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DECISION SUPPORT SYSTEMS HELP RAILNED TO SEARCH FOR 'WIN-WIN' SOLUTIONS IN RAILWAY NETWORK DESIGN

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Decision Support Systems help Railned to search for 'win-win' solutions in railway network design

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Railned BV advises the Dutch government on the investments in future railway infrastructure (tracks, stations, fly-overs, tunnels, security systems, energy supply systems, etc). For this purpose, Railned generates and evaluates infrastructural scenarios. These scenarios stem from governmental objectives and those of exploiters of the railway network, the Dutch railway company Nederlandse Spoorwegen (NS) being by far the largest. A major problem with these scenarios is that the government and NS have different objectives, which may be conflicting sometimes. The government finances and manages the infrastructure, and her main objective is to not exceed budget limits while meeting at the same time social and environmental priorities. NS exploits the infrastructure, and wishes to have an infrastructure that guarantees long-term profitability. To generate and evaluate infrastructural scenarios, Railned uses various Decision Support Systems (DSS). These DSSs have shown to be very successful in helping to find and analyze scenarios that yield 'win-win' solutions to the Dutch government and to NS.

In 1995 the railway network in the Netherlands consisted of about 2,800 railway kilometres, 400 stations, and handled each day about 5,000 trains. The network is operated by the Dutch railway company Nederlandse Spoorwegen (NS), which transported in 1995 about 1,000,000 passengers and 60,000 tons of cargo per day [NS homepage, 1996]. All railway infrastructure is financed and managed by the Dutch government. The rolling stock is owned and managed by NS.

At this time, the Dutch government and NS are under rather heavy pressure. Each day there are many traffic congestions on the Dutch highways, causing large economical and ecological damages. The Dutch government wants to reduce these damages by stimulating the use of trains for passenger and cargo transport.

In the urban (western) part of the country, with major cities like Amsterdam, Rotterdam, The Hague, and Utrecht, NS is faced with a substantial increase in the number of passengers over the past few years. The existing capacity of the trains and the railway infrastructure is hardly sufficient to handle the passenger flows, resulting in many train delays and complaints about service. Furthermore, the prices of train tickets are relatively high compared to the variable costs of travelling by car [Tielemans, 1995]. Further price increases in combination with low perceived service will let many train passengers decide to travel by car. The tariffs for rail cargo should also not further increase, since the tariffs for road cargo and shipping are relatively low and road cargo is also more flexible than rail cargo.

Another problem is that the traffic intensity in the regional parts of the country is less than the traffic intensity in the urban parts. Due to economies of scale effects, the profit per passenger kilometre in the regional areas is much lower than in the urban areas (several lines even cause a loss to NS). For the time being, NS has agreed with the government not to close all stations or lines in less profitable areas, even though NS has been privatized.

Finally, NS is confronted with a directive by the European Union allowing for competition on the railway network. In the near future, the 'monopolist' NS may therefore expect competitors to share the infrastructure with. In fact, at the moment of writing, a second exploiter has entered the railway network and others are expected to follow. However, to avoid obscuring the main point of this paper, the name NS will often be used throughout to denote all (future) railway exploiters together.

At the time NS was privatized, another (independent) organization called Railned was erected. Among other things, its task is to advise the government on investments in railway infrastructure and to balance the demands for capacity of competing exploiters. In this paper we focus on the former task which is much more difficult than before for two reasons. First of all, in the period stretching from 1985 to approximately 2010 large amounts of money will be invested in the railway network. Up to 1985, investments were mainly restricted to the upkeep of the infrastructure. Second, designing infrastructure to the satisfaction of more than one railway exploiter is clearly much more difficult than before when NS was a monopolist.

Rail 21

To meet the requirements for attractive and efficient railway services in the 21-*st* century, the Dutch government initially budgeted about 17 billion guilders for a project named *Rail 21* [Badcock, 1996]. This budget should mainly be used to develop new railway infrastructure and to improve the existing railway infrastructure between now and 2010. To keep this large scale project manageable, it has been subdivided into a number of subsequent phases. The first phase of Rail 21 will be finished in 1998. The total investments were 6 billion guilders. The second phase starts in 1998 and is planned to be finished in 2005. For the second phase also a budget of 6.5 billion guilders will be available, apart from about 20 billion guilders for new high speed lines (connections Amsterdam-Brussels/Paris and Amsterdam-Cologn) and a cargo line connecting the Port of Rotterdam to Germany.

Railned's role in the second phase has been to develop and evaluate alternative infrastructural proposals, and to fulfil an advisory role to the government in deciding which proposal(s) finally to implement.

Ideally, the proposals should match the *governmental priorities* on the one hand, and the *wishes of NS* on the other hand. One governmental priority has been the reduction of road traffic in the metropolitan area between Amsterdam, Rotterdam, The Hague and Utrecht. In this context, further improvements of the existing railway infrastructure between these cities and their suburbs are needed. Also, plans for new infrastructure to integrate the urban transportation systems (busses, trams and metro) with the existing railway system are studied.

The government formulated as a second priority the stimulation of regional economies by improvements of the railway connections between the smaller cities outside the metropolitan areas and the regional areas.

A third priority of the government is to stimulate rail cargo. For this purpose, further extensions of the existing railway infrastructure to transport cargo between the national mainports (Amsterdam Airport and the Port of Rotterdam) and the metropolitan areas in the Netherlands and Germany are necessary.

Finally, a last governmental priority is to reduce the number of short-distance passenger flights in Europe. For this purpose plans have been made to develop new infrastructure for a European network of high speed trains.

The wishes of NS are all in the context of efficiency and service improvements to establish long-term profitability. They include for instance the elimination of a number of historical infrastructural bottlenecks to obtain shorter travel times and to improve the reliability of the railway services (i.e., to minimize the delays), more frequent train services, shorter transfer times between trains, and more comfortable stations. Other prominent wishes of NS are a more powerful energy supply system to be able to use the infrastructure better, and an improvement of the safety around railway cross-overs to reduce the number of accidents.

Infrastructural cocktails

Based on the governmental priorities and budgets on one hand, and the wishes of NS on the other hand, Railned has developed a number of alternative infrastructural 'cocktails' (proposals) [Badcock 1996, Railned 1995]. All cocktails consist of investments to eliminate bottlenecks and to improve the power supply and safety of railway operations. The cocktails differ in the emphasis they give to each of the governmental priorities. The *'Metropolitan cocktail'* consists of a relatively large number of projects in the metropolitan area (see Table 1 and Figure 1). In the *'Mainport cocktail'* the majority of the projects relate to further improvements of the railway infrastructure in the mainport area (Amsterdam Airport and the Port of Rotterdam), and in the *'Regional cocktail'* the main emphasis is on projects in regional areas. Also, extensions of the Mainport and Metropolitan cocktail were considered including a 1.2 billion guilder investment to develop a new railway connection (the 'Hanze-line') between Lelystad and Zwolle. The Hanze-line is considered by the government as important, since it stimulates the development of several regional areas in the Netherlands.

Table 1. Projects in the Metropolitan cocktail.

Project	Investments (in million guilders)
Amsterdam WTC area 4 tracks (instead of 2)	66
Amsterdam CS-Utrecht CS trajectory 4 tracks (instead of 2)	1,270
Utrecht CS-Geldermalsen trajectory 4 tracks (instead of 2)	626
Vleuten-Utrecht CS trajectory 4 tracks (instead of 2)	326
Various capacity extensions around Utrecht CS	306
Various capacity extensions around Arnhem	117
Capacity extension at the Hemboog	306
Various capacity extensions at the Flevoline	92
Various safety improvements at cross-overs	333
Various station improvements	100
Various small projects (including energy supply)	170

Cocktail generation

To compose the list of projects corresponding to each cocktail, Railned has followed an iterative procedure (see Figure 2). In *Step 1* for each cocktail an initial list of projects has been composed by a team consisting of experts from Railned and the government, supported by experts from NS. The projects were chosen such that they match the particular objectives of the cocktail (for example, the stimulation of the regional economies for the Regional cocktail) and such that various well-known bottlenecks in the current railway network are eliminated. Of course, the total project investments must remain within the governmental budgets (recall that for the second phase of Rail 21 a budget of 6.5 billion guilders is available) and the projects must be chosen such that they match the long term-profitability and customer service requirements of NS as well as possible.

In *Step 2* the *'National Mobility Model'* is used to estimate at a high level of geographical detail the number of train passengers that NS may expect to be transported in the forthcoming years when the (initial) list of projects will be implemented.

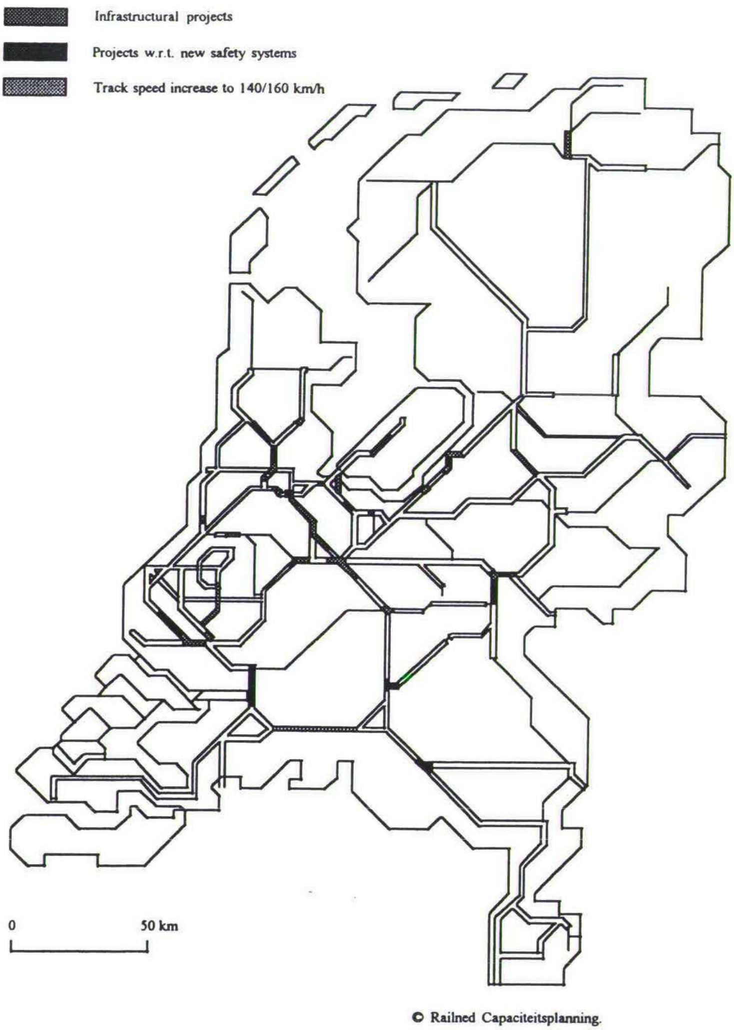

Figure 1: Geographical overview of projects in the Metropolitan cocktail (1998-2005).

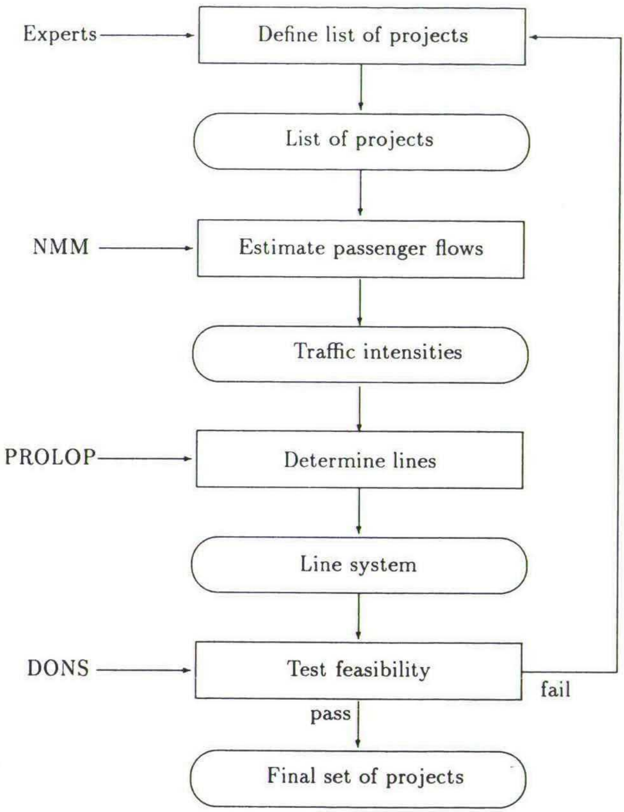

Figure 2: Defining a cocktail.

These estimates are used in *Step 3* by a Decision Support System named *'PROLOP'* to develop a consistent network of railway *lines* (i.e. direct railway connections) and to set the hourly frequency of each line, such that the customer service standards of NS' marketing department (NS Marketing) are satisfied.

To check whether the capacity of the railway infrastructure is sufficient to handle all the train movements proposed by PROLOP adequately, a Decision Support System named *'DONS'* searches in *Step 4* for a number of feasible timetables. If a feasible timetable exists, then the list of projects is logged as a cocktail. If no feasible timetable exists and the budget limits have not been attained, new projects may be added to the list in the geographical areas where problems occur in the timetable (Step 1). With the modified list of projects steps 2 to 4 are repeated.

In the following sections we will discuss the National Mobility Model, PROLOP, and DONS in more detail.

National Mobility Model

The National Mobility Model (NMM) is an econometric model that has been developed by the Dutch Traffic Ministry in cooperation with the Hague Consulting Group in the period 1981–1984 (see [Dutch Traffic Ministry, 1990]). It predicts the number of people that travel between different geographical areas in the Netherlands at different hours of the day and at different days of the week, their mode of transport (car, public transport, other), and their travelling motivation (commuter, business, other). For this purpose, the Netherlands have been subdivided into 345 geographical zones. For each combination of transport mode and travel motivation there is an *origin-destination matrix*. For example, the entry $a_{i,j}$ of the car/commuter origin-destination matrix indicates the number of people commuting by car between zone i and zone j during an average workday.

The estimates $\hat{a}_{i,j}$ are obtained from a system of regression equations in which for each pair of zones macro- and micro-economic data such as the average age, the education, the type of employment, the income and the composition of the households serve as input. Also, the function(s) (industrial, recreational, residential, etc), the number of driver licenses and cars, the quality of the road infrastructure and public transport, and a number of other characteristics of the zones are taken into account in the regression model. IN turn, the estimates $\hat{a}_{i,j}$ are used to predict the number of persons that travel at particular hours of the day (e.g. rush hours) and on Saturdays and Sundays.

The NMM is used in two different ways. First, it is used to forecast the number of persons travelling between zones in future years in case of a status quo, and second, it is used to forecast the number of persons travelling between zones in future years under *changes* in external circumstances, such as infrastructural improvements, or tax stimuli in favour of travelling by train.

PROLOP

The decision support system PROLOP (Program Line System Optimization) has been developed since the mid 1970's by IVV (Ingenieurgesellschaft für Verkehrsplanung und Verkehrssicherung Gmbh) in Braunschweig, Germany (see [Dienst, 1978], [Oltrogge, 1984], and [Bouma and Oltrogge, 1994]). It is used to determine the railway *lines*, their operating *frequencies* during the day, and the *type* of trains that will serve each line. Possible train types are Intercity (fast and comfortable long-distance trains that connect stations of larger cities in the Netherlands), Inter Regional (trains that operate between regions and also serve stations in smaller cities), or Agglo Regional (trains that operate inside a specific region and call at all stations).

A first input of PROLOP is the railway network, represented by *stations* and *tracks*. Each station is labelled by a particular *status* specifying both whether the station has suitable infrastructure to be a beginning/ending (b/e) station of a line, and the train types that stop at the station. For example, the Intercity and b/e status of Amsterdam Central Station indicates that all Intercity trains and all lower priority trains (Inter Regionals and Agglo Regionals) serve the station and that the station can be used as beginning/ending station for these trains. A second input of PROLOP is derived from the origin-destination matrices of the National Mobility Model. These matrices are transformed into a *station matrix* of which the entries $b_{p,q}$ indicate the hourly expected number of passengers that travel between stations p and q by train. In a next step, the entries $b_{p,q}$ are disaggregated into estimates of the hourly expected number of passengers travelling by each train type on each network segment. For example, the trajectory between Amsterdam CS and Utrecht CS consist of the segments Amsterdam CS-Amsterdam Muiderpoort, Amsterdam Muiderpoort-Amsterdam Amstel, Amsterdam Amstel-Duivendrecht, etc. InterCity trains only stop in Amsterdam CS and Utrecht CS and Interregio trains also stop in Amsterdam Amstel and Duivendrecht. The Agglo Regional trains call at all intermediate stations between Amsterdam CS and Utrecht CS. PROLOP assigns the $b_{AmsterdamCS,UtrechtCS}$ travellers per hour to the different train types between Amsterdam CS and Utrecht CS. If alternative routings exist to travel between two stations, PROLOP splits the passengers over the alternatives.

Based on the expected hourly number of travellers per train type and per segment, NS Marketing uses their customers service standards to determine the train type(s) that will operate at each segment and their minimum frequencies. For example, the standards of NS Marketing may require at least 2 Intercities and 4 Inter/Agglo Regional trains per hour on segments with 2,500 to 3,000 passengers per hour. Maxima on the train frequencies are derived from the speed limits in combination with the handling capacities of the segments.

The model underlying PROLOP is an Integer Linear Programming (ILP) which is solved to obtain the optimal design of the line-structure. Objective in the ILP is to obtain a set of lines for which the total number of train passengers in the station origin-destination matrix having a direct connection between their origin station and their destination station is maximal. Side-constraints in the ILP are minima and maxima on the frequencies per train type per segment and the status of the stations. The ILP is solved by several heuristic procedures (see [Dienst, 1978]). Other objectives, such as minimizing the operating costs of the line system, are investigated in [Claessens *et al.*, 1995].

Apart from the network design function of PROLOP, in a final step the system also estimates for any timetable (put out by DONS) the number of passengers that will travel by a particular train and the number of passengers that will pass or change trains at a particular station. Based on these estimates the required capacities of the trains and the stations can be determined.

DONS

Once the line system has been determined, a timetable is constructed to verify whether the capacity of the proposed railway infrastructure is sufficient to handle all the trains according to the frequencies and customer service constraints of PROLOP. The construction of the timetable is supported by DONS. This system consists of a data-base module, a graphical user-interface, and the algorithmic modules CADANS and STATIONS. The database module and the graphical user-interface have been developed by Origin in the period 1994 to 1996.

CADANS has been developed in the period 1993 to 1996 by the Centrum voor Wiskunde and Informatica (Eng. Center for Mathematics and Computer Science) in Amsterdam [Schrijver and Steenbeek, 1994]. It is used to determine for each train the arrival and departure times at the visited stations, thereby taking into account *'hard'* and *'soft'* constraints. Hard constraints must always be fulfilled, whereas soft constraints may be somewhat relaxed. The first set of hard constraints sets the time required for a train to run from one station to the next station, thereby taking into account speed limits on the different tracks of the railway network. A second set of hard constraints enforces headway times between trains to prevent collisions. A third set of hard constraints makes the timetable regular, i.e., if PROLOP has assigned a frequency of two trains per hour to a particular line, then the interval between two subsequent trains on that line should be about 30 minutes. A final set of hard constraints ensures that trains that must be physically (de-)coupled at a station have to be present at the station during overlapping time intervals. Most of the customer service requirements of NS Marketing are represented in CADANS as soft constraints. These soft constraints relate, for instance, to specific inter-connections or short waiting times between trains at the stations.

If CADANS does not succeed in the construction of a timetable that satisfies all specified hard (and soft) constraints, it reports on which trains and constraints cause a scheduling problem. The planning department will then negotiate with the other parties involved in the planning process (such as NS Marketing) on which soft constraints may be relaxed to arrive at a feasible timetable. If these relaxations still do not lead to a feasible timetable, then other possibilities have to be investigated, such as a modification of the line structure and/or the infrastructure.

The underlying ILP model of CADANS is solved by an algorithm based on constraint propagation and backtracking. This algorithm was initially developed by [Voorhoeve 1993]. Later on [Schrijver & Steenbeek 1994] improved the algorithm. The CPU-times to generate a nation-wide timetable are usually in the range of 1 to 3 hours. These figures compare very well to other algorithms like described in [Odijk 1996, Serafini and Ukovich 1989].

The timetable generated by CADANS does not provide a detailed schedule for the trains *inside* the station areas, i.e., it does not specify the routings the trains should follow through the stations and the platforms where they should stop. In fact, the problem of scheduling the trains inside the station areas in itself is so complex, that it can not be solved simultaneously with the construction of the timetable. To let CADANS still yield realistic timetables, it takes into account requirements on the minimal and maximal required halting times of the trains at the stations as hard constraints.

In the next step, STATIONS verifies station by station whether the arrival and departure times of CADANS can be met. Apart from the arrival and departure times, the inputs of STATIONS consist of a formal description of the lay-out of the station yard, including the locations of all platforms tracks and switches and the maximum speed at the tracks. In addition, headway times between trains and a number of operational constraints are specified. Some of the operational constraints are hard, such as the requirement that trains that will be (de-)coupled are assigned to the same platform, while others may be soft. An example of a soft constraint is the constraint specifying that several trains should be assigned to the same *preferred* platform. Another example is the desire to assign connecting trains to the same platform (both taking one side of the platform).

STATIONS has been developed at Erasmus University Rotterdam in the period 1994 to 1996 [Zwaneveld *et al.*, 1995]. It consists of an ILP model which is solved in a number of steps, including a model reformulation step, a step in which valid inequalities are added to the model formulation, and a branch & cut step. The procedure turns out to be very efficient. For the most complex stations in the Netherlands (Utrecht CS and Amsterdam CS) it takes about 1 minute to find an optimal solution.

If STATIONS concludes that, given the arrival and departure times suggested by CADANS, it is impossible to route all trains through a certain station, it indicates a probable cause. Furthermore, if appropriate, STATIONS suggests how the infeasibility may be resolved by a slight modification of some of the arrival or departure times. To that end, CADANS provides STATIONS with information about the range in which the arrival and departure times may be varied to maintain feasibility of the timetable for the other parts of the railway network. If the infeasibility can not be resolved in this way, some of the soft operational constraints have to be relaxed.

Cocktail evaluation

Cocktail evaluation is a very complex task, since the governmental priorities and the wishes of NS are often conflicting. As was explained earlier, NS wishes to have an infrastructure that guarantees long term profitability and allows maximum customer service, whereas the government wants to satisfy her social and environmental goals within the limited budget that is available for infrastructural investments.

Railned's task here has been to provide NS and the government with reliable information and with good instruments for further negotiation and decision making. For this purpose experts of Railned have developed a cost-benefit analysis (CBA) tool and a multi-criteria evaluation (MCE) tool. CBA is used to calculate for each cocktail the *'Return On Investment'* (ROI), which is defined as follows:

$$\text{ROI} = \frac{\text{capitalised net returns (in Dfl)}}{\text{total investments to carry out all projects (in Dfl)}} \tag{1}$$

The calculated ROIs were 1.99 for the Mainport Cocktail, 1.92 for the Metropolitan cocktail, and 1.93 for the Regional cocktail. The capitalised net returns (i.e. capitalised additional benefits - capitalised additional costs) in the nominator of (1) consist of tangible components (such as expected income increases to NS) and intangible ones (such as increased passenger comfort and shorter travel times). To compare these components, the CBA tool consists of a valuation model to express the intangible components in terms of money.

Table 2. Weight factors in the MCA tool

Criterion	Set A (%)	Set B (%)
Profitability-index	60	30
Better freight transport	9	12
More reliable services	1	2
Comfort improvements	1	2
Bottleneck elimination	1	2
Better pre and after transport	1	2
Improvements of bridges and tunnels	1	2
Reduction of congestions	6	11
Good connections to suburban areas	5	10
Good connections to mainports	6	11
Improvement of regional economies	6	11
Environment	1	1
Safety	1	2
Robustness w.r.t. future developments	1	2
Total	100	100

The MCE tool ranks the cocktails according to their total score on a set of 14 criteria (see Table 2). The criteria, their weights, and the individual scores on each of the criteria have been determined by a team of experts from the government, Railned and NS. In fact, two weight sets have been composed. In Set A the main emphasis is on the long-term profitability wishes of NS, whereas in Set B the main emphasis is on satisfying the governmental goals. The scores to each criterion have been assigned on a 1 to 5 scale. Based on the total scores to all criteria, a ranking of the cocktails has been made (see Table 3).

Table 3. Cocktail ranking according to CBA and MCE tools.

Cocktail	Profitability (CBA-tool)	Ranking (Set A) (MCE-tool)	Ranking (Set B)
Mainport	1.99	1	1
Metropolitan	1.92	3	2
Regional	1.93	2	3

Discussion

The National Mobility Model has been used successfully in several policy making studies of the Dutch Traffic Ministry and NS. In these studies the model provided valuable insights into the travelling behaviour of the Dutch population. Railned also used the model to obtain insight into the *robustness* of their cocktails with respect to the future expected travelling behaviour of train passengers. In this way, Railned attempted to minimize the risk that certain infrastructural investments will become superfluous or insufficient in the future due to changes in the demand for railway transportation.

Also, PROLOP and DONS have shown to be of great value to Railned. Without these systems the generation and evaluation of five cocktails in the seven months that were available to complete this task would have been impossible. In particular, the timetabling part of the cocktail generation procedure has always been very time consuming and requires highly skilled planners. Before the development of DONS, it took experienced planners about four man-years to manually construct a single feasible timetable. Lead times of one year were not unusual. With the help of DONS, timetable construction takes only four days per timetable. Taken that the labour costs of an experienced planner are around 100,000 guilders per year, the system reduced the construction costs alone from 400,000 guilders to 10,000 guilders per timetable. Given the investments of about 2 million guilders in the development of DONS version 1.0, this system pays itself back after the generation of only five timetables.

Apart from the *time* related cost reductions, the system also contributes to *quality* related cost reductions. Due to the relatively short time that it now takes to construct a single feasible timetable, it is possible to generate and evaluate for each cocktail many alternative timetables instead of just a single one. Therefore, the probability that capacity problems can be solved by the construction of a better timetable instead of by the implementation of very costly infrastructure has increased significantly. A recent example occurred, for instance, at Den Bosch, where experts expected that an expensive fly-over would be necessary to solve a capacity problem between the trains from Utrecht and Arnhem/Nijmegen. However, DONS came up with a timetable for which an investment of only 15 million guilders in a new safety system at Den Bosch would be sufficient already. The initial investment of 30 million guilders for the fly-over became superfluous.

That the CBA and MCE tools were originally developed for decision *support* and not for decision *taking* is illustrated by the fact that both systems recommended to implement the Mainport cocktail (see Table 3), whereas the Dutch Parliament finally decided in favour of the Metropolitan cocktail with the Hanze-line. Apparently, the experts involved in the development of the MCE tool underestimated the political pressure to improve the quality of public transport and to resolve the problem of traffic congestions in the metropolitan area. Nevertheless, the existence of the CBA and MCE tool enabled the politicians to quantify the effects of their political ideas in a more profound way than before.

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