Sensitivity Test of the STEM Method modified to prioritize the Allocation of Traffic Path Capacity

Pavel Purkart[1][0000-0002-5478-1258], Jan Kruntorád[2][0000-0002-3949-4779] and David Vodák[3][0000-0002-5598-5770]

[1] CTU in Prague, Faculty of Transportation Sciences, Konviktska 20, 11000 Prague 1, Czech Republic. purkapav@fd.cvut.cz
[2] CTU in Prague, Faculty of Transportation Sciences, Konviktska 20, 11000 Prague 1, Czech Republic. kruntjan@fd.cvut.cz
[3] CTU in Prague, Faculty of Transportation Sciences, Konviktska 20, 11000 Prague 1, Czech Republic. vodakdav@fd.cvut.cz

Abstract. CTU in Prague Faculty of Transportation Sciences, Department of Transport Systems, deals in its research with the issue of allocating the capacity of a railway transport path. The capacity of any transport route is a limiting element in terms of its functionality. It is not always possible to meet all requirements and the allocator has to decide how to allocate capacity, so that it is as efficient as possible and achieves as many societal benefits as possible. The research team deals with this issue by using a modified STEM (Step Method) method for its research, which is a tool for linear optimization. The article presents the use of this method on the railway line Plzeň - Žatec in the Czech Republic. It deals with its sensitivity while changing the parameter of the number of passengers in the individual segments of the passenger rail transport. There are many requirements for the allocation of railway capacity, but the infrastructure is not able to satisfy all of them. The article presents a simulation of three variants of the number of passengers expected in regional expresses. This represents the possibility of allocating capacity to different train segments in situations when the infrastructure cannot satisfy all requirements for railway capacity allocation.

Keywords: Railway infrastructure capacity, Requirements of operators and regional public transport managers, STEM method, Plzeň – Žatec railway line, Optimization.

1 Introduction

The capacity of the railway infrastructure is a parameter which influences its usability. Not only in the Czech Republic, but in all developed countries, where rail transport is used as the backbone of transport services in regions, its capacity is a major problem, often failing to meet all requirements. This brings the question of how to realize the operation of trains so that this is as effective as possible with regard to the infrastructure restrictions [1],[2]. There are no universal methods and practically every infrastructure manager solves this issue differently.

This issue is a part of the research, which is currently conducted by CTU in Prague, Faculty of Transportation Sciences, Department of Transportation Systems, which encounters this issue not only in scientific work, but also while solving practical studies for various subjects. To solve the problem, the STEM (Step Method) method is currently being considered and tested.

2 Using the STEM method

The STEM method can solve linear mathematical problems with more purpose functions. The aim of this method is to find compromise solutions, whose realization should bring the most benefits. The main principle of the method is the calculation of purpose function ideal values for individual cases. This calculation is followed by minimizing the compromise solution deviation from the ideal purpose function values. The basic of the method is an interactive procedure of searching the compromise solution.

Benefit of the STEM method is that there is only minimal need of communication between a submitter and a solver (compared to another methods). The scale method for individual criterion is set by calculation. The submitter must decide whether the result of the calculation is acceptable for him or not. Therefore, the method consists of a calculation and decision-making process. The calculation is stopped, if the submitter finds the result acceptable, otherwise the solver must be informed by the submitter in order to change the criterions or their numbers, the whole calculation is made again.

The STEM method consists of the following steps:

1. Solver calculates the optimal solution for individual criterions (purpose function) separately. The number of calculations fits the number of criterions.
2. Solver calculates the scales of individual criterions according to formula (1):

$$w_i = \frac{z_{ii} - \min\limits_{i=j...k} z_{ij}}{z_{ii}} \frac{\alpha}{\sqrt{\sum\limits_{i=1}^{n} c_{ij}^2}} \tag{1}$$

where: z_{ij} – element of optimization criterion values matrix for optimization in the individual optimization criterion (z_{ij} is the value of optimization criterion $j = 1,...,k$ in the case of optimization according to the criterion $i = 1,...,k$),

c_{ij} – element of the price matrix – element of individual optimization criterion coefficients matrix.

Value α comes from equation (2):

$$\sum_{i=1}^{k} \frac{z_{ii} - \min\limits_{i=j...k} z_{ij}}{z_{ii}} \frac{\alpha}{\sqrt{\sum\limits_{i=1}^{n} c_{ij}^2}} = 1 \tag{2}$$

In reality, we have to calculate the coefficient alfa value first and then count the scales of individual criterions. If the scale fits the constraint $w_i \geq 0$ for more criterions, the solver adds a new variable $d \geq 0$ and solves the model with a new optimization criterion (3).

$$\min\ f(x,d) = d \tag{3}$$

There is a form (4) for variable d:

$$d = \max_{i=j\ldots k} \left\{ w_i \left(z_{ii} - \sum_{j \in J} c_{ij} X_j \right) \right\} \tag{4}$$

We have to implement constraint (5) for the correct calculation:

$$w_{ii} \left(z_{ii} - \sum_{j \in J} c_{ij} X_j \right) \leq d \tag{5}$$

If the constraint $w_i > 0$ fits for only one value $i = 1,\ldots,k$, the solver can simplify the constraint (5) to (6):

$$\min\ f(x) = \sum_{i=1}^{k} w_{ii} \left(z_{ii} - \sum_{j \in J} c_{ij} X_j \right) \tag{6}$$

3. Solver presents the results to the submitter. The submitter must modify the criterions or add/remove some of them, if he does not find the results acceptable. Solver goes back to step 2. Solver has found a compromise solution if the submitter of is satisfied with the result. The solution is optimal if the value $d = 0$ is reached.

3 Model modification and determination of stable values

Established evaluation criterions for individual lines for the modified STEM method:

Daily estimated average number of passengers in the limiting railway section in thousands

This parameter presents the daily average number of passengers on the route in the limiting section - the section with the lowest capacity. The value presents the passenger numbers in the trains of the given line in this section.

Daily estimated average number of passengers on the route in thousands

This parameter presents the daily average number of passengers on the route or on the logically selected section of the route. This parameter provides an evaluation of the total route use. It is not sufficient to consider the potential only on the limiting section mentioned above, but it is also crucial to assess the potential of the whole route.

The use of maximal line speed in a logically selected railway section

Trains are often unable to reach the line's maximal speed so they cannot make the full use of railway line parameters – this is the reason for implementing this parameter. When the train is able to reach the railway line maximal speed in the chosen section, the ratio will be 1 (100 %). If the speed is not reached, the ratio will decrease. If the line's maximal speed is up to 100 km/h in the selected section and the train is able to reach a speed of only 80 km/h, the ratio will logically decrease to 0.8 (80 %).

Evaluation of system links on the route in selected section

The parameter should evaluate the links to other lines, the aim is to identify the importance of route in the network. The overall value of the parameters is the sum of the following points for all transfer nodes/points in the selected section of the route. The transfer nodes/points are evaluated as follows:

- 2 points – a transfer node with system links to railway routes in at least three other directions (at least a crossroad station, but rather nodal station) with the possibility of system links to bus routes or city public transport,
- 1 point – a transfer point with system links to railway routes in at least one or two other directions with the possibility of system links also to bus routes/city public transport or a transfer point with frequent system links to bus routes or city public transport

If a route is routed through an important transfer node, it receives 2 points for that node. It receives 1 point for each transfer point (lower importance). The higher the sum of points, the more frequent and important the links are, and therefore the operation of the route is crucial for the public transport routes network.

Comparison of travel times between individual car transport and railway route in the three selected sections with the highest passenger numbers

This parameter is set in order to compare the ability of the train route to compete with individual car transport. In the selected section of the line, the three busiest connections will be selected and the ratio of the travel time of individual car transport in the given section to the travel time using the railway route will be determined. For the mentioned group of three connections, the value will be determined separately and then the average of the three values that will be included in the evaluation will be calculated. If the value exceeds number 1, public transport is on average in a selected connections faster than individual car transport.

The railway line Plzeň - Žatec was chosen for the model test. The line runs from the regional capital city of Plzeň (Pilsen) in the western part of the Czech Republic to the agglomeration in the Podkrušnohorská basin in the northern part of the country (cities of Žatec, Chomutov, Most and Jirkov). Especially in the Pilsen agglomeration, the capacity of the railway line is very restrictive, therefore it was chosen for model test. The STEM method has been modified. It was originally intended for project evaluation, providing evaluation and results for prioritization of projects in relation to a limited budget. It calculates the occupancy options of the selected section of the railway line in the selected time interval, so we can decide which trans should be allowed to pass the section in order to maximize benefits for society after the modification.

Following conflicts of regional public transport managers demands are expected:

- route R (fast train) Plzeň – Most in 120 minute interval,
- route Sp (regional express) Plzeň – Žihle in 120 minute interval,
- route Os no. 1 (regional train no. 1) Plzeň – Žihle in 60 minute interval,
- route Os no. 2 (regional train no. 2) Nýřany – Plzeň – Plasy in 60 minute interval.

This route schema ensures that the total interval of the fast segment of trains in the section Plzeň – Žihle will be 60 minutes and 30 minutes for regional trains in the peak period.

Given the fact that the basic interval of the most sparsely represented train segments is 120 minutes, this value was also chosen as the starting point for determining the length of the evaluation period. We consider even traffic in both directions, so for each direction in this period there are 60 minutes of the track capacity available, including all the operations (operation of railway signalling equipment, etc.), if expressed by the number of minutes, not the number of paths, as considered in the model. This value is reduced to *50 minutes* in order not to reach the occupancy rate of 100 %. We considered minimal operation of the freight trains on this line, so there are no requirements for their paths. This is based on the usual prioritization of passenger trains at the expense of freight trains during the peak hours in the railway sections with capacity restrictions.

According to the graphical timetable the most restrictive section is the *Horní Bříza – Kaznějov* section [5]. This section is considered for the calculation with the following occupancy time for individual routes:

- route R 8 minutes,
- route Sp 9 minutes,
- route Os 10 minutes.

The following parameters were stable for the STEM sensitivity test:

The use of maximal line speed in a logically selected railway section

For the use of maximal line speed, the determined parameters are set in the Table 1.

Table 1. The use of maximal line speed in a logically selected railway section.

Route	The use of maximal line speed in a logically selected railway section
R	1,00
Sp	1,00
Os no. 1	2 x 1,00 = 2,00 *
Os no. 2	2 x 1,00 = 2,00 *

* For regional trains, the value is multiplied by two, as two trains pass in each direction over a reference period of 120 minutes.

In the case of all connections, the full use of maximal line speed is planned.

Evaluation of system connection links on the line in a logically defined section

The below mentioned nodes are served by the individual routes. The evaluation of individual nodes according to their significance are summarized in the Table 2 and Table 3.

Table 2. Evaluation of system connection links of model routes in individual nodes. Part 1.

Route	Nodes – evaluation						
	Nýřany	Plzeň – Jižní P.	Plzeň hl.n.	Plzeň-Bolevec	Třemošná	Horní Bříza	Kaznějov
R	-	-	2	0	0	0	1
Sp	-	-	2	0	0	1	1
Os no. 1	-	-	2	1	1	1	1
Os no. 2	1	2	2	1	1	1	1

Table 3. Evaluation of system connection links of model routes in individual nodes. Part 2.

Route	Nodes – evaluation						
	Plasy	Mladotic e	Žihle	Blatno	Žatec	Cho-mutov	Most
R	1	0	1	1	1	2	2
Sp	1	1	1	-	-	-	-
Os no. 1	1	1	1	-	-	-	-
Os no. 2	1	-	-	-	-	-	-

The values for the individual routes are summed into the model as one number, and the accumulation of these values is expressed in Table 4. For experimental reasons, the values of the routes that passes through the section twice during the evaluation interval are not multiplied by two.

Table 4. Cumulative evaluation of system connection links of model routes.

Route	Cumulative evaluation of system connection links of model routes
R	11
Sp	7
Os no. 1	9
Os no. 2	10

Comparison of travel times between individual car transport and the railway route in the three selected sections with the highest passenger numbers

The values of this parameter were determined for individual routes from the average values of the following important connections:

- R: Plzeň – Mostecko, Plzeň – Plasy, Plzeň – Žihle,
- Sp: Plzeň – Kaznějov, Plzeň – Plasy, Plzeň – Žihle,
- Os no. 1: Plzeň – Horní Bříza, Plzeň – Plasy, Plzeň – Žihle,
- Os no. 2: Plzeň – Plasy, Plzeň – Horní Bříza, Plzeň – Nýřany.

The results are summarized in Table 5.

Table 5. Comparison of travel times between individual car transport and railway route in the three selected sections with the highest passenger numbers.

Route	Comparison of travel times between individual car transport and railway route in the three selected sections with the highest passenger numbers
R	0,80
Sp	0,87
Os no. 1	0,80
Os no. 2	0,87

4 Sensitivity test of the STEM method modified to the transport problem of railway capacity allocation

The sensitivity of the STEM method was practically tested on changes in passenger numbers. The change was made in the regional express segment, which is not operated on the line today, but due to the fast and more frequent connection of the northern Pilsen region to the regional city of Pilsen, it is worth to consider operations of these trains. The aim of the test was to try to determine from roughly what border of passengers it is appropriate to run these trains at the expense of other segments of passenger transport.

The following daily values of the number of passengers were selected as input data (var. 0) summarized in Table 6.

Table 6. Passenger numbers of model lines – var. 0.

Line	Daily estimated average number of passengers in the limiting railway section in thousands [thousands of passengers per 24 hours]	Daily estimated average number of passengers on the whole route of the line [thousands of passengers per 24 hours]
R	0,9	1,4
Sp	0,8	0,9
Os no. 1	0,5	1,5
Os no. 2	0,3	2,5

Var. 0 model prefers *R, Sp and Os no. 2* lines, while d = 0,167. It is a compromise solution, which can be represented by the fact that the stated daily number of passengers for regional express is sufficient to conclude that it is purposeful to operate them at the expense of other routes.

For the next test, the daily numbers of passengers on regional express were reduced. In the variant A, the expected numbers of passengers in express trains were reduced according to Table 7.

Table 7. Passenger numbers of model lines – var. A.

Line	Daily estimated average number of passengers in the limiting railway section in thousands [thousands of passengers per 24 hours]	Daily estimated average number of passengers on the whole route of the line [thousands of passengers per 24 hours]
R	0,9	1,4
Sp	0,7	0,8
Os no. 1	0,5	1,5
Os no. 2	0,3	2,5

Var. A assumes d = 0,1638. It is also a compromise solution, not a global optimum.

According to the above stated, the switching value has still not been detected (a value that determines when another line is selected to be preferred). The third test of variant B was made, while the number of passengers in regional express was reduced by another 100 passengers per day. The inputs of variant B are summarized in Table 8.

Table 8. Passenger numbers of model lines – var. B.

Line	Daily estimated average number of passengers in the limiting railway section in thousands [thousands of passengers per 24 hours]	Daily estimated average number of passengers on the whole route of the line [thousands of passengers per 24 hours]
R	0,9	1,4
Sp	0,6	0,7
Os no. 1	0,5	1,5
Os no. 2	0,3	2,5

Variant B contains a final calculation and chooses lines *R*, *Os no. 1 and Os no. 2* for railway capacity assignment. *Value d reached 0,1695, so we have a compromise solution. The calculation results in the switching value for starting the operation of regional expresses being between 600–700 passengers per day in the restricted section Kaznějov - Horní Bříza and 700–800 passengers per day on the entire regional express line, assuming that the numbers of passengers on other lines are stable and do not change.* However, with such small changes, there were also minimal changes in the weights of individual evaluation criterions, so we can state that the modified method is also very well applicable in practice.

Figure 1 shows the window of one of the specific tests in the FICO Xpress software environment, which was used for linear optimization of the problem.

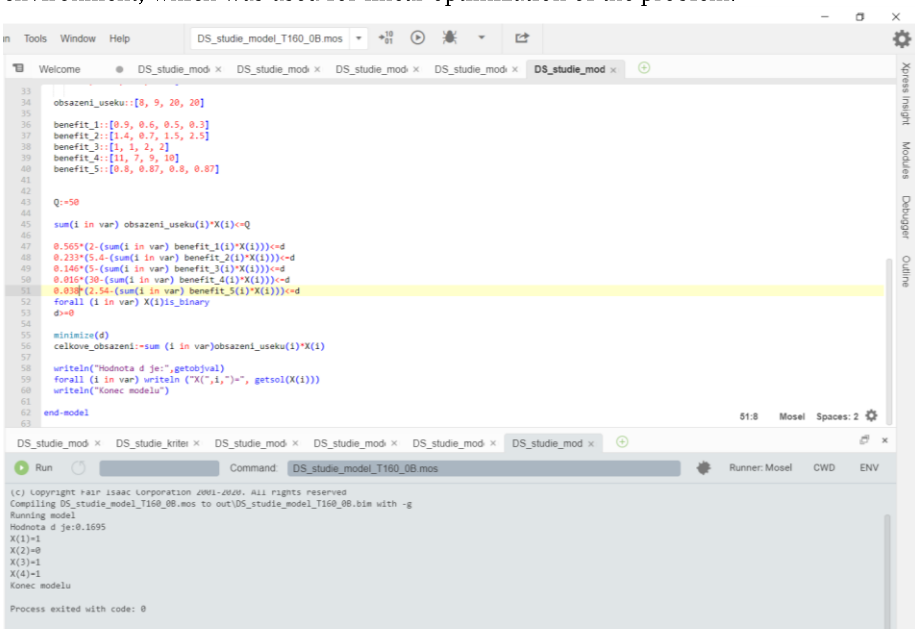

Fig. 1. Specific example of a model in FICO Xpress environment.

5 Conclusion

The above-mentioned form of the research shows that the STEM method is practically usable for solving problems in determining the preference for the allocation of capacity of the transport route, and that it works satisfactorily even with the change of selected parameters. The challenge is to test the parameters changes in a specific case.

It will probably be possible to modify the STEM method not only for the problem of railway capacity, but also for solving other tasks by computational path. In the above task, the method achieves relatively satisfactory results. Another task of the scientific team is to test other specific cases of railway lines as well as other methods and compare the results achieved by them.

It is obvious that the evaluation criterions must be chosen carefully and responsibly, otherwise the method will not give satisfactory results. If this is met, it can be a suitable tool for deciding or assessing situations whose optimal or suboptimal solution is not obvious.

References

1. Hansen, I. A., Pachl, J.: Railway timetable and traffic. DVV Media Group GmbH – Eurailpress, Hamburg (2008). ISBN 978-3-7771-0371-6.
2. Pachl, J.: Systemtechnik des Schienenverkehrs: Bahnbetrieb planen, steuern und sichern, mit Beispielen. 4., überarb. und erw. Aufl. B.G. Teubner, Stuttgart (2004). ISBN 3-519-36383-6.
3. Purkart, P.: Optimal cooperation of public transport segments. Praha: Defense date 2019-12-06. Doctoral Minimum. CTU FTS. Department of Transportation Systems. Supervised by Týfa, L.
4. Teichmann, D., Dorda, M.: Comparison of Two Selected Methods In Evaluating Of Investments in Transport Infrastructure. In: Finance and Performance of Firms in Science, Education and Practice: proceedings of the 7th International Scientific Conference: April 23-24, 2015, Zlín, Czech Republic. pp. 1524-1536. Tomas Bata University in Zlín, Zlín (2015). ISBN 978-80-7454-482-8.
5. Public available operational documents (timetables, etc.) of Správa železnic, state organization (Czech state railway infrastructure manager)

All the facts presented in this article are based on the results of the research of the CTU Faculty of Transportation Sciences, Department of Transport Systems. This research was supported by the Grant Agency of the Czech Technical University in Praha, grant No. SGS18/150/OHK2/2T/16 Railway track parameters for transportation service optimization and No. SGS20/138/OHK2/2T/16 Design and optimal use of railway infrastructure parameters.