Optimisation of cargo services for the Slovak railways

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Abstract

Political changes in Slovakia and neighbouring Central and East European countries caused important changes in cargo flows. Moreover, much more attention is paid to the efficiency of railway operations and to the higher quality of services for customers. These are the reasons why a project of an optimisation of cargo operations for the Slovak Railways was launched in the year 2001. The project was aimed on analysis and optimisation of operations in cargo traffic on three levels:

- location of marshalling yards,
- choice of cargo trains,
- simulation of traffic in a marshalling yard.

A model of cargo traffic on the railway network was designed using available input data on network infrastructure, transportation flows and estimated costs. The first two tasks were formulated as location problem and network design problem and suitable methods were implemented for their solution. A simulation model was developed to approach the third problem.

The major attention in this paper will be paid to a network design problem and to an implementation of results under real life conditions.

1 Introduction

Restructuring of economy brought dramatic changes in cargo flows in the railway network in Slovakia. Important material flows, which used to be directed towards East European countries, were only partially replaced by weaker flows to the West Europe and the total intensity of traffic is much lower now. The railway should enhance the efficiency of their operations and offer higher service quality to its customers. That is why a better control and
higher service quality to its customers. That is why a better control and management of operations should be implemented. The knowledge and long term experience of dispatchers need to be backed by modern information and decision support systems.

The following figure shows the network of Slovak railways. The picture should illustrate a limited scope of the optimisation problem, even if the railway network in Slovakia is quite dense.

Figure 1: Network of Slovak Railways

Three problems on different levels of planning and management were chosen for evaluation and possible improvement:
- location of marshalling yards,
- choice of cargo trains,
- traffic in a marshalling yard.

The first problem (the optimal location of marshalling yards in a network) means optimal distribution of a workload among railway stations, which participate on a sorting of cargo trains in the network. This task is not aimed at a purely theoretical estimation of an “optimal” place to build a new marshalling yard, but rather should decide which operations will be allocated to a station. Certain recommendations, such as which stations should be reconstructed with an installation of modern automated equipment and/or which stations should be exploited or should be closed for cargo traffic, may result from the optimisation according to a predicted distribution of sorting operations in the network. The planned allocation of a sorting workload in the network is a basic strategic decision, which will have a major impact on operations at lower control levels.

Any decision on a distribution of sorting operations in the network must be feasible, which means that it must respect capacity limits in each station. That is why the sorting capacity at a station must be checked. The sorting capacity should be evaluated also for supposed future transportation flows or for some planned changes due to a reconstruction or modernisation of a technology in the
station. The capacity limits for a contemporary situation can be estimated based on a known traffic in a station. More difficult task is an estimation of the capacity for future flows or for proposed technological changes in a station. This can be done using simulation models of a marshalling yard.

Such a simulation model was built for a sorting yard Teplička, which is major but incomplete sorting installation near to Žilina, the main railway node in northern Slovakia. The simulation model represents the layout of the equipment and the whole traffic in the marshalling yard using a simulation tool VirtuOS. It should serve to analyse operations in the yard and to verify the capacity and efficiency of the new installation, which should process more effectively the workloads of several neighbouring stations in the future. The marshalling yard in Teplička presents a very sensitive problem, because huge investments were allocated to build the yard, but the construction was not finished due to lack of financial resources. A similar simulation model can be built and capacity experiments can be performed for any other marshalling yard.

The choice of a set of cargo trains serving transportation flows in a network is the most complex problem from the three tasks mentioned above. It is not only hard to solve but even the interpretation of results and their comparison with the contemporary traffic is difficult without a computer support. That is why only a heuristic method was used to find a sub-optimal solution and major attention was paid to prepare an interactive environment in which a user can consult the results or propose his own solutions. Discussion of optimisation models can be found in Ball [1], Nemhauser [2], Cenek [3].

2 Location problem

The location of marshalling yards should optimise the distribution of a sorting workload in a network. The results of this step are used as input data for the choice of cargo trains and also for simulation of traffic in chosen stations. An example of results is shown in Figure 2.

Figure 2: An optimised choice of station for sorting of cargo trains
The optimisation problem is formulated as minimisation of a sum of weighted minimal distances from an origin/destination station to the nearest sorting station. A statistically estimated average number of wagons is used as a weight. The result of this optimisation problem should serve as a strategic decision saying which yards should be modernised to increase their capacity and which can decrease their performance or be closed at all. An optimal algorithm using dual approach was developed to solve these problems. The estimated result is optimal for the used parameters of the model (more in Nemahauser [4], Janáček [5] and [7], Jánošíková [6]).

3 Network design problem

A choice of a sub-optimal set of cargo trains serving the transportation flow on a network can be formulated as a network design problem. The design of a transportation network does not mean necessarily building a physical infrastructure but just organising a network of services (cargo trains) which will transport the goods among the nodes of a network. The goal will be to choose such a subset from a set of all feasible trains, that the total costs to transport all wagons in a network will be minimal. The costs to be optimised can be defined in units of time or in financial units. Both optimisation models will be described in following paragraphs (see also Magnanti [8]).

3.1 Model for time-optimal choice

The cost function is composed of two parts. First sum describes fixed costs to be paid on an operating cargo train independent of the number of wagons in the train. The second part represents the costs of transportation of individual wagons in a train. The costs can be formulated as follows

\[
\min \left[ \sum_{(i,j) \in H} Tsh_{ij} \cdot y_{ij} + \sum_{(r,s) \in K} p_{rs} \cdot d_{rs} \right],
\]

where

- \( y_{ij} \) – boolean variable with a value \( y_{ij} = 1 \) meaning that the train from station \( i \) to station \( j \) will operate, otherwise \( y_{ij} = 0 \).
- \( Tsh_{ij} \) – time lost by wagons waiting for an accumulation of a train from station \( i \) to station \( j \). The time loss will be estimated as \( Tsh_{ij} = 12 \cdot M_j \), where \( M_j \) is a number of wagons in a train for destination \( j \).
- \( p_{rs} \) – intensity of a transportation flow from station \( r \) to station \( s \).
- \( d_{rs} \) – total time spent by a wagon on its way from station \( r \) to station \( s \). This total time can be evaluated as

\[
d_{rs} = \sum_{(i,j) \in H} (t_{ij} + tzp_{ij}) \cdot x_{ij}^{rs}
\]

or a sum of all time delays experienced by one wagon in a train \((i,j)\).

- \( x_{ij}^{rs} \) – boolean variable with a value \( x_{ij}^{rs} = 1 \) meaning that the wagon from \( r \) to \( s \) will be transported by the train from station \( i \) to station \( j \).
- \( t_{ij} \) – travel time from station \( i \) to station \( j \).
average time loss by manipulations of one wagon for a train from station
\(i\) to station \(j\).

### 3.2 Model for costs-optimal choice

The cost function is similar to the cost function eq.(1), only the meaning of used
parameters will be different

\[
\min \left[ \sum_{(i,j) \in H} F_{ij} \cdot y_{ij} + \sum_{(r,s) \in K} p_r^{rs} \cdot d_r^{rs} \right],
\]

the following symbols stand for

- \(F_{ij}\) – fixed costs to create a relation (to operate a train) independent from the
number of wagons in the train; fixed costs can be calculated as

\[
F_{ij} = 12 \cdot M_j^* \cdot n_c + d_{ij},
\]

where \(M_j^*\) is the number of wagons in a train for
destination \(j\), \(n_c\) stands for costs of one hour wagon waiting in a station
during an accumulation of a train and \(d_{ij}\) are fixed costs for a train going
from station \(i\) to station \(j\) (independent of the number of wagons in the
train - costs of crew’s salaries can be mentioned as an example).

- \(p_r^{rs}\) – intensity of a transportation flow from a station \(r\) to station \(s\).

- \(d_r^{rs}\) – total costs spent on a wagon to be transported from a station \(r\) to station \(s\).

These total costs can be evaluated as

\[
d_r^{rs} = \sum_{(i,j) \in H} \left( \frac{c_{p_i} + c_{p_j}}{2} + c_{ij} \right) \cdot x_{ij}^{rs} \text{ or a sum of all partial costs to transport }
\text{the wagon by trains } (i,j).
\]

- \(c_{p_i}, c_{p_j}\) – average costs of wagon manipulations for a train from station \(i\) to
station \(j\).

- \(c_{ij}\) – costs of a wagon travelling from station \(i\) to station \(j\).

Meaning of variables \(y_{ij}\) and \(x_{ij}^{rs}\) is the same as in the model eq.(1)

### 3.3 Algorithm for solving a network design problem

The network design is a typical combinatorial problem with a vast number of
possible solutions, which can be estimated by \(O(2^{n(n-1)})\) where \(n\) stands for the
number of stations in a network. The network of cargo services of Slovak
railways has approximately 50 stations. A network design problem of this size
has, roughly estimated, \(10^{15}\) possible solutions and such a number of solutions
cannot be enumerated to find an optimal solution. Moreover, the whole project
was designed as an interactive decision support system, which must offer a
reasonably fast response time and so the calculations should run in order of
seconds. The mentioned conditions posed severe preconditions on the solving
algorithm and a heuristic searching algorithm was chosen to solve the problem.

The network design problem can be seen from another point of view, too.
There is a defined set of all feasible cargo trains \(E\) and the set \(N\) contains all
stations in the network. If there are no technological or other limits, which
would forbid some trains, then a graph \(G = (N, E)\) is a complete graph. The
solution of a network design problem is then represented by a graph \(G_I = (N,\)
where \( R \subseteq E \) is any feasible subset, which can guarantee, that all transportation flows in a network will be served.

The cost function will be calculated according to eq. (1) for time-optimal or according to eq. (2) for costs-optimal optimisation. Fixed costs can be easily evaluated using design values \( y_j \) and fixed constants \( F_f \). The second part of the cost function is more difficult to calculate. The value of \( d^\pi \) was described as a sum of costs (time delays) for all operations performed with a wagon on its way from an origin to a destination station. A minimal value should be used to find an optimal solution and this minimal value represents the shortest path from an origin to destination node in a graph \( G_f \).

The heuristic solving method can be now described as an iterative process. An alternative of a subset \( R \) is defined at first and a matrix \( \{d^\pi\} \) of shortest paths on a graph \( G_f \) is evaluated thereafter. The cost function is evaluated and a decision is to be taken. If the solution satisfies a finishing criterion, the current subset \( R \) will be taken as a solution, otherwise the whole process will be repeated with a new alternative of a subset \( R \). The next subset \( R \) should be chosen according to a suitable searching strategy. A pseudogradient strategy was used in the project.

The pseudogradient strategy can be described as follows. An alternative \( R \) is defined by values \( y_j \). A gain or a loss is now to be calculated for each cargo train from a set \( E \) by changing its status. The change of the status means that the new value of a variable will be \( y_j = 1 - y_j \). Each train included in a subset \( R \) will be removed and each train not included will be inserted in a subset \( R \). The change of a status for each train will result in a changed value of the cost function, where a negative value is a gain and a positive value means a loss. The search strategy then chooses several best changes (the highest gains) and tries to change the status of those trains. This approach reminds a gradient search method, only gradient is not estimated as derivatives of a continuous function by individual variables but as a response on a discrete change of the subset \( R \).

The process will be repeated until no gain can be found any more. The pseudogradient search strategy offers a fast approximation to a local optimum and so the result is just a sub-optimal alternative. The strategy brings one more advantage. Any alternative of a feasible subset \( R \) can be taken as an input value for the optimisation algorithm. The current plan of cargo trains in the network is also a feasible alternative and can be processed by the optimisation algorithm. The results can serve for validation of the used model parameters and/or for showing recommended changes against the current plan.

An estimation of a pseudogradient is a computational intensive procedure as it needs \( n^2 \) times calculations of a matrix of shortest distances. The change of a status of one train at a time means than only one edge in the graph \( G_f \) has changed (was inserted or removed from a subset \( R \)). So only minor changes in the matrix can be expected in many cases and that is why a modified label-correct algorithm was implemented and used for a search of changes in a matrix of shortest paths when just one edge is inserted or removed from a graph. This modified algorithm works by one order faster than classical algorithms. The whole optimisation runs fast now and can be used in an interactive environment. The performance can be illustrated by an example. The optimisation task was
solved for the network of Slovak railways with chosen 50 stations for sorting operations running on a fast PC computer with a Pentium III, 800 Mhz processor. The search algorithm using a full computation of the matrix of shortest paths demanded about 15 to 30 minutes while an improved algorithm (calculating only the changes in the matrix) was finished in 1 minute only (algorithms for shortest paths e.g. Klingman [9]).

4 Implementation and calibration of the model

The mathematical model of both optimisation problems (for a location of marshalling yards and choice of cargo trains) is more or less known. Also various solving methods can be used, even if the combinatorial characteristics of the optimisation problem indicate, that the computation can be time consuming. The most difficult part of the project were two tasks:
- collecting input data,
- calibration of the model and application of results.

4.1 Input data

The input data were not ready available for the project and had to be compiled from available sources. The infrastructure was digitised from a map, all the other data as statistical values of cargo flows in the network or economic parameters, costs and times of various operations were extracted from the information system of Slovak railways.

The input data are crucial for the correctness of the model. Some problems originated from the methods how the economic data are processed and presented. The costs of sorting a train in a station can be taken as an example. According to the used methodology the most expensive is a wagon processing in an automated station with a modern technology. It is due to the fact that all investment costs are calculated into processing costs of one wagon at relatively low exploitation of the station. These costs are therefore not usable in a model, because the optimisation algorithm would prefer sorting of trains in small stations with the simplest technological equipment, as there are almost no investments to be included in the price of processing. On the other hand the most modern station would be avoided because of higher costs of processing. It is clear that the installed equipment should be possibly well exploited because no savings can be gained by leaving this modern equipment idle.

4.2 Application of results

Maybe the most interesting part of the project was a conflict between a theoretical academic model and a practical experience of railway planning and dispatching staff. Even if the input parameters of the model were selected with the highest attainable precision and also the model was designed as detailed as possible, the first results and their comparison to a real traffic have shown an important discrepancy. That is why a difficult and time-consuming process was
important discrepancy. That is why a difficult and time-consuming process was started to approximate the results and the parameters of the model so that they will be acceptable for practice. This process seems to be quite difficult, because the optimisation should find some reserves to enhance the effectiveness of operations, but on the other hand the model cannot be unrealistic and offer solutions not acceptable in the practice. So a suitable compromise must be done.

5 User environment

The optimisation program should serve as a decision support system. Such a system should provide a user-friendly environment for a user. The system works under operating system WINDOWS and offers interactive components for editing of input data as well as for designing an alternative solution or visualisation of results. The data can be shown in an alphanumeric or graphic form, so that it is easily understandable and comfortably accessible. An example of data output, which contains routing for a cargo flow from Bratislava to Brezno station, is shown in Figure 3.

Figure 3: Results of routing – graphical and alphanumerical output
6 Conclusions

Presented optimisation methods and results can be seen as a first step to improve the control of cargo services for Slovak Railways. The size of a network and the number of trains to be managed are fortunately not very large and so even if the optimisation problem is a hard combinatorial task, it could have been solved in a reasonable time. The algorithm can be run in an interactive environment allowing an operator to consult his problems in real time.

The problem was solved as a "pure" theoretical model and the practical application of results has shown that a real everyday traffic in the railway network is at least partially different. That is why a new calibration of the model had to be done and further co-operation with the railway company will be necessary for a full implementation of the system in practice.

References