393286	1589	2,79%	2,72%
R17,F05,C2	20	318	100	761041	695446	811097	12	14,26%	6,17%
R17,F10,C2	20	318	100	1195710	971426	1178350	58	17,56%	-1,47%
R17,F01,C8	20	318	100	531791	523185	547553	55	4,45%	2,88%
R17,F05,C8	20	318	100	1284720	1195670	1347910	501	11,29%	4,69%
R17,F10,C8	20	318	100	2047390	1927200	2324470	437	17,09%	11,92%
R18,F01,C1	20	315	200	869263	772151	885329	50	12,78%	1,81%
R18,F05,C1	20	315	200	1869230	1302720	1694040	3571	23,10%	-10,34%
R18,F10,C1	20	315	200	2390740	1793780	2366280	72	24,19%	-1,03%
R18,F01,C2	20	315	200	980178	900627	982740	119	8,36%	0,26%
R18,F05,C2	20	315	200	2146670	1730640	1960070	179	11,71%	-9,52%
R18,F10,C2	20	315	200	n/a	2478890	3058080	418	18,94%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1620230	304	6,94%	3,67%
R18,F05,C8	20	315	200	4230970	3817170	4556300	262	16,22%	7,14%
R18,F10,C8	20	315	200	n/a	6180620	7622690	602	18,92%	n/a

Computational results for paramter setting 5									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	103180	3346	16,48%	2,00%
C20,230,200,F,L	20	230	200	153534	122311	150542	162	18,75%	-1,99%
C20,230,200,V,T	20	229	200	105840	92608	107791	167	14,09%	1,81%
C20,230,200,F,T	20	228	200	154026	124358	149213	564	16,66%	-3,23%
C20,300,200,V,L	20	294	200	81184	73894	80666	549	8,40%	-0,64%
C20,300,200,F,L	20	292	200	131876	110533	127267	156	13,15%	-3,62%
C20,300,200,V,T	20	291	200	78675	74583	80828	2466	7,73%	2,66%
C20,300,200,F,T	20	291	200	127412	106628	117735	2534	9,43%	-8,22%
C30,520,100,V,L	30	518	100	55138	54160	55786	41	2,91%	1,16%
C30,520,100,F,L	30	516	100	n/a	92636	104988	247	11,77%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54375	47	3,12%	2,30%
C30,520,100,F,T	30	517	100	106761	97653	107142	297	8,86%	0,36%
C30,520,400,V,L	30	520	400	n/a	111054	118071	3264	5,94%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	164402	3239	12,81%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	122065	3304	6,01%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	165207	3580	10,29%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49852	443	2,91%	2,01%
C30,700,100,F,L	30	680	100	65516	59483	63524	125	6,36%	-3,14%
C30,700,100,V,T	30	687	100	47052	46260	48034	1669	3,69%	2,04%
C30,700,100,F,T	30	686	100	57447	55123	58663	282	6,03%	2,07%
C30,700,400,V,L	30	685	400	n/a	94725	105367	2867	10,10%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	148114	3357	12,94%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103101	2483	7,68%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	143464	3446	10,47%	n/a
R13,F01,C1	20	220	40	147349	147349	147950	3082	0,41%	0,41%
R13,F05,C1	20	220	40	281283	269793	283627	154	4,88%	0,83%
R13,F10,C1	20	220	40	404045	365588	405120	3467	9,76%	0,27%
R13,F01,C2	20	220	40	155887	155887	159532	2340	2,28%	2,28%
R13,F05,C2	20	220	40	295180	292249	309382	884	5,54%	4,59%
R13,F10,C2	20	220	40	443831	411984	459974	872	10,43%	3,51%
R13,F01,C8	20	220	40	218787	218787	226194	3	3,27%	3,27%
R13,F05,C8	20	220	40	502811	480366	525794	1610	8,64%	4,37%
R13,F10,C8	20	220	40	812606	764751	880867	3176	13,18%	7,75%
R14,F01,C1	20	220	100	422709	422709	429768	241	1,64%	1,64%
R14,F05,C1	20	220	100	835597	717432	824588	2032	13,00%	-1,34%
R14,F10,C1	20	220	100	1259890	954048	1163220	623	17,98%	-8,31%
R14,F01,C2	20	220	100	452591	452591	467670	2332	3,22%	3,22%
R14,F05,C2	20	220	100	912189	848873	945729	3485	10,24%	3,55%
R14,F10,C2	20	220	100	1397100	1210230	1380610	49	12,34%	-1,19%
R14,F01,C8	20	220	100	704719	699947	724014	27	3,32%	2,67%
R14,F05,C8	20	220	100	1696780	1659720	1885780	1201	11,99%	10,02%
R14,F10,C8	20	220	100	2874660	2681490	3131330	94	14,37%	8,20%
R15,F01,C1	20	220	200	1042790	969165	1045970	2362	7,34%	0,30%
R15,F05,C1	20	220	200	2297560	1718650	2139830	820	19,68%	-7,37%
R15,F10,C1	20	220	200	3304180	2436030	3151150	501	22,69%	-4,86%
R15,F01,C2	20	220	200	1176860	1164850	1209210	1217	3,67%	2,68%
R15,F05,C2	20	220	200	2723740	2368130	2717790	1602	12,87%	-0,22%
R15,F10,C2	20	220	200	4349910	3467490	4438640	3342	21,88%	2,00%
R15,F01,C8	20	220	200	2402800	2392650	2467320	3146	3,03%	2,61%
R15,F05,C8	20	220	200	5807050	5774260	6075910	512	4,96%	4,43%
R15,F10,C8	20	220	200	9169890	9025170	10236700	526	11,84%	10,42%
R16,F01,C1	20	314	40	140082	140082	142035	4	1,38%	1,38%
R16,F05,C1	20	314	40	259840	236810	268456	1180	11,79%	3,21%
R16,F10,C1	20	314	40	364786	310584	372741	926	16,68%	2,13%
R16,F01,C2	20	314	40	142381	142381	147852	2020	3,70%	3,70%
R16,F05,C2	20	314	40	275626	251711	282524	15	10,91%	2,44%
R16,F10,C2	20	314	40	396966	341107	391957	25	12,97%	-1,28%
R16,F01,C8	20	314	40	180199	178497	192871	2	7,45%	6,57%
R16,F05,C8	20	314	40	396721	376351	440662	1754	14,59%	9,97%
R16,F10,C8	20	314	40	637944	571578	663326	9	13,83%	3,83%
R17,F01,C1	20	318	100	364784	362602	365913	1465	0,90%	0,31%
R17,F05,C1	20	318	100	730195	583094	717959	26	18,78%	-1,70%
R17,F10,C1	20	318	100	1150630	769660	1043070	27	26,21%	-10,31%
R17,F01,C2	20	318	100	382593	382315	392530	167	2,60%	2,53%
R17,F05,C2	20	318	100	761041	695446	810488	43	14,19%	6,10%
R17,F10,C2	20	318	100	1195710	971426	1193660	225	18,62%	-0,17%
R17,F01,C8	20	318	100	531791	523185	558823	3238	6,38%	4,84%
R17,F05,C8	20	318	100	1284720	1195670	1350530	629	11,47%	4,87%
R17,F10,C8	20	318	100	2047390	1927200	2221550	118	13,25%	7,84%
R18,F01,C1	20	315	200	869263	772151	884529	52	12,70%	1,73%
R18,F05,C1	20	315	200	1869230	1302720	1689150	75	22,88%	-10,66%
R18,F10,C1	20	315	200	2390740	1793780	2560970	57	29,96%	6,65%
R18,F01,C2	20	315	200	980178	900627	964013	121	6,58%	-1,68%
R18,F05,C2	20	315	200	2146670	1730640	2036480	83	15,02%	-5,41%
R18,F10,C2	20	315	200	n/a	2478890	3001470	3014	17,41%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1630160	438	7,50%	4,26%
R18,F05,C8	20	315	200	4230970	3817170	4379190	255	12,83%	3,38%
R18,F10,C8	20	315	200	n/a	6180620	7717420	492	19,91%	n/a

Computational results for paramter setting 6									
Data set	**nodes**	**arcs**	**com.**	**Opt.**	**Bound**	**TS sol**	**TS Time**	**Gap Bound**	**Gap Opt.**
C20,230,200,V,L	20	228	200	101112	86180	103404	76	16,66%	2,22%
C20,230,200,F,L	20	230	200	153534	122311	152402	49	19,74%	-0,74%
C20,230,200,V,T	20	229	200	105840	92608	107273	1748	13,67%	1,34%
C20,230,200,F,T	20	228	200	154026	124358	151329	196	17,82%	-1,78%
C20,300,200,V,L	20	294	200	81184	73894	80143	82	7,80%	-1,30%
C20,300,200,F,L	20	292	200	131876	110533	127572	142	13,36%	-3,37%
C20,300,200,V,T	20	291	200	78675	74583	79835	39	6,58%	1,45%
C20,300,200,F,T	20	291	200	127412	106628	118791	125	10,24%	-7,26%
C30,520,100,V,L	30	518	100	55138	54160	56578	2669	4,27%	2,55%
C30,520,100,F,L	30	516	100	n/a	92636	103095	105	10,14%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54272	40	2,93%	2,11%
C30,520,100,F,T	30	517	100	106761	97653	106286	346	8,12%	-0,45%
C30,520,400,V,L	30	520	400	n/a	111054	120340	2602	7,72%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	163578	2878	12,38%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	121804	2040	5,81%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	163248	3202	9,21%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49805	1472	2,82%	1,92%
C30,700,100,F,L	30	680	100	65516	59483	63461	80	6,27%	-3,24%
C30,700,100,V,T	30	687	100	47052	46260	48004	499	3,63%	1,98%
C30,700,100,F,T	30	686	100	57447	55123	58398	328	5,61%	1,63%
C30,700,400,V,L	30	685	400	n/a	94725	105560	2596	10,26%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	163604	3393	21,18%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103163	3191	7,74%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	142607	2926	9,93%	n/a
R13,F01,C1	20	220	40	147349	147349	147349	59	0,00%	0,00%
R13,F05,C1	20	220	40	281283	269793	287564	3014	6,18%	2,18%
R13,F10,C1	20	220	40	404045	365588	406914	1217	10,16%	0,71%
R13,F01,C2	20	220	40	155887	155887	158592	2904	1,71%	1,71%
R13,F05,C2	20	220	40	295180	292249	318117	2410	8,13%	7,21%
R13,F10,C2	20	220	40	443831	411984	437396	2151	5,81%	-1,47%
R13,F01,C8	20	220	40	218787	218787	226406	6	3,37%	3,37%
R13,F05,C8	20	220	40	502811	480366	533519	1628	9,96%	5,76%
R13,F10,C8	20	220	40	812606	764751	823314	3	7,11%	1,30%
R14,F01,C1	20	220	100	422709	422709	428310	1981	1,31%	1,31%
R14,F05,C1	20	220	100	835597	717432	831182	953	13,69%	-0,53%
R14,F10,C1	20	220	100	1259890	954048	1180220	228	19,16%	-6,75%
R14,F01,C2	20	220	100	452591	452591	464210	655	2,50%	2,50%
R14,F05,C2	20	220	100	912189	848873	956853	1898	11,28%	4,67%
R14,F10,C2	20	220	100	1397100	1210230	1445450	12	16,27%	3,34%
R14,F01,C8	20	220	100	704719	699947	735538	15	4,84%	4,19%
R14,F05,C8	20	220	100	1696780	1659720	1865990	61	11,05%	9,07%
R14,F10,C8	20	220	100	2874660	2681490	3208180	2015	16,42%	10,40%
R15,F01,C1	20	220	200	1042790	969165	1034840	1220	6,35%	-0,77%
R15,F05,C1	20	220	200	2297560	1718650	2132570	2282	19,41%	-7,74%
R15,F10,C1	20	220	200	3304180	2436030	3185140	1556	23,52%	-3,74%
R15,F01,C2	20	220	200	1176860	1164850	1213660	117	4,02%	3,03%
R15,F05,C2	20	220	200	2723740	2368130	2733670	1123	13,37%	0,36%
R15,F10,C2	20	220	200	4349910	3467490	4429520	508	21,72%	1,80%
R15,F01,C8	20	220	200	2402800	2392650	2472860	631	3,24%	2,83%
R15,F05,C8	20	220	200	5807050	5774260	5969370	586	3,27%	2,72%
R15,F10,C8	20	220	200	9169890	9025170	9935400	708	9,16%	7,70%
R16,F01,C1	20	314	40	140082	140082	140149	3332	0,05%	0,05%
R16,F05,C1	20	314	40	259840	236810	261503	58	9,44%	0,64%
R16,F10,C1	20	314	40	364786	310584	358550	1531	13,38%	-1,74%
R16,F01,C2	20	314	40	142381	142381	144877	3003	1,72%	1,72%
R16,F05,C2	20	314	40	275626	251711	277587	6	9,32%	0,71%
R16,F10,C2	20	314	40	396966	341107	375041	197	9,05%	-5,85%
R16,F01,C8	20	314	40	180199	178497	188347	1351	5,23%	4,33%
R16,F05,C8	20	314	40	396721	376351	422522	1565	10,93%	6,11%
R16,F10,C8	20	314	40	637944	571578	654184	1480	12,63%	2,48%
R17,F01,C1	20	318	100	364784	362602	366433	1121	1,05%	0,45%
R17,F05,C1	20	318	100	730195	583094	743623	3157	21,59%	1,81%
R17,F10,C1	20	318	100	1150630	769660	1002660	9	23,24%	-14,76%
R17,F01,C2	20	318	100	382593	382315	389469	2716	1,84%	1,77%
R17,F05,C2	20	318	100	761041	695446	799201	3280	12,98%	4,77%
R17,F10,C2	20	318	100	1195710	971426	1188930	14	18,29%	-0,57%
R17,F01,C8	20	318	100	531791	523185	557320	62	6,12%	4,58%
R17,F05,C8	20	318	100	1284720	1195670	1353450	475	11,66%	5,08%
R17,F10,C8	20	318	100	2047390	1927200	2306880	873	16,46%	11,25%
R18,F01,C1	20	315	200	869263	772151	884284	2820	12,68%	1,70%
R18,F05,C1	20	315	200	1869230	1302720	1700660	94	23,40%	-9,91%
R18,F10,C1	20	315	200	2390740	1793780	2418640	107	25,84%	1,15%
R18,F01,C2	20	315	200	980178	900627	966381	72	6,80%	-1,43%
R18,F05,C2	20	315	200	2146670	1730640	2032340	105	14,84%	-5,63%
R18,F10,C2	20	315	200	n/a	2478890	3037120	209	18,38%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1608600	209	6,26%	2,97%
R18,F05,C8	20	315	200	4230970	3817170	4392010	411	13,09%	3,67%
R18,F10,C8	20	315	200	n/a	6180620	7774120	852	20,50%	n/a

Computational results for paramter setting 7									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	102855	580	16,21%	1,69%
C20,230,200,F,L	20	230	200	153534	122311	151340	1416	19,18%	-1,45%
C20,230,200,V,T	20	229	200	105840	92608	105724	1498	12,41%	-0,11%
C20,230,200,F,T	20	228	200	154026	124358	148244	1958	16,11%	-3,90%
C20,300,200,V,L	20	294	200	81184	73894	80269	624	7,94%	-1,14%
C20,300,200,F,L	20	292	200	131876	110533	128859	240	14,22%	-2,34%
C20,300,200,V,T	20	291	200	78675	74583	79919	2858	6,68%	1,56%
C20,300,200,F,T	20	291	200	127412	106628	120035	3598	11,17%	-6,15%
C30,520,100,V,L	30	518	100	55138	54160	56269	289	3,75%	2,01%
C30,520,100,F,L	30	516	100	n/a	92636	104226	727	11,12%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54092	2967	2,61%	1,79%
C30,520,100,F,T	30	517	100	106761	97653	108446	2122	9,95%	1,55%
C30,520,400,V,L	30	520	400	n/a	111054	120448	3101	7,80%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	160979	3392	10,96%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	121172	2759	5,32%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	166500	3502	10,98%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49690	1734	2,60%	1,69%
C30,700,100,F,L	30	680	100	65516	59483	63577	2924	6,44%	-3,05%
C30,700,100,V,T	30	687	100	47052	46260	48087	1814	3,80%	2,15%
C30,700,100,F,T	30	686	100	57447	55123	58069	1217	5,07%	1,07%
C30,700,400,V,L	30	685	400	n/a	94725	107273	1761	11,70%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	157085	2762	17,91%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103377	2442	7,93%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	142699	3233	9,99%	n/a
R13,F01,C1	20	220	40	147349	147349	147837	749	0,33%	0,33%
R13,F05,C1	20	220	40	281283	269793	286288	1810	5,76%	1,75%
R13,F10,C1	20	220	40	404045	365588	404957	209	9,72%	0,23%
R13,F01,C2	20	220	40	155887	155887	157324	1168	0,91%	0,91%
R13,F05,C2	20	220	40	295180	292249	310513	117	5,88%	4,94%
R13,F10,C2	20	220	40	443831	411984	437396	3240	5,81%	-1,47%
R13,F01,C8	20	220	40	218787	218787	226336	878	3,34%	3,34%
R13,F05,C8	20	220	40	502811	480366	530625	1984	9,47%	5,24%
R13,F10,C8	20	220	40	812606	764751	895038	1510	14,56%	9,21%
R14,F01,C1	20	220	100	422709	422709	433785	1564	2,55%	2,55%
R14,F05,C1	20	220	100	835597	717432	830048	1214	13,57%	-0,67%
R14,F10,C1	20	220	100	1259890	954048	1157500	3270	17,58%	-8,85%
R14,F01,C2	20	220	100	452591	452591	462277	3181	2,10%	2,10%
R14,F05,C2	20	220	100	912189	848873	917832	3375	7,51%	0,61%
R14,F10,C2	20	220	100	1397100	1210230	1374090	2470	11,92%	-1,67%
R14,F01,C8	20	220	100	704719	699947	734184	27	4,66%	4,01%
R14,F05,C8	20	220	100	1696780	1659720	1847150	71	10,15%	8,14%
R14,F10,C8	20	220	100	2874660	2681490	3071920	56	12,71%	6,42%
R15,F01,C1	20	220	200	1042790	969165	1041550	521	6,95%	-0,12%
R15,F05,C1	20	220	200	2297560	1718650	2116750	70	18,81%	-8,54%
R15,F10,C1	20	220	200	3304180	2436030	3184080	2934	23,49%	-3,77%
R15,F01,C2	20	220	200	1176860	1164850	1203480	2521	3,21%	2,21%
R15,F05,C2	20	220	200	2723740	2368130	2751360	3321	13,93%	1,00%
R15,F10,C2	20	220	200	4349910	3467490	4350510	1141	20,30%	0,01%
R15,F01,C8	20	220	200	2402800	2392650	2465650	1341	2,96%	2,55%
R15,F05,C8	20	220	200	5807050	5774260	6132470	2213	5,84%	5,31%
R15,F10,C8	20	220	200	9169890	9025170	10189800	2873	11,43%	10,01%
R16,F01,C1	20	314	40	140082	140082	141688	2624	1,13%	1,13%
R16,F05,C1	20	314	40	259840	236810	263993	2871	10,30%	1,57%
R16,F10,C1	20	314	40	364786	310584	363522	3187	14,56%	-0,35%
R16,F01,C2	20	314	40	142381	142381	144614	1564	1,54%	1,54%
R16,F05,C2	20	314	40	275626	251711	277713	632	9,36%	0,75%
R16,F10,C2	20	314	40	396966	341107	387601	1958	12,00%	-2,42%
R16,F01,C8	20	314	40	180199	178497	193920	919	7,95%	7,08%
R16,F05,C8	20	314	40	396721	376351	428574	3438	12,19%	7,43%
R16,F10,C8	20	314	40	637944	571578	663963	53	13,91%	3,92%
R17,F01,C1	20	318	100	364784	362602	367780	919	1,41%	0,81%
R17,F05,C1	20	318	100	730195	583094	719373	3187	18,94%	-1,50%
R17,F10,C1	20	318	100	1150630	769660	1032850	3362	25,48%	-11,40%
R17,F01,C2	20	318	100	382593	382315	391455	308	2,33%	2,26%
R17,F05,C2	20	318	100	761041	695446	801298	1446	13,21%	5,02%
R17,F10,C2	20	318	100	1195710	971426	1166490	1385	16,72%	-2,50%
R17,F01,C8	20	318	100	531791	523185	550971	3213	5,04%	3,48%
R17,F05,C8	20	318	100	1284720	1195670	1363490	1178	12,31%	5,78%
R17,F10,C8	20	318	100	2047390	1927200	2277280	3044	15,37%	10,09%
R18,F01,C1	20	315	200	869263	772151	882040	614	12,46%	1,45%
R18,F05,C1	20	315	200	1869230	1302720	1693220	1366	23,06%	-10,39%
R18,F10,C1	20	315	200	2390740	1793780	2395090	92	25,11%	0,18%
R18,F01,C2	20	315	200	980178	900627	975036	2009	7,63%	-0,53%
R18,F05,C2	20	315	200	2146670	1730640	2014890	207	14,11%	-6,54%
R18,F10,C2	20	315	200	n/a	2478890	3030460	3258	18,20%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1613790	111	6,57%	3,28%
R18,F05,C8	20	315	200	4230970	3817170	4579920	3410	16,65%	7,62%
R18,F10,C8	20	315	200	n/a	6180620	7194120	318	14,09%	n/a

Computational results for paramter setting 8									
Data set	nodes	arcs	com.	Opt.	Bound	TS sol	TS Time	Gap Bound	Gap Opt.
C20,230,200,V,L	20	228	200	101112	86180	101345	724	14,96%	0,23%
C20,230,200,F,L	20	230	200	153534	122311	148384	115	17,57%	-3,47%
C20,230,200,V,T	20	229	200	105840	92608	103428	81	10,46%	-2,33%
C20,230,200,F,T	20	228	200	154026	124358	145565	1774	14,57%	-5,81%
C20,300,200,V,L	20	294	200	81184	73894	80519	1374	8,23%	-0,83%
C20,300,200,F,L	20	292	200	131876	110533	126258	200	12,45%	-4,45%
C20,300,200,V,T	20	291	200	78675	74583	78444	1162	4,92%	-0,29%
C20,300,200,F,T	20	291	200	127412	106628	120114	789	11,23%	-6,08%
C30,520,100,V,L	30	518	100	55138	54160	56431	2708	4,02%	2,29%
C30,520,100,F,L	30	516	100	n/a	92636	104343	143	11,22%	n/a
C30,520,100,V,T	30	519	100	53125	52681	54284	59	2,95%	2,14%
C30,520,100,F,T	30	517	100	106761	97653	104702	146	6,73%	-1,97%
C30,520,400,V,L	30	520	400	n/a	111054	118910	3600	6,61%	n/a
C30,520,400,F,L	30	520	400	n/a	143335	162866	3646	11,99%	n/a
C30,520,400,V,T	30	516	400	n/a	114725	121194	3861	5,34%	n/a
C30,520,400,F,T	30	518	400	n/a	148210	163600	4100	9,41%	n/a
C30,700,100,V,L	30	680	100	48849	48400	49520	226	2,26%	1,36%
C30,700,100,F,L	30	680	100	65516	59483	63395	831	6,17%	-3,35%
C30,700,100,V,T	30	687	100	47052	46260	47487	2915	2,58%	0,92%
C30,700,100,F,T	30	686	100	57447	55123	57187	1676	3,61%	-0,45%
C30,700,400,V,L	30	685	400	n/a	94725	104350	3885	9,22%	n/a
C30,700,400,F,L	30	679	400	n/a	128950	154326	3734	16,44%	n/a
C30,700,400,V,T	30	678	400	n/a	95183	103959	3682	8,44%	n/a
C30,700,400,F,T	30	683	400	n/a	128441	138609	4839	7,34%	n/a
R13,F01,C1	20	220	40	147349	147349	147798	1225	0,30%	0,30%
R13,F05,C1	20	220	40	281283	269793	282651	2837	4,55%	0,48%
R13,F10,C1	20	220	40	404045	365588	400656	3171	8,75%	-0,85%
R13,F01,C2	20	220	40	155887	155887	158745	1128	1,80%	1,80%
R13,F05,C2	20	220	40	295180	292249	307180	2480	4,86%	3,91%
R13,F10,C2	20	220	40	443831	411984	449884	28	8,42%	1,35%
R13,F01,C8	20	220	40	218787	218787	225034	1678	2,78%	2,78%
R13,F05,C8	20	220	40	502811	480366	510887	3575	5,97%	1,58%
R13,F10,C8	20	220	40	812606	764751	850913	2911	10,13%	4,50%
R14,F01,C1	20	220	100	422709	422709	427872	2970	1,21%	1,21%
R14,F05,C1	20	220	100	835597	717432	827195	1722	13,27%	-1,02%
R14,F10,C1	20	220	100	1259890	954048	1163880	2160	18,03%	-8,25%
R14,F01,C2	20	220	100	452591	452591	458240	2135	1,23%	1,23%
R14,F05,C2	20	220	100	912189	848873	918420	1344	7,57%	0,68%
R14,F10,C2	20	220	100	1397100	1210230	1356910	2580	10,81%	-2,96%
R14,F01,C8	20	220	100	704719	699947	729376	193	4,03%	3,38%
R14,F05,C8	20	220	100	1696780	1659720	1806180	101	8,11%	6,06%
R14,F10,C8	20	220	100	2874660	2681490	3001860	48	10,67%	4,24%
R15,F01,C1	20	220	200	1042790	969165	1032640	3295	6,15%	-0,98%
R15,F05,C1	20	220	200	2297560	1718650	2082990	2947	17,49%	-10,30%
R15,F10,C1	20	220	200	3304180	2436030	3116770	294	21,84%	-6,01%
R15,F01,C2	20	220	200	1176860	1164850	1197760	3049	2,75%	1,74%
R15,F05,C2	20	220	200	2723740	2368130	2717910	1342	12,87%	-0,21%
R15,F10,C2	20	220	200	4349910	3467490	4431260	826	21,75%	1,84%
R15,F01,C8	20	220	200	2402800	2392650	2472860	972	3,24%	2,83%
R15,F05,C8	20	220	200	5807050	5774260	6055080	651	4,64%	4,10%
R15,F10,C8	20	220	200	9169890	9025170	9726680	453	7,21%	5,72%
R16,F01,C1	20	314	40	140082	140082	142110	3191	1,43%	1,43%
R16,F05,C1	20	314	40	259840	236810	262173	4	9,67%	0,89%
R16,F10,C1	20	314	40	364786	310584	365200	1644	14,96%	0,11%
R16,F01,C2	20	314	40	142381	142381	143921	335	1,07%	1,07%
R16,F05,C2	20	314	40	275626	251711	276244	1694	8,88%	0,22%
R16,F10,C2	20	314	40	396966	341107	396847	2088	14,05%	-0,03%
R16,F01,C8	20	314	40	180199	178497	185397	15	3,72%	2,80%
R16,F05,C8	20	314	40	396721	376351	434102	52	13,30%	8,61%
R16,F10,C8	20	314	40	637944	571578	682154	14	16,21%	6,48%
R17,F01,C1	20	318	100	364784	362602	366823	1552	1,15%	0,56%
R17,F05,C1	20	318	100	730195	583094	714247	2974	18,36%	-2,23%
R17,F10,C1	20	318	100	1150630	769660	1026040	226	24,99%	-12,14%
R17,F01,C2	20	318	100	382593	382315	389249	3048	1,78%	1,71%
R17,F05,C2	20	318	100	761041	695446	799193	193	12,98%	4,77%
R17,F10,C2	20	318	100	1195710	971426	1176430	2798	17,43%	-1,64%
R17,F01,C8	20	318	100	531791	523185	546891	1302	4,33%	2,76%
R17,F05,C8	20	318	100	1284720	1195670	1323330	3641	9,65%	2,92%
R17,F10,C8	20	318	100	2047390	1927200	2217340	2113	13,09%	7,66%
R18,F01,C1	20	315	200	869263	772151	881235	1136	12,38%	1,36%
R18,F05,C1	20	315	200	1869230	1302720	1627700	105	19,97%	-14,84%
R18,F10,C1	20	315	200	2390740	1793780	2385110	70	24,79%	-0,24%
R18,F01,C2	20	315	200	980178	900627	971832	68	7,33%	-0,86%
R18,F05,C2	20	315	200	2146670	1730640	1975600	198	12,40%	-8,66%
R18,F10,C2	20	315	200	n/a	2478890	2993360	1539	17,19%	n/a
R18,F01,C8	20	315	200	1560790	1507840	1616120	662	6,70%	3,42%
R18,F05,C8	20	315	200	4230970	3817170	4355920	216	12,37%	2,87%
R18,F10,C8	20	315	200	n/a	6180620	7478230	1087	17,35%	n/a

Appendix C – local search candidate selection distribution

Candidate selection for best neighbour solution, paramter setting 1

Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	15,30%	62,01%	0,00%	22,70%	53,93%	5,99%	17,36%	22,73%
C20,230,200,F,L	18,63%	71,76%	0,93%	8,68%	71,81%	9,69%	7,71%	10,79%
C20,230,200,V,T	42,04%	53,08%	1,06%	3,82%	61,79%	5,46%	19,49%	13,26%
C20,230,200,F,T	42,44%	48,45%	2,58%	6,53%	63,73%	16,61%	11,53%	8,14%
C20,300,200,V,L	57,58%	28,91%	5,21%	8,29%	65,43%	7,81%	13,38%	13,38%
C20,300,200,F,L	51,92%	28,02%	10,44%	9,62%	68,70%	11,79%	8,94%	10,57%
C20,300,200,V,T	12,27%	55,68%	0,18%	31,87%	64,37%	5,67%	9,31%	20,65%
C20,300,200,F,T	23,06%	53,89%	0,28%	22,78%	67,66%	11,44%	6,47%	14,43%
C30,520,100,V,L	5,39%	61,90%	0,12%	32,59%	42,02%	4,34%	17,23%	36,40%
C30,520,100,F,L	24,23%	58,38%	0,09%	17,30%	59,79%	6,63%	9,79%	23,80%
C30,520,100,V,T	7,48%	71,76%	0,48%	20,29%	36,20%	3,56%	22,11%	38,13%
C30,520,100,F,T	23,42%	66,01%	0,00%	10,57%	53,50%	7,86%	9,23%	29,40%
C30,520,400,V,L	3,92%	49,02%	0,00%	47,06%	47,73%	31,82%	4,55%	15,91%
C30,520,400,F,L	15,28%	48,61%	0,00%	36,11%	65,00%	22,50%	5,00%	7,50%
C30,520,400,V,T	7,32%	56,10%	0,00%	36,59%	58,14%	27,91%	4,65%	9,30%
C30,520,400,F,T	30,23%	44,19%	0,00%	25,58%	64,86%	32,43%	0,00%	2,70%
C30,700,100,V,L	58,87%	12,81%	25,67%	2,64%	53,38%	13,22%	9,56%	23,84%
C30,700,100,F,L	52,42%	13,03%	30,75%	3,80%	56,94%	18,20%	8,54%	16,32%
C30,700,100,V,T	37,77%	36,24%	16,52%	9,48%	51,88%	10,41%	15,70%	22,01%
C30,700,100,F,T	50,06%	21,66%	21,06%	7,22%	56,43%	12,23%	10,82%	20,53%
C30,700,400,V,L	17,28%	55,56%	0,00%	27,16%	44,44%	40,74%	5,56%	9,26%
C30,700,400,F,L	31,43%	31,43%	0,00%	37,14%	74,07%	25,93%	0,00%	0,00%
C30,700,400,V,T	21,95%	41,46%	0,00%	36,59%	53,13%	43,75%	0,00%	3,13%
C30,700,400,F,T	13,73%	54,90%	1,96%	29,41%	57,14%	39,29%	0,00%	3,57%
R13,F01,C1	26,68%	69,04%	0,02%	4,26%	28,54%	2,66%	34,20%	34,59%
R13,F05,C1	48,66%	50,29%	0,00%	1,05%	35,52%	7,39%	21,86%	35,23%
R13,F10,C1	92,78%	3,15%	4,03%	0,04%	53,47%	12,79%	13,64%	20,09%
R13,F01,C2	84,63%	3,80%	11,47%	0,09%	51,31%	6,41%	21,32%	20,95%
R13,F05,C2	66,31%	0,35%	33,27%	0,08%	58,33%	17,28%	11,05%	13,34%
R13,F10,C2	54,53%	0,44%	44,94%	0,10%	58,34%	21,78%	8,54%	11,34%
R13,F01,C8	14,76%	71,65%	3,11%	10,47%	34,19%	2,79%	30,86%	32,16%
R13,F05,C8	16,73%	66,89%	1,27%	15,11%	42,74%	11,73%	17,24%	28,29%
R13,F10,C8	23,57%	62,51%	4,11%	9,81%	43,45%	18,47%	15,25%	22,83%
R14,F01,C1	75,94%	6,04%	17,67%	0,34%	56,77%	7,10%	21,18%	14,94%
R14,F05,C1	62,38%	1,49%	35,68%	0,45%	61,85%	15,45%	10,18%	12,53%
R14,F10,C1	51,95%	1,48%	46,10%	0,46%	64,77%	19,47%	6,31%	9,45%
R14,F01,C2	63,22%	3,72%	32,36%	0,70%	59,97%	10,66%	16,57%	12,80%
R14,F05,C2	56,62%	3,41%	39,05%	0,92%	63,49%	20,37%	6,92%	9,23%
R14,F10,C2	54,71%	4,35%	39,71%	1,23%	62,12%	23,58%	4,87%	9,43%
R14,F01,C8	14,05%	62,70%	7,30%	15,95%	46,60%	8,60%	26,00%	18,80%
R14,F05,C8	6,47%	61,71%	2,45%	29,37%	65,45%	13,35%	11,26%	9,95%
R14,F10,C8	2,99%	57,29%	0,40%	39,32%	64,79%	15,09%	7,10%	13,02%
R15,F01,C1	44,35%	49,10%	4,12%	2,43%	50,63%	4,78%	30,18%	14,42%
R15,F05,C1	67,49%	10,16%	17,65%	4,71%	65,08%	18,62%	8,46%	7,85%
R15,F10,C1	60,39%	10,39%	24,94%	4,27%	62,35%	24,10%	5,42%	8,13%
R15,F01,C2	28,59%	52,98%	9,00%	9,43%	60,32%	10,67%	19,03%	9,98%
R15,F05,C2	28,19%	44,97%	6,71%	20,13%	64,00%	19,56%	8,44%	8,00%
R15,F10,C2	34,29%	35,71%	12,29%	17,71%	59,04%	27,31%	4,02%	9,64%
R15,F01,C8	0,00%	10,00%	73,75%	16,25%	86,81%	0,00%	12,09%	1,10%
R15,F05,C8	0,00%	0,00%	66,22%	33,78%	84,06%	0,00%	13,04%	2,90%
R15,F10,C8	0,00%	12,86%	24,29%	62,86%	77,63%	1,32%	10,53%	10,53%
R16,F01,C1	74,46%	0,58%	24,79%	0,17%	53,34%	11,60%	11,69%	23,38%
R16,F05,C1	49,39%	0,32%	50,14%	0,15%	59,16%	19,67%	7,37%	13,80%
R16,F10,C1	39,96%	0,35%	59,61%	0,08%	60,09%	23,25%	5,60%	11,06%
R16,F01,C2	48,58%	0,45%	50,77%	0,19%	60,18%	13,43%	9,81%	16,58%
R16,F05,C2	40,05%	0,42%	59,42%	0,12%	61,53%	19,36%	6,21%	12,89%
R16,F10,C2	35,58%	0,36%	63,91%	0,15%	60,75%	23,44%	5,03%	10,78%
R16,F01,C8	38,09%	10,55%	51,08%	0,28%	60,61%	11,83%	10,44%	17,12%
R16,F05,C8	55,13%	1,85%	42,56%	0,45%	55,11%	22,27%	7,02%	15,60%
R16,F10,C8	53,92%	2,09%	43,54%	0,45%	54,85%	24,98%	5,72%	14,45%
R17,F01,C1	38,78%	1,59%	59,03%	0,59%	67,27%	11,52%	11,87%	9,34%
R17,F05,C1	30,55%	1,49%	66,97%	0,99%	66,83%	18,45%	6,22%	8,51%
R17,F10,C1	27,53%	1,84%	69,82%	0,81%	65,94%	22,51%	4,07%	7,48%
R17,F01,C2	40,53%	2,22%	56,05%	1,20%	64,98%	13,89%	10,07%	11,06%
R17,F05,C2	41,37%	2,99%	54,31%	1,33%	64,32%	19,72%	5,85%	10,11%
R17,F10,C2	43,38%	4,70%	50,15%	1,78%	63,74%	22,47%	4,64%	9,15%
R17,F01,C8	37,25%	30,24%	26,56%	5,96%	56,79%	19,09%	11,24%	12,88%
R17,F05,C8	44,22%	27,46%	19,65%	8,67%	55,47%	25,73%	7,66%	11,13%
R17,F10,C8	48,47%	25,12%	19,00%	7,41%	49,09%	33,00%	2,82%	15,09%
R18,F01,C1	16,86%	41,07%	0,00%	42,06%	40,06%	3,63%	34,08%	22,22%
R18,F05,C1	25,35%	47,91%	0,31%	26,43%	63,83%	5,10%	10,97%	20,09%
R18,F10,C1	35,24%	60,42%	0,45%	3,89%	66,77%	11,02%	7,14%	15,06%
R18,F01,C2	19,39%	54,76%	0,59%	25,26%	54,45%	9,11%	19,70%	16,74%
R18,F05,C2	43,45%	47,82%	0,21%	8,52%	68,35%	15,49%	6,40%	9,76%
R18,F10,C2	45,36%	44,94%	0,21%	9,49%	63,82%	18,09%	6,48%	11,60%
R18,F01,C8	7,80%	67,38%	2,84%	21,99%	43,90%	21,95%	19,51%	14,63%
R18,F05,C8	3,30%	65,93%	0,00%	30,77%	68,49%	8,22%	6,85%	16,44%
R18,F10,C8	5,43%	63,04%	1,09%	30,43%	53,23%	19,35%	4,84%	22,58%

Candidate selection for best neighbour solution, paramter setting 2								
Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	24,73%	44,50%	0,29%	30,48%	57,37%	6,32%	15,79%	20,53%
C20,230,200,F,L	25,79%	52,15%	1,58%	20,48%	74,70%	9,92%	6,07%	9,31%
C20,230,200,V,T	41,96%	38,29%	1,32%	18,43%	58,79%	6,39%	20,25%	14,56%
C20,230,200,F,T	58,24%	28,87%	4,24%	8,65%	69,05%	13,10%	9,52%	8,33%
C20,300,200,V,L	61,20%	26,10%	5,54%	7,16%	63,03%	9,15%	11,97%	15,85%
C20,300,200,F,L	56,84%	20,64%	9,38%	13,14%	61,07%	18,32%	11,45%	9,16%
C20,300,200,V,T	54,04%	16,36%	18,22%	11,39%	64,33%	12,42%	11,78%	11,47%
C20,300,200,F,T	46,92%	26,03%	14,73%	12,33%	73,76%	12,67%	6,79%	6,79%
C30,520,100,V,L	68,33%	13,59%	14,17%	3,91%	57,53%	7,44%	13,40%	21,62%
C30,520,100,F,L	16,84%	43,85%	0,00%	39,32%	54,07%	6,70%	10,21%	29,03%
C30,520,100,V,T	9,00%	48,15%	0,99%	41,85%	29,95%	3,17%	22,50%	44,37%
C30,520,100,F,T	13,44%	53,42%	0,00%	33,15%	38,25%	7,38%	7,38%	46,99%
C30,520,400,V,L	3,92%	50,98%	1,96%	43,14%	63,27%	20,41%	2,04%	14,29%
C30,520,400,F,L	35,59%	28,81%	0,00%	35,59%	65,22%	19,57%	0,00%	15,22%
C30,520,400,V,T	19,51%	53,66%	0,00%	26,83%	67,31%	21,15%	5,77%	5,77%
C30,520,400,F,T	36,59%	34,15%	0,00%	29,27%	70,00%	25,00%	2,50%	2,50%
C30,700,100,V,L	29,35%	53,29%	0,63%	16,73%	46,47%	3,24%	12,57%	37,71%
C30,700,100,F,L	80,77%	10,40%	4,93%	3,90%	57,93%	7,49%	10,95%	23,63%
C30,700,100,V,T	19,53%	56,84%	1,12%	22,51%	47,46%	5,43%	16,30%	30,80%
C30,700,100,F,T	66,99%	19,70%	2,88%	10,44%	54,27%	6,86%	11,74%	27,13%
C30,700,400,V,L	29,27%	39,02%	0,00%	31,71%	47,92%	39,58%	2,08%	10,42%
C30,700,400,F,L	65,63%	21,88%	0,00%	12,50%	54,55%	45,45%	0,00%	0,00%
C30,700,400,V,T	48,39%	29,03%	0,00%	22,58%	69,70%	27,27%	0,00%	3,03%
C30,700,400,F,T	51,11%	35,56%	0,00%	13,33%	66,67%	33,33%	0,00%	0,00%
R13,F01,C1	29,85%	33,12%	0,37%	36,65%	30,17%	3,35%	31,86%	34,62%
R13,F05,C1	91,04%	7,15%	1,61%	0,20%	45,37%	10,10%	19,36%	25,17%
R13,F10,C1	72,06%	0,25%	27,50%	0,18%	55,98%	19,33%	10,72%	13,97%
R13,F01,C2	70,91%	0,70%	28,11%	0,28%	56,69%	8,68%	18,34%	16,30%
R13,F05,C2	56,96%	0,33%	42,53%	0,18%	59,41%	18,75%	9,95%	11,90%
R13,F10,C2	47,21%	0,27%	52,31%	0,21%	59,99%	21,87%	6,93%	11,21%
R13,F01,C8	16,39%	51,06%	18,81%	13,74%	43,08%	4,88%	26,98%	25,06%
R13,F05,C8	20,03%	63,37%	3,14%	13,46%	41,24%	10,15%	20,32%	28,30%
R13,F10,C8	23,93%	57,28%	3,56%	15,23%	43,17%	16,46%	15,63%	24,74%
R14,F01,C1	60,94%	34,48%	2,30%	2,27%	51,65%	4,33%	24,50%	19,52%
R14,F05,C1	70,75%	1,41%	27,06%	0,78%	61,66%	13,80%	11,25%	13,29%
R14,F10,C1	57,42%	1,10%	40,59%	0,89%	64,05%	19,31%	6,45%	10,19%
R14,F01,C2	67,96%	4,71%	26,12%	1,21%	58,50%	10,41%	18,21%	12,88%
R14,F05,C2	56,97%	2,96%	38,57%	1,50%	63,95%	20,12%	7,17%	8,76%
R14,F10,C2	37,77%	39,50%	0,16%	22,57%	59,50%	10,36%	9,10%	21,04%
R14,F01,C8	15,46%	41,72%	35,43%	7,39%	56,47%	14,63%	16,89%	12,01%
R14,F05,C8	15,15%	57,04%	13,73%	14,08%	52,35%	22,47%	12,10%	13,09%
R14,F10,C8	8,28%	53,25%	17,36%	21,10%	59,59%	21,74%	9,21%	9,46%
R15,F01,C1	59,29%	16,94%	20,21%	3,56%	58,39%	7,26%	25,08%	9,27%
R15,F05,C1	61,28%	5,56%	27,59%	5,56%	68,15%	19,08%	7,32%	5,45%
R15,F10,C1	52,63%	7,02%	34,09%	6,27%	60,52%	28,42%	3,84%	7,22%
R15,F01,C2	29,79%	36,01%	9,98%	24,22%	64,55%	8,56%	15,89%	11,00%
R15,F05,C2	29,03%	41,35%	1,17%	28,45%	67,89%	14,68%	8,26%	9,17%
R15,F10,C2	43,79%	33,62%	0,56%	22,03%	58,04%	21,88%	8,48%	11,61%
R15,F01,C8	0,00%	2,22%	97,78%	0,00%	92,13%	1,12%	6,74%	0,00%
R15,F05,C8	0,00%	0,00%	100,00%	0,00%	92,68%	0,00%	3,66%	3,66%
R15,F10,C8	0,00%	0,00%	100,00%	0,00%	83,17%	0,99%	6,93%	8,91%
R16,F01,C1	37,90%	22,94%	0,02%	39,14%	31,09%	3,98%	17,89%	47,03%
R16,F05,C1	88,11%	10,71%	0,88%	0,31%	50,81%	5,17%	13,37%	30,65%
R16,F10,C1	72,89%	0,31%	26,68%	0,12%	58,55%	16,38%	8,27%	16,79%
R16,F01,C2	76,52%	0,82%	22,43%	0,24%	52,52%	10,77%	12,22%	24,49%
R16,F05,C2	55,97%	0,23%	43,52%	0,28%	58,55%	18,47%	6,92%	16,06%
R16,F10,C2	45,70%	0,29%	53,76%	0,26%	59,09%	23,06%	5,54%	12,31%
R16,F01,C8	11,48%	58,39%	0,25%	29,88%	29,29%	4,03%	18,57%	48,11%
R16,F05,C8	28,54%	49,46%	0,05%	21,95%	40,33%	12,21%	12,77%	34,69%
R16,F10,C8	42,15%	42,09%	0,10%	15,67%	40,88%	16,37%	11,76%	30,99%
R17,F01,C1	83,96%	2,33%	12,93%	0,77%	60,03%	7,21%	15,65%	17,12%
R17,F05,C1	63,23%	0,97%	34,68%	1,12%	62,64%	16,70%	8,32%	12,33%
R17,F10,C1	52,71%	1,36%	44,84%	1,09%	63,06%	21,56%	5,26%	10,11%
R17,F01,C2	64,14%	1,98%	32,67%	1,20%	61,61%	10,83%	12,14%	15,42%
R17,F05,C2	52,43%	1,81%	44,04%	1,71%	63,67%	19,62%	6,35%	10,36%
R17,F10,C2	51,25%	3,53%	43,41%	1,81%	63,93%	23,09%	4,20%	8,78%
R17,F01,C8	43,74%	31,74%	16,71%	7,81%	57,61%	15,78%	9,92%	16,69%
R17,F05,C8	42,19%	42,90%	0,42%	14,49%	53,17%	22,46%	6,72%	17,66%
R17,F10,C8	46,02%	38,81%	0,25%	14,93%	50,35%	24,83%	9,09%	15,73%
R18,F01,C1	27,07%	32,31%	0,13%	40,49%	40,59%	3,51%	33,57%	22,32%
R18,F05,C1	34,59%	34,22%	0,89%	30,30%	64,18%	8,37%	10,33%	17,12%
R18,F10,C1	56,84%	35,39%	0,79%	6,97%	66,62%	15,67%	6,27%	11,44%
R18,F01,C2	27,65%	47,32%	0,48%	24,55%	54,98%	8,17%	19,52%	17,33%
R18,F05,C2	38,08%	28,26%	0,20%	33,47%	70,30%	12,21%	5,61%	11,88%
R18,F10,C2	43,82%	29,66%	0,00%	26,52%	64,39%	18,35%	4,32%	12,95%
R18,F01,C8	14,91%	60,25%	8,70%	16,15%	46,74%	23,91%	16,30%	13,04%
R18,F05,C8	8,79%	71,43%	2,20%	17,58%	58,21%	17,91%	8,96%	14,93%
R18,F10,C8	5,56%	58,89%	1,11%	34,44%	52,63%	30,26%	5,26%	11,84%

Candidate selection for best neighbour solution, paramter setting 3								
Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	32,02%	36,76%	0,00%	31,23%	54,73%	4,16%	20,32%	20,79%
C20,230,200,F,L	37,52%	53,46%	0,22%	8,80%	75,88%	8,90%	7,73%	7,49%
C20,230,200,V,T	60,71%	35,69%	0,00%	3,60%	60,47%	5,73%	20,36%	13,44%
C20,230,200,F,T	30,03%	45,05%	0,31%	24,62%	75,11%	10,41%	7,69%	6,79%
C20,300,200,V,L	30,09%	43,84%	0,00%	26,07%	60,81%	5,41%	15,32%	18,47%
C20,300,200,F,L	36,08%	42,91%	0,00%	21,02%	67,98%	12,81%	10,34%	8,87%
C20,300,200,V,T	63,07%	29,60%	0,27%	7,07%	60,61%	7,58%	14,39%	17,42%
C20,300,200,F,T	74,34%	12,22%	4,07%	9,37%	74,78%	11,95%	5,31%	7,96%
C30,520,100,V,L	67,61%	28,68%	0,03%	3,67%	50,54%	7,89%	13,84%	27,74%
C30,520,100,F,L	26,99%	40,46%	0,00%	32,55%	60,00%	6,48%	6,67%	26,86%
C30,520,100,V,T	20,93%	46,08%	0,12%	32,88%	33,65%	4,35%	19,47%	42,53%
C30,520,100,F,T	29,14%	41,79%	0,07%	29,00%	53,16%	7,63%	5,01%	34,20%
C30,520,400,V,L	12,26%	46,23%	0,00%	41,51%	64,86%	13,51%	8,11%	13,51%
C30,520,400,F,L	31,25%	35,71%	0,00%	33,04%	65,71%	25,71%	0,00%	8,57%
C30,520,400,V,T	25,93%	50,62%	0,00%	23,46%	77,42%	16,13%	0,00%	6,45%
C30,520,400,F,T	29,79%	32,98%	0,00%	37,23%	68,75%	18,75%	3,13%	9,38%
C30,700,100,V,L	73,77%	23,39%	0,04%	2,80%	46,57%	5,44%	13,99%	34,00%
C30,700,100,F,L	89,62%	5,66%	1,61%	3,11%	55,58%	10,43%	9,50%	24,48%
C30,700,100,V,T	49,68%	37,84%	0,00%	12,48%	51,04%	6,06%	13,15%	29,76%
C30,700,100,F,T	23,18%	42,96%	0,00%	33,87%	50,73%	4,37%	7,77%	37,14%
C30,700,400,V,L	36,88%	33,33%	0,00%	29,79%	70,00%	13,33%	3,33%	13,33%
C30,700,400,F,L	41,67%	29,76%	0,00%	28,57%	80,95%	19,05%	0,00%	0,00%
C30,700,400,V,T	33,77%	31,17%	0,00%	35,06%	63,33%	30,00%	3,33%	3,33%
C30,700,400,F,T	35,14%	38,74%	0,00%	26,13%	85,71%	9,52%	4,76%	0,00%
R13,F01,C1	48,11%	39,05%	0,01%	12,83%	28,92%	2,32%	32,77%	35,99%
R13,F05,C1	97,19%	0,20%	2,55%	0,06%	45,50%	11,47%	18,01%	25,01%
R13,F10,C1	67,66%	0,12%	32,16%	0,07%	56,41%	23,08%	9,27%	11,25%
R13,F01,C2	71,19%	0,17%	28,56%	0,08%	59,31%	10,15%	15,89%	14,65%
R13,F05,C2	56,70%	33,14%	0,00%	10,17%	44,66%	8,53%	17,38%	29,43%
R13,F10,C2	97,01%	2,80%	0,14%	0,05%	52,40%	12,47%	12,34%	22,79%
R13,F01,C8	31,55%	49,90%	0,20%	18,35%	38,36%	3,58%	27,35%	30,72%
R13,F05,C8	37,37%	42,52%	0,09%	20,02%	49,03%	14,40%	14,43%	22,14%
R13,F10,C8	45,73%	41,69%	0,29%	12,29%	46,97%	20,23%	12,57%	20,23%
R14,F01,C1	84,03%	0,48%	15,12%	0,37%	58,69%	7,69%	18,91%	14,72%
R14,F05,C1	55,98%	0,62%	42,89%	0,50%	59,31%	21,98%	9,38%	9,33%
R14,F10,C1	39,93%	41,32%	0,00%	18,74%	64,80%	8,30%	10,31%	16,59%
R14,F01,C2	34,25%	37,48%	0,04%	28,23%	49,37%	6,14%	23,09%	21,39%
R14,F05,C2	93,92%	4,99%	0,42%	0,67%	65,82%	11,58%	10,03%	12,58%
R14,F10,C2	82,45%	1,49%	14,97%	1,09%	62,35%	22,45%	5,81%	9,38%
R14,F01,C8	35,37%	39,89%	4,76%	19,98%	52,45%	17,17%	19,81%	10,57%
R14,F05,C8	27,74%	47,41%	1,35%	23,50%	59,95%	20,41%	8,27%	11,37%
R14,F10,C8	32,98%	44,95%	2,44%	19,63%	55,09%	25,85%	5,74%	13,32%
R15,F01,C1	24,57%	36,71%	0,03%	38,69%	44,43%	3,17%	34,11%	18,29%
R15,F05,C1	51,01%	28,13%	0,06%	20,81%	68,63%	12,16%	10,00%	9,22%
R15,F10,C1	82,51%	14,67%	0,38%	2,45%	70,51%	14,66%	6,63%	8,20%
R15,F01,C2	34,75%	37,18%	0,17%	27,90%	64,66%	8,62%	19,61%	7,11%
R15,F05,C2	63,44%	27,72%	0,51%	8,33%	67,62%	21,31%	5,74%	5,33%
R15,F10,C2	69,95%	18,00%	0,68%	11,38%	56,57%	31,08%	4,78%	7,57%
R15,F01,C8	0,00%	14,81%	72,84%	12,35%	85,71%	1,43%	12,86%	0,00%
R15,F05,C8	0,00%	8,64%	67,90%	23,46%	87,34%	0,00%	8,86%	3,80%
R15,F10,C8	0,00%	5,94%	60,40%	33,66%	85,87%	1,09%	2,17%	10,87%
R16,F01,C1	48,26%	29,97%	0,00%	21,77%	34,21%	4,15%	16,08%	45,56%
R16,F05,C1	98,31%	0,31%	1,31%	0,07%	52,44%	6,45%	12,55%	28,57%
R16,F10,C1	68,19%	0,21%	31,51%	0,08%	59,21%	18,47%	7,18%	15,14%
R16,F01,C2	75,85%	0,19%	23,83%	0,13%	56,27%	10,19%	10,93%	22,61%
R16,F05,C2	53,69%	0,20%	46,01%	0,10%	60,26%	19,53%	5,61%	14,61%
R16,F10,C2	44,82%	0,21%	54,87%	0,10%	58,68%	25,53%	5,09%	10,70%
R16,F01,C8	37,03%	34,31%	0,09%	28,57%	41,23%	7,20%	13,60%	37,97%
R16,F05,C8	49,36%	27,14%	0,00%	23,50%	48,23%	15,21%	9,80%	26,76%
R16,F10,C8	64,45%	27,71%	0,00%	7,84%	46,27%	16,74%	9,29%	27,70%
R17,F01,C1	83,42%	0,57%	15,46%	0,55%	62,62%	7,25%	14,43%	15,71%
R17,F05,C1	64,62%	1,14%	33,51%	0,73%	60,80%	20,50%	7,92%	10,77%
R17,F10,C1	46,50%	1,12%	51,67%	0,71%	60,27%	27,89%	4,46%	7,38%
R17,F01,C2	65,74%	1,00%	32,63%	0,64%	66,05%	10,72%	10,24%	13,00%
R17,F05,C2	54,75%	1,39%	42,82%	1,04%	61,18%	23,44%	5,92%	9,46%
R17,F10,C2	45,53%	1,37%	51,54%	1,56%	59,75%	30,09%	3,43%	6,73%
R17,F01,C8	78,31%	5,59%	10,96%	5,14%	58,24%	20,94%	7,97%	12,86%
R17,F05,C8	78,53%	8,07%	6,42%	6,97%	52,48%	32,48%	4,96%	10,09%
R17,F10,C8	44,93%	30,74%	0,00%	24,33%	48,37%	29,07%	7,93%	14,63%
R18,F01,C1	35,43%	34,28%	0,00%	30,30%	46,99%	3,94%	30,56%	18,52%
R18,F05,C1	92,33%	4,44%	1,53%	1,69%	66,10%	10,38%	10,91%	12,62%
R18,F10,C1	75,42%	2,72%	18,87%	2,99%	64,60%	23,69%	4,04%	7,67%
R18,F01,C2	68,05%	27,08%	0,00%	4,87%	58,49%	8,82%	20,00%	12,69%
R18,F05,C2	71,37%	8,14%	15,06%	5,43%	58,72%	26,91%	7,03%	7,34%
R18,F10,C2	66,25%	7,05%	18,40%	8,30%	62,13%	30,67%	2,13%	5,07%
R18,F01,C8	20,09%	49,11%	0,45%	30,36%	46,07%	33,71%	14,61%	5,62%
R18,F05,C8	27,66%	53,90%	0,00%	18,44%	34,29%	50,00%	4,29%	11,43%
R18,F10,C8	15,17%	50,34%	0,69%	33,79%	45,45%	36,36%	4,55%	13,64%

Candidate selection for best neighbour solution, paramter setting 4								
Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	36,28%	31,82%	0,08%	31,82%	59,93%	4,33%	18,05%	17,69%
C20,230,200,F,L	34,06%	41,87%	0,54%	23,54%	72,97%	9,35%	6,10%	11,59%
C20,230,200,V,T	40,02%	35,84%	0,29%	23,86%	56,76%	8,73%	18,09%	16,42%
C20,230,200,F,T	33,67%	43,45%	0,83%	22,06%	74,34%	12,45%	5,28%	7,92%
C20,300,200,V,L	39,39%	41,56%	0,22%	18,83%	65,83%	5,83%	13,33%	15,00%
C20,300,200,F,L	47,67%	24,35%	0,00%	27,98%	66,67%	11,84%	10,09%	11,40%
C20,300,200,V,T	42,83%	34,93%	0,83%	21,41%	66,67%	5,24%	14,23%	13,86%
C20,300,200,F,T	65,36%	21,08%	1,20%	12,35%	74,54%	11,57%	5,09%	8,80%
C30,520,100,V,L	40,32%	37,26%	0,17%	22,25%	48,48%	5,63%	16,83%	29,06%
C30,520,100,F,L	30,29%	39,27%	0,00%	30,45%	56,47%	7,96%	10,45%	25,12%
C30,520,100,V,T	16,00%	45,20%	0,31%	38,49%	30,06%	4,27%	23,42%	42,25%
C30,520,100,F,T	33,15%	37,47%	0,11%	29,27%	54,65%	9,29%	7,06%	29,00%
C30,520,400,V,L	15,63%	37,50%	1,56%	45,31%	60,78%	19,61%	1,96%	17,65%
C30,520,400,F,L	37,80%	35,37%	0,00%	26,83%	72,50%	20,00%	5,00%	2,50%
C30,520,400,V,T	34,62%	44,23%	0,00%	21,15%	73,08%	17,31%	1,92%	7,69%
C30,520,400,F,T	43,33%	35,00%	0,00%	21,67%	80,00%	17,14%	2,86%	0,00%
C30,700,100,V,L	24,99%	41,72%	0,00%	33,30%	40,33%	2,72%	12,33%	44,62%
C30,700,100,F,L	27,93%	36,55%	0,13%	35,39%	54,62%	5,64%	10,38%	29,36%
C30,700,100,V,T	27,14%	39,49%	0,35%	33,03%	43,30%	4,33%	12,99%	39,38%
C30,700,100,F,T	26,87%	34,33%	0,00%	38,81%	47,63%	3,08%	9,24%	40,05%
C30,700,400,V,L	48,15%	25,93%	0,00%	25,93%	58,62%	24,14%	3,45%	13,79%
C30,700,400,F,L	60,61%	18,18%	0,00%	21,21%	64,52%	35,48%	0,00%	0,00%
C30,700,400,V,T	54,55%	38,18%	0,00%	7,27%	65,71%	28,57%	0,00%	5,71%
C30,700,400,F,T	42,86%	33,93%	0,00%	23,21%	77,42%	19,35%	0,00%	3,23%
R13,F01,C1	42,60%	29,13%	0,05%	28,23%	33,37%	2,86%	29,57%	34,21%
R13,F05,C1	84,81%	13,79%	0,01%	1,39%	41,71%	10,04%	20,11%	28,14%
R13,F10,C1	86,04%	0,09%	13,79%	0,08%	54,88%	15,25%	12,70%	17,17%
R13,F01,C2	39,00%	33,18%	0,10%	27,71%	37,60%	4,74%	27,36%	30,29%
R13,F05,C2	64,02%	23,90%	0,03%	12,05%	48,05%	9,13%	16,32%	26,50%
R13,F10,C2	91,20%	1,23%	7,36%	0,22%	54,12%	13,47%	12,02%	20,40%
R13,F01,C8	30,13%	51,03%	1,46%	17,38%	41,56%	3,37%	28,37%	26,71%
R13,F05,C8	36,13%	48,05%	0,82%	15,01%	47,43%	14,00%	15,84%	22,73%
R13,F10,C8	37,67%	46,04%	0,58%	15,71%	45,92%	18,97%	13,47%	21,64%
R14,F01,C1	49,86%	32,18%	0,12%	17,84%	50,89%	4,32%	24,23%	20,57%
R14,F05,C1	84,98%	0,95%	13,56%	0,50%	62,23%	10,12%	11,66%	15,98%
R14,F10,C1	38,94%	32,50%	0,13%	28,42%	65,18%	7,89%	10,11%	16,83%
R14,F01,C2	39,05%	32,08%	0,11%	28,76%	48,01%	5,82%	24,48%	21,69%
R14,F05,C2	48,30%	31,08%	0,09%	20,54%	66,57%	9,55%	10,49%	13,39%
R14,F10,C2	91,19%	5,83%	1,84%	1,14%	65,98%	14,02%	7,44%	12,56%
R14,F01,C8	33,25%	41,60%	12,64%	12,52%	56,26%	18,69%	17,94%	7,10%
R14,F05,C8	23,00%	50,67%	5,67%	20,67%	63,75%	19,75%	8,50%	8,00%
R14,F10,C8	30,22%	44,65%	3,40%	21,73%	62,47%	22,72%	6,91%	7,90%
R15,F01,C1	68,91%	2,40%	26,28%	2,40%	59,45%	8,33%	22,77%	9,45%
R15,F05,C1	60,11%	5,96%	30,64%	3,30%	66,99%	19,45%	6,85%	6,71%
R15,F10,C1	58,74%	5,86%	30,64%	4,76%	64,25%	25,64%	4,42%	5,70%
R15,F01,C2	67,13%	12,98%	8,29%	11,60%	65,56%	11,00%	15,77%	7,68%
R15,F05,C2	44,90%	29,20%	9,37%	16,53%	61,90%	26,59%	5,56%	5,95%
R15,F10,C2	56,91%	17,89%	8,67%	16,53%	60,15%	24,81%	6,39%	8,65%
R15,F01,C8	0,00%	2,47%	97,53%	0,00%	89,53%	1,16%	8,14%	1,16%
R15,F05,C8	0,00%	0,00%	100,00%	0,00%	91,40%	0,00%	7,53%	1,08%
R15,F10,C8	0,00%	0,00%	100,00%	0,00%	86,79%	0,00%	6,60%	6,60%
R16,F01,C1	52,25%	19,30%	0,01%	28,43%	37,18%	4,15%	15,59%	43,08%
R16,F05,C1	77,57%	19,78%	0,00%	2,66%	47,58%	4,35%	14,02%	34,06%
R16,F10,C1	86,66%	0,16%	13,08%	0,09%	57,72%	10,73%	10,46%	21,10%
R16,F01,C2	91,93%	0,30%	7,58%	0,19%	48,03%	6,79%	14,34%	30,83%
R16,F05,C2	68,20%	0,24%	31,37%	0,20%	59,21%	13,30%	8,08%	19,41%
R16,F10,C2	56,09%	0,19%	43,48%	0,25%	59,52%	19,45%	6,30%	14,73%
R16,F01,C8	87,81%	1,80%	9,92%	0,47%	51,30%	9,63%	13,50%	25,58%
R16,F05,C8	78,51%	0,76%	20,25%	0,49%	53,57%	21,45%	7,33%	17,65%
R16,F10,C8	74,83%	0,66%	23,97%	0,54%	51,56%	24,30%	6,71%	17,43%
R17,F01,C1	51,25%	0,61%	47,39%	0,75%	66,67%	9,92%	11,92%	11,48%
R17,F05,C1	43,34%	0,78%	54,98%	0,91%	64,24%	18,34%	7,59%	9,83%
R17,F10,C1	39,29%	1,05%	58,61%	1,05%	65,11%	22,11%	4,58%	8,20%
R17,F01,C2	51,31%	1,33%	46,30%	1,05%	66,91%	10,99%	9,98%	12,12%
R17,F05,C2	48,52%	1,57%	48,45%	1,47%	65,92%	17,63%	6,50%	9,95%
R17,F10,C2	41,16%	2,52%	54,85%	1,47%	63,82%	23,29%	4,12%	8,77%
R17,F01,C8	69,76%	11,07%	13,41%	5,76%	57,68%	17,94%	10,79%	13,60%
R17,F05,C8	66,97%	12,22%	12,52%	8,30%	52,23%	32,13%	4,30%	11,34%
R17,F10,C8	68,35%	13,87%	7,00%	10,78%	49,65%	35,04%	4,75%	10,56%
R18,F01,C1	50,07%	29,30%	0,00%	20,63%	48,13%	3,73%	31,87%	16,27%
R18,F05,C1	80,90%	4,09%	12,34%	2,67%	69,16%	12,47%	7,14%	11,22%
R18,F10,C1	74,54%	4,36%	16,46%	4,65%	64,77%	19,82%	5,81%	9,60%
R18,F01,C2	62,67%	23,96%	0,46%	12,90%	57,46%	9,48%	17,14%	15,93%
R18,F05,C2	64,92%	12,42%	10,24%	12,42%	66,86%	21,01%	2,96%	9,17%
R18,F10,C2	58,06%	15,44%	13,82%	12,67%	62,72%	25,74%	3,25%	8,28%
R18,F01,C8	20,14%	56,25%	1,39%	22,22%	51,28%	26,92%	10,26%	11,54%
R18,F05,C8	25,27%	46,15%	0,00%	28,57%	41,67%	33,33%	9,72%	15,28%
R18,F10,C8	27,16%	50,62%	0,00%	22,22%	39,74%	37,18%	8,97%	14,10%

Candidate selection for best neighbour solution, paramter setting 5								
Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	19,51%	43,44%	0,08%	36,97%	56,95%	6,02%	17,11%	19,92%
C20,230,200,F,L	18,42%	55,07%	0,20%	26,31%	73,87%	10,02%	7,27%	8,84%
C20,230,200,V,T	31,30%	45,61%	0,18%	22,90%	60,89%	7,90%	18,50%	12,72%
C20,230,200,F,T	27,53%	55,06%	0,74%	16,67%	73,50%	12,62%	7,26%	6,62%
C20,300,200,V,L	14,42%	52,50%	0,00%	33,08%	60,42%	7,50%	9,58%	22,50%
C20,300,200,F,L	23,11%	48,66%	0,00%	28,22%	67,57%	12,61%	7,66%	12,16%
C20,300,200,V,T	19,34%	48,36%	0,00%	32,30%	62,45%	7,43%	12,64%	17,47%
C20,300,200,F,T	24,93%	49,30%	0,00%	25,77%	76,88%	9,55%	6,03%	7,54%
C30,520,100,V,L	6,34%	55,62%	0,07%	37,97%	42,63%	3,47%	18,39%	35,51%
C30,520,100,F,L	14,69%	49,60%	0,16%	35,55%	61,57%	7,40%	6,77%	24,25%
C30,520,100,V,T	7,38%	52,15%	0,23%	40,23%	30,04%	2,70%	20,86%	46,40%
C30,520,100,F,T	14,78%	55,56%	0,24%	29,43%	55,29%	6,01%	7,45%	31,25%
C30,520,400,V,L	2,82%	38,03%	1,41%	57,75%	76,09%	10,87%	6,52%	6,52%
C30,520,400,F,L	20,88%	42,86%	0,00%	36,26%	65,22%	15,22%	8,70%	10,87%
C30,520,400,V,T	21,15%	48,08%	0,00%	30,77%	70,21%	21,28%	6,38%	2,13%
C30,520,400,F,T	21,79%	33,33%	0,00%	44,87%	78,13%	18,75%	0,00%	3,13%
C30,700,100,V,L	11,11%	50,34%	0,00%	38,56%	37,00%	2,92%	10,99%	49,09%
C30,700,100,F,L	13,41%	50,74%	0,00%	35,85%	54,71%	4,47%	10,51%	30,31%
C30,700,100,V,T	11,97%	52,40%	0,10%	35,53%	44,34%	4,41%	15,36%	35,89%
C30,700,100,F,T	14,29%	55,74%	0,00%	29,97%	49,06%	5,81%	10,86%	34,27%
C30,700,400,V,L	19,10%	41,57%	0,00%	39,33%	65,38%	23,08%	5,77%	5,77%
C30,700,400,F,L	22,22%	34,92%	0,00%	42,86%	74,29%	25,71%	0,00%	0,00%
C30,700,400,V,T	24,39%	41,46%	0,00%	34,15%	80,00%	20,00%	0,00%	0,00%
C30,700,400,F,T	13,33%	55,00%	0,00%	31,67%	60,00%	36,67%	0,00%	3,33%
R13,F01,C1	26,62%	40,02%	0,27%	33,10%	30,88%	2,48%	31,90%	34,74%
R13,F05,C1	65,12%	34,34%	0,00%	0,54%	42,46%	9,80%	19,69%	28,05%
R13,F10,C1	85,98%	0,70%	13,20%	0,12%	55,53%	15,78%	11,80%	16,89%
R13,F01,C2	85,25%	1,96%	12,63%	0,16%	51,79%	8,07%	20,12%	20,02%
R13,F05,C2	67,77%	0,34%	31,70%	0,19%	58,65%	16,34%	10,88%	14,13%
R13,F10,C2	54,42%	0,23%	45,22%	0,12%	59,85%	21,30%	8,08%	10,78%
R13,F01,C8	19,18%	60,98%	0,34%	19,50%	35,97%	3,25%	30,13%	30,64%
R13,F05,C8	22,61%	56,50%	0,10%	20,79%	44,73%	14,45%	17,30%	23,52%
R13,F10,C8	25,12%	53,34%	0,11%	21,43%	46,52%	19,48%	12,56%	21,43%
R14,F01,C1	23,16%	39,25%	0,09%	37,50%	45,39%	3,11%	24,46%	27,04%
R14,F05,C1	27,56%	51,74%	0,03%	20,66%	60,66%	5,06%	15,97%	18,32%
R14,F10,C1	84,30%	13,13%	1,88%	0,69%	67,30%	9,26%	9,15%	14,29%
R14,F01,C2	37,91%	56,16%	0,17%	5,76%	51,79%	6,85%	22,86%	18,49%
R14,F05,C2	82,43%	5,44%	10,75%	1,37%	66,02%	14,09%	8,56%	11,33%
R14,F10,C2	79,27%	3,52%	14,99%	2,22%	66,14%	19,02%	5,41%	9,43%
R14,F01,C8	21,00%	52,44%	8,85%	17,71%	53,95%	16,52%	15,47%	14,06%
R14,F05,C8	6,61%	56,61%	1,53%	35,25%	63,90%	17,07%	9,51%	9,51%
R14,F10,C8	5,51%	57,66%	1,89%	34,94%	69,15%	16,17%	5,72%	8,96%
R15,F01,C1	15,71%	42,54%	0,08%	41,67%	44,25%	2,06%	36,18%	17,50%
R15,F05,C1	27,03%	36,36%	0,00%	36,61%	69,48%	9,27%	11,80%	9,44%
R15,F10,C1	38,57%	41,38%	0,29%	19,77%	68,50%	16,01%	6,02%	9,47%
R15,F01,C2	18,92%	45,54%	0,24%	35,30%	61,09%	9,78%	18,70%	10,43%
R15,F05,C2	31,43%	37,86%	0,95%	29,76%	62,31%	22,01%	6,34%	9,33%
R15,F10,C2	34,31%	38,69%	0,24%	26,76%	59,76%	23,11%	7,97%	9,16%
R15,F01,C8	0,00%	1,41%	81,69%	16,90%	84,34%	0,00%	14,46%	1,20%
R15,F05,C8	0,00%	1,23%	86,42%	12,35%	88,89%	0,00%	8,64%	2,47%
R15,F10,C8	0,00%	2,82%	60,56%	36,62%	83,33%	2,38%	5,95%	8,33%
R16,F01,C1	37,12%	0,32%	62,27%	0,28%	62,18%	14,41%	9,00%	14,40%
R16,F05,C1	32,55%	0,31%	66,92%	0,22%	62,65%	19,82%	5,87%	11,67%
R16,F10,C1	32,79%	0,35%	66,69%	0,17%	62,16%	22,62%	4,99%	10,23%
R16,F01,C2	43,13%	0,56%	56,01%	0,31%	62,03%	12,66%	9,35%	15,96%
R16,F05,C2	35,91%	0,45%	63,45%	0,19%	62,94%	18,49%	6,03%	12,54%
R16,F10,C2	34,15%	0,39%	65,23%	0,23%	62,99%	21,53%	4,39%	11,09%
R16,F01,C8	55,30%	1,85%	42,34%	0,50%	61,57%	11,43%	9,93%	17,06%
R16,F05,C8	56,83%	1,24%	41,04%	0,89%	56,43%	22,43%	6,04%	15,10%
R16,F10,C8	55,55%	1,36%	42,36%	0,73%	53,96%	25,35%	5,61%	15,08%
R17,F01,C1	15,34%	45,76%	0,00%	38,90%	49,23%	2,94%	17,78%	30,05%
R17,F05,C1	24,71%	47,19%	0,00%	28,11%	60,98%	7,10%	11,13%	20,78%
R17,F10,C1	67,23%	31,15%	0,27%	1,36%	66,45%	10,20%	7,82%	15,53%
R17,F01,C2	43,96%	52,54%	0,09%	3,41%	53,97%	5,46%	14,76%	25,81%
R17,F05,C2	83,45%	7,14%	7,78%	1,63%	65,37%	12,23%	8,86%	13,54%
R17,F10,C2	74,52%	4,72%	18,44%	2,32%	66,03%	18,58%	4,90%	10,50%
R17,F01,C8	25,35%	45,92%	0,22%	28,51%	54,07%	14,94%	10,37%	20,62%
R17,F05,C8	37,94%	37,52%	0,00%	24,55%	52,23%	29,18%	5,76%	12,83%
R17,F10,C8	37,76%	37,61%	0,15%	24,48%	48,13%	31,67%	6,04%	14,17%
R18,F01,C1	51,44%	6,52%	38,40%	3,64%	61,49%	11,44%	17,80%	9,26%
R18,F05,C1	46,08%	5,88%	43,94%	4,10%	65,72%	21,80%	4,05%	8,43%
R18,F10,C1	47,25%	6,73%	40,97%	5,05%	61,61%	27,92%	3,89%	6,58%
R18,F01,C2	55,51%	16,29%	17,92%	10,28%	59,43%	13,35%	16,37%	10,85%
R18,F05,C2	50,82%	23,05%	15,64%	10,49%	66,37%	21,13%	3,27%	9,23%
R18,F10,C2	56,85%	19,92%	11,83%	11,41%	66,18%	23,82%	3,53%	6,47%
R18,F01,C8	8,28%	57,96%	1,27%	32,48%	52,94%	29,41%	8,24%	9,41%
R18,F05,C8	5,94%	53,47%	0,00%	40,59%	57,14%	28,57%	5,95%	8,33%
R18,F10,C8	4,94%	34,57%	0,00%	60,49%	53,42%	24,66%	8,22%	13,70%

Candidate selection for best neighbour solution, paramter setting 6

Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	15,07%	52,33%	0,00%	32,60%	49,02%	5,21%	19,74%	26,03%
C20,230,200,F,L	15,51%	60,84%	0,32%	23,34%	72,21%	10,92%	7,20%	9,68%
C20,230,200,V,T	33,38%	48,68%	0,00%	17,94%	57,60%	8,16%	21,09%	13,15%
C20,230,200,F,T	28,50%	60,45%	0,24%	10,81%	70,97%	12,10%	7,26%	9,68%
C20,300,200,V,L	34,08%	56,75%	0,16%	9,00%	58,33%	8,33%	14,91%	18,42%
C20,300,200,F,L	57,17%	28,87%	4,59%	9,37%	68,69%	14,49%	5,61%	11,22%
C20,300,200,V,T	65,51%	21,63%	6,20%	6,66%	63,25%	9,89%	14,49%	12,37%
C20,300,200,F,T	52,53%	23,52%	12,97%	10,99%	65,18%	23,66%	6,25%	4,91%
C30,520,100,V,L	64,85%	30,34%	2,12%	2,69%	54,78%	8,27%	12,93%	24,02%
C30,520,100,F,L	70,78%	11,01%	14,07%	4,14%	63,09%	13,43%	6,78%	16,69%
C30,520,100,V,T	35,64%	55,23%	2,40%	6,72%	46,34%	6,07%	16,83%	30,76%
C30,520,100,F,T	12,38%	58,11%	0,00%	29,51%	40,66%	6,43%	7,47%	45,44%
C30,520,400,V,L	2,47%	51,85%	0,00%	45,68%	60,00%	17,78%	4,44%	17,78%
C30,520,400,F,L	18,81%	40,59%	0,00%	40,59%	63,64%	20,45%	2,27%	13,64%
C30,520,400,V,T	16,39%	45,90%	0,00%	37,70%	80,95%	9,52%	2,38%	7,14%
C30,520,400,F,T	18,42%	40,79%	0,00%	40,79%	68,97%	31,03%	0,00%	0,00%
C30,700,100,V,L	15,81%	65,17%	0,04%	18,98%	41,81%	3,72%	14,79%	39,68%
C30,700,100,F,L	38,62%	56,59%	0,05%	4,73%	57,16%	6,66%	9,66%	26,53%
C30,700,100,V,T	11,28%	68,39%	0,00%	20,33%	43,46%	3,87%	14,73%	37,94%
C30,700,100,F,T	30,99%	59,88%	0,23%	8,90%	54,44%	8,02%	7,34%	30,20%
C30,700,400,V,L	22,77%	52,48%	0,00%	24,75%	60,00%	26,67%	4,44%	8,89%
C30,700,400,F,L	37,74%	28,30%	0,00%	33,96%	73,08%	26,92%	0,00%	0,00%
C30,700,400,V,T	25,42%	38,98%	0,00%	35,59%	52,00%	44,00%	0,00%	4,00%
C30,700,400,F,T	29,63%	48,15%	0,00%	22,22%	53,57%	32,14%	0,00%	14,29%
R13,F01,C1	26,01%	44,73%	0,01%	29,25%	21,47%	1,90%	38,50%	38,13%
R13,F05,C1	70,47%	29,35%	0,01%	0,17%	39,32%	9,94%	19,27%	31,47%
R13,F10,C1	83,95%	0,66%	15,29%	0,10%	52,75%	20,42%	11,42%	15,41%
R13,F01,C2	83,29%	1,77%	14,76%	0,18%	53,90%	8,39%	17,95%	19,77%
R13,F05,C2	65,83%	0,39%	33,67%	0,11%	57,02%	20,54%	9,93%	12,51%
R13,F10,C2	41,50%	38,48%	0,00%	20,02%	43,06%	7,20%	17,51%	32,23%
R13,F01,C8	18,27%	61,18%	7,03%	13,52%	39,65%	3,34%	27,66%	29,35%
R13,F05,C8	19,58%	61,48%	1,69%	17,25%	42,93%	12,94%	17,22%	26,91%
R13,F10,C8	26,76%	56,18%	2,66%	14,40%	44,43%	18,58%	14,04%	22,95%
R14,F01,C1	20,92%	44,31%	0,01%	34,76%	35,98%	2,94%	29,81%	31,27%
R14,F05,C1	29,57%	54,61%	0,02%	15,80%	57,49%	5,75%	16,25%	20,52%
R14,F10,C1	87,96%	8,70%	2,97%	0,37%	66,26%	12,12%	9,51%	12,12%
R14,F01,C2	43,36%	53,89%	0,61%	2,14%	50,16%	6,29%	24,32%	19,23%
R14,F05,C2	85,43%	4,04%	9,79%	0,73%	65,46%	15,44%	8,86%	10,24%
R14,F10,C2	75,64%	3,71%	19,62%	1,03%	59,71%	25,51%	5,47%	9,31%
R14,F01,C8	14,81%	38,49%	35,75%	10,94%	56,85%	17,81%	15,41%	9,93%
R14,F05,C8	10,96%	57,37%	4,75%	26,92%	57,72%	21,01%	10,38%	10,89%
R14,F10,C8	9,39%	53,66%	4,88%	32,07%	57,91%	23,72%	7,65%	10,71%
R15,F01,C1	10,94%	48,03%	0,12%	40,91%	42,10%	2,33%	33,94%	21,63%
R15,F05,C1	32,30%	34,67%	0,00%	33,03%	69,02%	7,69%	13,51%	9,77%
R15,F10,C1	43,29%	39,25%	0,23%	17,23%	67,30%	15,50%	7,64%	9,55%
R15,F01,C2	16,00%	51,99%	0,11%	31,90%	56,76%	9,46%	20,54%	13,24%
R15,F05,C2	32,89%	38,19%	0,95%	27,98%	61,90%	20,48%	8,10%	9,52%
R15,F10,C2	37,36%	39,34%	0,00%	23,30%	59,61%	19,21%	7,88%	13,30%
R15,F01,C8	0,00%	14,08%	59,15%	26,76%	87,50%	0,00%	8,75%	3,75%
R15,F05,C8	0,00%	0,00%	100,00%	0,00%	90,00%	0,00%	5,00%	5,00%
R15,F10,C8	0,00%	0,00%	82,00%	18,00%	92,22%	1,11%	2,22%	4,44%
R16,F01,C1	39,91%	49,61%	0,01%	10,48%	32,40%	5,09%	15,92%	46,59%
R16,F05,C1	89,33%	1,35%	9,19%	0,12%	55,36%	10,15%	10,67%	23,82%
R16,F10,C1	68,81%	0,56%	30,42%	0,21%	56,04%	21,76%	6,88%	15,32%
R16,F01,C2	74,73%	0,73%	24,31%	0,23%	55,08%	11,46%	10,00%	23,46%
R16,F05,C2	55,61%	0,44%	43,82%	0,13%	57,93%	21,59%	6,38%	14,09%
R16,F10,C2	42,73%	36,89%	0,00%	20,38%	45,20%	5,48%	13,19%	36,13%
R16,F01,C8	13,83%	61,68%	0,00%	24,49%	28,81%	4,67%	16,63%	49,89%
R16,F05,C8	27,20%	49,37%	0,00%	23,43%	39,64%	12,66%	12,74%	34,97%
R16,F10,C8	46,53%	46,17%	0,01%	7,29%	41,50%	16,05%	10,42%	32,04%
R17,F01,C1	12,00%	48,49%	0,00%	39,51%	44,11%	2,67%	17,43%	35,79%
R17,F05,C1	22,97%	51,71%	0,00%	25,31%	59,89%	7,63%	11,74%	20,75%
R17,F10,C1	73,02%	26,11%	0,14%	0,73%	66,73%	10,54%	7,68%	15,05%
R17,F01,C2	45,30%	52,93%	0,16%	1,61%	53,72%	4,85%	15,89%	25,54%
R17,F05,C2	82,82%	4,34%	11,74%	1,11%	64,23%	15,59%	8,09%	12,09%
R17,F10,C2	69,65%	2,24%	26,64%	1,46%	59,98%	25,59%	5,07%	9,37%
R17,F01,C8	24,22%	54,04%	0,60%	21,14%	49,87%	14,68%	14,42%	21,04%
R17,F05,C8	46,94%	37,13%	0,47%	15,46%	51,71%	26,21%	6,82%	15,26%
R17,F10,C8	47,89%	40,32%	0,21%	11,58%	46,19%	31,14%	6,36%	16,31%
R18,F01,C1	68,32%	27,38%	1,51%	2,79%	52,75%	5,29%	27,53%	14,43%
R18,F05,C1	65,68%	5,63%	25,67%	3,02%	62,81%	23,55%	5,79%	7,85%
R18,F10,C1	55,64%	7,06%	33,77%	3,53%	62,78%	30,79%	2,28%	4,15%
R18,F01,C2	65,33%	22,48%	4,90%	7,29%	58,92%	8,82%	17,42%	14,84%
R18,F05,C2	59,97%	13,78%	17,74%	8,50%	60,29%	27,94%	2,94%	8,82%
R18,F10,C2	54,09%	13,64%	23,76%	8,51%	58,88%	33,02%	3,43%	4,67%
R18,F01,C8	9,50%	67,50%	1,50%	21,50%	50,00%	30,26%	7,89%	11,84%
R18,F05,C8	6,38%	58,87%	0,71%	34,04%	60,61%	24,24%	4,55%	10,61%
R18,F10,C8	6,61%	52,89%	0,00%	40,50%	45,16%	27,42%	8,06%	19,35%

Candidate selection for best neighbour solution, paramter setting 7								
Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	29,50%	38,58%	0,00%	31,91%	57,68%	5,54%	19,29%	17,50%
C20,230,200,F,L	28,44%	48,19%	0,21%	23,16%	76,48%	10,96%	3,42%	9,13%
C20,230,200,V,T	38,56%	40,84%	0,09%	20,51%	60,49%	5,91%	15,48%	18,13%
C20,230,200,F,T	31,05%	42,43%	0,47%	26,05%	70,98%	13,33%	9,02%	6,67%
C20,300,200,V,L	27,27%	49,26%	0,21%	23,26%	62,17%	4,78%	12,61%	20,43%
C20,300,200,F,L	28,98%	44,91%	0,00%	26,11%	67,14%	13,15%	5,63%	14,08%
C20,300,200,V,T	26,56%	42,95%	0,00%	30,49%	66,04%	4,91%	10,94%	18,11%
C20,300,200,F,T	31,02%	35,48%	0,00%	33,50%	68,84%	11,56%	8,54%	11,06%
C30,520,100,V,L	16,52%	48,53%	0,53%	34,43%	46,61%	3,19%	16,52%	33,68%
C30,520,100,F,L	28,98%	41,05%	0,00%	29,97%	58,68%	6,11%	8,36%	26,85%
C30,520,100,V,T	16,26%	48,66%	0,20%	34,88%	32,01%	3,30%	19,64%	45,05%
C30,520,100,F,T	29,23%	41,14%	0,10%	29,53%	52,70%	9,34%	8,09%	29,88%
C30,520,400,V,L	17,28%	44,44%	1,23%	37,04%	60,53%	21,05%	7,89%	10,53%
C30,520,400,F,L	33,33%	36,78%	0,00%	29,89%	79,41%	20,59%	0,00%	0,00%
C30,520,400,V,T	25,40%	44,44%	0,00%	30,16%	60,38%	24,53%	7,55%	7,55%
C30,520,400,F,T	31,17%	33,77%	0,00%	35,06%	70,97%	25,81%	3,23%	0,00%
C30,700,100,V,L	20,40%	44,38%	0,04%	35,19%	36,43%	2,14%	13,06%	48,37%
C30,700,100,F,L	22,94%	45,24%	0,00%	31,82%	55,73%	6,00%	8,27%	30,00%
C30,700,100,V,T	16,85%	44,79%	0,00%	38,36%	38,26%	4,05%	17,41%	40,28%
C30,700,100,F,T	24,26%	42,41%	0,00%	33,33%	51,39%	4,50%	10,71%	33,40%
C30,700,400,V,L	30,86%	33,33%	0,00%	35,80%	52,94%	33,33%	5,88%	7,84%
C30,700,400,F,L	36,54%	28,85%	0,00%	34,62%	70,97%	29,03%	0,00%	0,00%
C30,700,400,V,T	34,67%	24,00%	0,00%	41,33%	63,33%	23,33%	0,00%	13,33%
C30,700,400,F,T	30,00%	37,14%	0,00%	32,86%	66,67%	25,93%	0,00%	7,41%
R13,F01,C1	39,67%	34,79%	0,00%	25,54%	28,17%	1,96%	33,76%	36,11%
R13,F05,C1	65,68%	28,55%	0,01%	5,76%	40,11%	8,13%	19,26%	32,50%
R13,F10,C1	82,32%	17,60%	0,00%	0,08%	51,35%	9,34%	14,46%	24,85%
R13,F01,C2	56,11%	40,89%	0,01%	2,99%	38,09%	4,25%	27,78%	29,88%
R13,F05,C2	90,12%	9,73%	0,01%	0,13%	48,43%	9,79%	15,79%	25,99%
R13,F10,C2	55,60%	27,37%	0,02%	17,01%	46,28%	8,20%	17,14%	28,39%
R13,F01,C8	24,57%	57,55%	0,48%	17,40%	35,10%	3,40%	30,20%	31,29%
R13,F05,C8	32,41%	49,96%	0,19%	17,44%	43,80%	13,78%	16,45%	25,98%
R13,F10,C8	34,66%	46,53%	0,21%	18,60%	47,22%	17,08%	13,57%	22,13%
R14,F01,C1	43,89%	43,68%	0,02%	12,40%	48,90%	3,65%	24,65%	22,80%
R14,F05,C1	96,72%	2,32%	0,54%	0,42%	63,32%	5,50%	14,31%	16,86%
R14,F10,C1	34,34%	37,37%	0,06%	28,22%	64,14%	7,36%	9,87%	18,64%
R14,F01,C2	29,82%	38,33%	0,03%	31,82%	45,88%	5,09%	23,49%	25,54%
R14,F05,C2	36,43%	37,62%	0,06%	25,90%	64,99%	8,12%	10,85%	16,03%
R14,F10,C2	38,70%	37,68%	0,04%	23,59%	61,90%	10,45%	9,52%	18,12%
R14,F01,C8	35,77%	47,85%	1,16%	15,21%	55,63%	9,55%	20,81%	14,01%
R14,F05,C8	27,71%	51,39%	0,77%	20,12%	63,68%	17,65%	8,95%	9,72%
R14,F10,C8	21,26%	54,59%	0,48%	23,67%	60,99%	20,33%	9,34%	9,34%
R15,F01,C1	23,50%	37,59%	0,04%	38,87%	42,92%	2,36%	37,45%	17,27%
R15,F05,C1	40,12%	30,23%	0,00%	29,65%	71,10%	7,79%	10,65%	10,46%
R15,F10,C1	47,63%	27,20%	0,29%	24,88%	69,40%	13,65%	7,02%	9,94%
R15,F01,C2	20,58%	37,55%	0,29%	41,58%	59,22%	9,35%	21,56%	9,87%
R15,F05,C2	33,92%	33,17%	0,00%	32,92%	67,21%	18,03%	7,38%	7,38%
R15,F10,C2	46,49%	28,11%	0,00%	25,41%	59,75%	24,58%	7,20%	8,47%
R15,F01,C8	0,00%	9,86%	76,06%	14,08%	80,77%	0,00%	17,95%	1,28%
R15,F05,C8	0,00%	0,00%	80,28%	19,72%	89,19%	0,00%	5,41%	5,41%
R15,F10,C8	0,00%	12,68%	39,44%	47,89%	80,72%	0,00%	13,25%	6,02%
R16,F01,C1	75,19%	0,14%	24,58%	0,09%	55,47%	7,78%	11,77%	24,99%
R16,F05,C1	57,27%	0,20%	42,45%	0,08%	61,89%	13,55%	8,45%	16,12%
R16,F10,C1	48,83%	0,17%	50,89%	0,11%	62,35%	17,71%	6,74%	13,20%
R16,F01,C2	63,17%	0,20%	36,48%	0,15%	58,49%	10,46%	10,55%	20,51%
R16,F05,C2	53,45%	0,22%	46,19%	0,14%	62,27%	14,91%	6,96%	15,86%
R16,F10,C2	48,57%	0,26%	51,03%	0,14%	61,72%	19,51%	5,62%	13,14%
R16,F01,C8	79,23%	0,85%	19,56%	0,36%	54,87%	10,28%	12,98%	21,87%
R16,F05,C8	75,61%	0,89%	23,00%	0,50%	55,95%	18,82%	7,03%	18,19%
R16,F10,C8	71,46%	0,68%	27,34%	0,52%	52,21%	24,47%	6,12%	17,20%
R17,F01,C1	23,99%	39,74%	0,01%	36,25%	47,44%	2,50%	19,94%	30,12%
R17,F05,C1	31,30%	35,69%	0,00%	33,01%	60,55%	6,72%	10,68%	22,05%
R17,F10,C1	41,56%	42,74%	0,00%	15,70%	65,66%	8,78%	7,97%	17,60%
R17,F01,C2	32,40%	37,07%	0,00%	30,52%	51,16%	3,87%	15,04%	29,94%
R17,F05,C2	45,47%	38,29%	0,00%	16,25%	63,56%	9,61%	8,96%	17,87%
R17,F10,C2	57,91%	39,12%	0,00%	2,98%	67,27%	12,38%	7,35%	13,00%
R17,F01,C8	35,59%	36,09%	0,43%	27,89%	52,11%	14,19%	11,73%	21,96%
R17,F05,C8	49,88%	27,28%	0,00%	22,84%	51,47%	26,03%	8,61%	13,89%
R17,F10,C8	52,94%	27,49%	0,00%	19,57%	49,49%	30,22%	4,46%	15,82%
R18,F01,C1	86,96%	9,73%	0,86%	2,46%	49,47%	4,95%	30,42%	15,16%
R18,F05,C1	76,60%	4,58%	16,15%	2,66%	67,40%	13,85%	6,62%	12,13%
R18,F10,C1	72,67%	5,54%	17,72%	4,06%	67,47%	19,87%	4,27%	8,40%
R18,F01,C2	56,86%	34,14%	0,12%	8,88%	57,67%	9,61%	14,11%	18,61%
R18,F05,C2	72,49%	15,99%	1,07%	10,45%	66,45%	15,48%	6,45%	11,61%
R18,F10,C2	75,16%	13,61%	0,86%	10,37%	71,28%	18,34%	4,50%	5,88%
R18,F01,C8	19,05%	58,33%	0,60%	22,02%	45,98%	29,89%	11,49%	12,64%
R18,F05,C8	16,22%	56,76%	0,00%	27,03%	62,96%	23,46%	6,17%	7,41%
R18,F10,C8	6,17%	58,02%	0,00%	35,80%	73,44%	12,50%	4,69%	9,38%

Candidate selection for best neighbour solution, paramter setting 8

Data set	Phase 1				Phase 2			
	fixed cost	residual cost	penalty cost	variable cost	flow path, close	max.fix. cost path, close	var. cost path, open	fix. cost path, open
C20,230,200,V,L	12,31%	60,08%	0,00%	27,61%	50,53%	5,54%	20,90%	23,03%
C20,230,200,F,L	9,29%	67,86%	0,78%	22,06%	69,83%	9,98%	6,48%	13,72%
C20,230,200,V,T	18,76%	56,83%	0,54%	23,86%	56,92%	5,58%	17,41%	20,09%
C20,230,200,F,T	11,92%	62,48%	0,32%	25,28%	71,72%	6,97%	11,07%	10,25%
C20,300,200,V,L	18,90%	61,57%	0,21%	19,32%	59,14%	3,89%	14,40%	22,57%
C20,300,200,F,L	22,41%	55,91%	0,00%	21,67%	59,73%	10,62%	13,72%	15,93%
C20,300,200,V,T	19,96%	61,04%	0,58%	18,43%	59,85%	8,88%	14,29%	16,99%
C20,300,200,F,T	24,43%	59,09%	0,28%	16,19%	69,85%	10,55%	7,04%	12,56%
C30,520,100,V,L	5,93%	63,79%	0,08%	30,19%	43,38%	4,21%	18,12%	34,29%
C30,520,100,F,L	19,31%	66,31%	0,00%	14,38%	55,83%	5,83%	11,81%	26,54%
C30,520,100,V,T	6,64%	69,73%	0,88%	22,74%	35,62%	4,35%	24,08%	35,95%
C30,520,100,F,T	16,70%	64,47%	0,00%	18,83%	49,45%	7,48%	10,95%	32,12%
C30,520,400,V,L	1,92%	69,23%	0,00%	28,85%	57,14%	30,95%	4,76%	7,14%
C30,520,400,F,L	18,31%	47,89%	0,00%	33,80%	65,85%	24,39%	4,88%	4,88%
C30,520,400,V,T	1,96%	50,98%	0,00%	47,06%	72,34%	17,02%	4,26%	6,38%
C30,520,400,F,T	25,49%	47,06%	0,00%	27,45%	54,76%	38,10%	2,38%	4,76%
C30,700,100,V,L	4,36%	66,13%	0,00%	29,51%	22,40%	1,12%	12,32%	64,17%
C30,700,100,F,L	6,99%	61,59%	0,00%	31,42%	42,78%	3,40%	12,89%	40,93%
C30,700,100,V,T	2,50%	73,46%	0,39%	23,65%	28,22%	1,46%	14,36%	55,96%
C30,700,100,F,T	10,30%	61,06%	0,00%	28,64%	40,81%	2,47%	13,23%	43,50%
C30,700,400,V,L	14,75%	52,46%	0,00%	32,79%	50,00%	36,54%	3,85%	9,62%
C30,700,400,F,L	34,15%	31,71%	0,00%	34,15%	65,63%	31,25%	0,00%	3,13%
C30,700,400,V,T	19,35%	48,39%	0,00%	32,26%	55,17%	44,83%	0,00%	0,00%
C30,700,400,F,T	7,84%	56,86%	1,96%	33,33%	51,52%	36,36%	6,06%	6,06%
R13,F01,C1	20,01%	53,79%	0,07%	26,13%	22,01%	1,84%	39,31%	36,84%
R13,F05,C1	44,77%	51,58%	0,00%	3,65%	33,56%	7,72%	21,02%	37,69%
R13,F10,C1	59,38%	40,53%	0,00%	0,09%	48,38%	9,20%	14,98%	27,44%
R13,F01,C2	28,00%	71,21%	0,10%	0,68%	35,01%	3,57%	28,95%	32,47%
R13,F05,C2	64,98%	34,85%	0,07%	0,09%	45,57%	10,06%	17,54%	26,83%
R13,F10,C2	91,77%	5,67%	2,45%	0,12%	53,61%	12,98%	12,17%	21,25%
R13,F01,C8	12,72%	76,23%	1,25%	9,79%	24,47%	1,61%	34,86%	39,05%
R13,F05,C8	14,03%	69,77%	0,03%	16,18%	34,68%	7,87%	22,23%	35,22%
R13,F10,C8	15,72%	67,20%	0,08%	17,00%	35,53%	11,71%	20,45%	32,32%
R14,F01,C1	23,53%	61,20%	0,06%	15,21%	43,04%	3,15%	27,38%	26,43%
R14,F05,C1	47,13%	52,39%	0,08%	0,39%	61,02%	5,45%	15,58%	17,95%
R14,F10,C1	20,32%	53,20%	0,15%	26,32%	63,60%	5,61%	10,94%	19,85%
R14,F01,C2	17,70%	56,29%	0,07%	25,94%	37,80%	2,99%	28,11%	31,10%
R14,F05,C2	25,40%	48,84%	0,06%	25,71%	55,60%	8,03%	14,76%	21,61%
R14,F10,C2	27,49%	51,72%	0,00%	20,79%	59,50%	9,53%	10,88%	20,09%
R14,F01,C8	10,76%	61,01%	11,27%	16,96%	49,05%	8,97%	24,81%	17,18%
R14,F05,C8	9,54%	63,37%	3,92%	23,17%	56,65%	15,16%	11,97%	16,22%
R14,F10,C8	7,23%	62,31%	0,86%	29,60%	61,64%	11,78%	10,41%	16,16%
R15,F01,C1	8,38%	54,40%	0,14%	37,08%	35,19%	2,51%	38,15%	24,15%
R15,F05,C1	20,09%	45,71%	0,18%	34,01%	65,52%	8,00%	11,43%	15,05%
R15,F10,C1	33,91%	38,87%	0,61%	26,62%	67,34%	14,00%	9,33%	9,33%
R15,F01,C2	11,43%	56,01%	0,43%	32,13%	53,89%	6,97%	24,93%	14,21%
R15,F05,C2	23,68%	45,03%	0,29%	30,99%	62,73%	15,91%	10,00%	11,36%
R15,F10,C2	20,51%	48,40%	0,00%	31,09%	51,17%	27,23%	6,57%	15,02%
R15,F01,C8	0,00%	14,29%	54,29%	31,43%	78,95%	2,63%	15,79%	2,63%
R15,F05,C8	0,00%	1,67%	43,33%	55,00%	84,51%	0,00%	11,27%	4,23%
R15,F10,C8	0,00%	8,57%	15,71%	75,71%	85,54%	0,00%	8,43%	6,02%
R16,F01,C1	74,01%	0,53%	25,29%	0,17%	53,87%	10,80%	11,84%	23,48%
R16,F05,C1	58,50%	0,33%	41,01%	0,16%	57,20%	18,40%	8,42%	15,97%
R16,F10,C1	48,09%	0,27%	51,55%	0,09%	58,92%	22,37%	6,07%	12,64%
R16,F01,C2	64,12%	0,46%	35,25%	0,17%	56,62%	12,05%	10,40%	20,93%
R16,F05,C2	53,28%	0,45%	46,19%	0,08%	59,09%	18,39%	6,72%	15,80%
R16,F10,C2	45,03%	0,40%	54,45%	0,12%	58,93%	23,29%	5,38%	12,40%
R16,F01,C8	47,74%	25,78%	26,05%	0,43%	53,73%	9,95%	13,11%	23,21%
R16,F05,C8	72,59%	2,83%	24,13%	0,45%	53,40%	19,67%	8,44%	18,49%
R16,F10,C8	71,85%	2,52%	25,21%	0,42%	51,76%	24,05%	7,11%	17,09%
R17,F01,C1	9,10%	51,54%	0,02%	39,35%	43,26%	1,46%	21,20%	34,08%
R17,F05,C1	18,85%	51,89%	0,00%	29,26%	58,69%	6,27%	10,69%	24,35%
R17,F10,C1	25,61%	60,69%	0,00%	13,70%	63,99%	8,38%	9,49%	18,14%
R17,F01,C2	15,30%	60,58%	0,04%	24,08%	44,36%	3,36%	19,61%	32,67%
R17,F05,C2	29,71%	59,92%	0,03%	10,34%	60,90%	8,55%	10,55%	20,00%
R17,F10,C2	39,93%	57,46%	0,04%	2,57%	66,42%	10,78%	7,09%	15,71%
R17,F01,C8	14,48%	57,92%	0,76%	26,84%	45,33%	9,49%	17,71%	27,48%
R17,F05,C8	30,35%	50,00%	0,00%	19,65%	50,61%	18,03%	9,43%	21,93%
R17,F10,C8	27,53%	48,41%	0,00%	24,05%	45,88%	23,39%	8,24%	22,49%
R18,F01,C1	57,67%	37,55%	1,52%	3,27%	49,90%	4,33%	27,97%	17,81%
R18,F05,C1	74,93%	8,27%	13,17%	3,63%	68,04%	14,73%	5,12%	12,11%
R18,F10,C1	70,11%	8,75%	17,31%	3,83%	66,05%	21,30%	5,06%	7,59%
R18,F01,C2	31,96%	57,18%	0,87%	9,99%	55,80%	8,10%	20,79%	15,32%
R18,F05,C2	48,88%	41,34%	1,63%	8,15%	70,59%	13,40%	6,54%	9,48%
R18,F10,C2	44,93%	42,17%	1,61%	11,29%	71,33%	15,70%	3,41%	9,56%
R18,F01,C8	9,70%	70,15%	2,24%	17,91%	50,68%	16,44%	20,55%	12,33%
R18,F05,C8	2,20%	63,74%	1,10%	32,97%	60,56%	16,90%	11,27%	11,27%
R18,F10,C8	3,70%	61,73%	0,00%	34,57%	55,38%	21,54%	6,15%	16,92%

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ISSN-1600 1575
ISBN-87-91137-17-9