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A TWO-PHASE VIKOR MODEL FOR TRACK LAYOUT EVALUATION OF PASSENGER RAIL STATIONS

ABSTRACT

Passenger stations are transit hubs where several railway lines interchange. They have important roles in providing train operations and passenger services. Interrelations between track layouts and technological performances are important for reducing bottleneck effects and raising the operational effectiveness of rail networks. To the best of our knowledge, in previous research the assessment of track layouts has not been considered with respect to various technological aspects including railway operations, safety, and passenger services but rather as a single criterion for analysis of different individual performance indicators. We propose a new two-phase decision making approach for the complex evaluation of track layout alternatives. The first phase model is a VIKOR method for ranking track layouts by criteria related to: railway capacity, safety issue, and passenger-pedestrian fluctuations. Next, in the second phase, we use marginal analysis to find Pareto front and compare the alternatives ratings by calculating performance-benefit coefficients. To show the applicability of the proposed model, we employ an illustrative example of a passenger rail station and evaluate six different track layout alternatives. The effectiveness of the proposed model is demonstrated comparing the proposed two-phase model with traditional VIKOR.

KEYWORDS

multi-criteria decision making; compromise programming; VIKOR; pareto efficiency; rail stations; track layouts.

1. INTRODUCTION

From the early stages of rail development, passenger stations have been participating as a fundamental element of transportation systems. At first, they were introduced as places where trains meet and interact with passengers providing an interface between passengers and boarding trains. The first passenger stations were built in a basic form with a few tracks and simple facilities required for passengers boarding. In parallel with the expansion of railway networks, stations became prominent structures with complex track layouts and gained important roles in providing train operations and traffic management. They evolved into crucial transit hubs where several railway lines interchange with complex traffic management functions and significant facilities to handle large amounts of commuters. Today, the role of stations is not only related to passenger services, train operations, and traffic management functions, but also to supporting urban planning and sustainable development of cities including various economic, social, and environmental aspects.

As a place where trains interact with each other according to the plan (timetable), stations have to be managed and organised to facilitate all train movements, operational conditions, and technological processes. Consequently, stations are usually capacity bottlenecks of railway networks. Furthermore, the relation between capacity utilisation and service quality is increasingly important as passengers demand maximal reliability and punctuality [1]. Therefore, there are many research studies related to rail stations and their role in the railway system [2]. The main principle when preparing station track layout designs is to minimise infrastructural requirements (such as tracks, switches, and crossings) as well as to maximise the flexibility of operations and usage of station tracks [3]. Train route conflicts occur at the station areas, where tracks and switches are crossing and thus creating a conflict zone. Specifically, station capacity is mostly dependent on the number of trains, train mix, and infrastructural and signalling characteristics (number of tracks and track layouts) [4]. Estimating capacity of a station is more challenging than assessing capacity of the railway line [3, 5–8]. For the specific conditions, a track layout can cause some conflicting train routes, such that a station becomes a bottleneck and limits the railway capacity. Furthermore, the risk analysis research [9] shows that safety is a particularly important issue when making a rail passenger station design. Risks related to safety in rail stations are identified and special attention is given to signal malfunctions, train collisions, passenger falls, and similar accidents and events. As these risks could be triggered by failure operation of various facilities and equipment, the model for rail passenger station design must incorporate criteria that encompass safety issues, both for train movement and alighting, boarding, and passenger flows [9].

When appraising a station track layout, several alternatives should be predefined and comprehensively compared in the decision-making process instead of using a basic economic appraisal either as a part of a project for building, modernising, or reconstructing the station. The selected modelling tool should not use only costs but various other criteria related to the project. Multi-Criteria Decision Making (MCDM) is commonly used for such a problem as it analyses alternatives with respect to non-commensurable criteria and uses a predefined mathematical transformation to compare the alternatives. The multi-criteria analysis is used to rank and select a solution among predefined alternatives based on criteria which are usually expressed in different quantitative and qualitative measures. In literature, various MCDM methods have been reviewed as an applicable tool for decision making problems related to transport and infrastructure engineering [10–12]. Among these methods, VIKOR has been intensively applied in the recent literature regarding the appraisal of railway projects. Firstly, a basic VIKOR method with deterministic values of alternative's attributes was used as a part of the methodology for planning railway lines [13]. Afterwards, two fuzzy extensions of the VIKOR method were proposed. The first was applied as a part of group decision making process for the evaluation of route alternatives at the early stage of the railway line reconstruction project [14]. The second was applied within the methodology for planning railway lines incorporating the uncertainties related to several attributes of route alternatives [15].

To the best of our knowledge, previous research studies on track layouts have not considered comprehensive assessment of railway capacity, safety, and passenger fluctuations as input parameters for a complex multi-criteria analysis, but rather as individual outputs used as a performance indicator within different single criterion analysis. In contrast, in this paper a new two-phase decision making approach is proposed for the evaluation of track layout alternatives applicable as part of the methodology for planning passenger rail stations. In the first phase, we propose the VIKOR method for ranking track layouts in terms of several technological criteria (railway capacity assessment, safety, and passenger-pedestrian fluctuations). The obtained distances from the theory of compromise programming are used to rank alternative layouts regarding the comprehensive technological performance. In this phase of decision making, we exclude the cost criterion from the assessment procedure and incorporate it for the final phase as part of marginal analysis. In the second phase, we propose considering trade-offs between comprehensive technological performance and required investments in order to determine the most favourable track layout. In the paper [16], the principal of Pareto optimal decisions based on trade-offs is given advantaged to be applied as a final stage of a decision making procedure. Following this idea, we propose the approach with the abovementioned two-phase decision making model as our main original contribution.

The remainder of the article is structured as follows. Chapter 2 describes preliminary definitions for the compromise programming concept, VIKOR method, and the Pareto efficiency concept applied in multi-criteria optimisation. Chapter 3 explains the algorithms in the proposed two-phase model for track layout alternative selection. In Chapter 4 an illustrative example is given with a discussion of results, while Chapter 5 provides conclusions.

2. PRELIMINARY DEFINITIONS

In this section, we briefly review relevant theories important for conceptual understanding of the proposed model. For the purpose of reference, some important notations and mathematical formulations will be summarised.

Compromise programming

Compromise programming is introduced by Zeleny [17] for use in a continuous context to find a compromise solution within a set of conflicting objectives. It implements the principle of "closeness" to the ideal point as a reference point in the solution space. *Equation 1* is used to express the family of distance metrics for measuring "closeness":

$$L^p = \left\{ \sum_{j=1}^{n} (z_j^* - z_j)^p \right\}^{1/p} \tag{1}$$

where z_j^* and z_j are the ideal point and the solution under consideration, respectively; while p is a parameter used to reflect the importance of the maximal deviation from the ideal point. Using the parameter p value in range from 1 to infinity, it is possible to implement different decision-making strategies, from minimising the sum of all individual deviations (known as the Manhattan distance) to minimising the maximal individual deviation (known as the Chebyshev distance).

This mathematical programming technique is used by many researchers to formulate various analytical methods for solving multi-criteria optimisation problems. All these methods belong to a class of multi-criteria decision making procedures known as "distance-based" methods. The application of the compromise programming technique is considered to be a relatively simple, but efficient approach for evaluating alternatives in the presence of conflicting and heterogeneous criteria.

VIKOR method

VIKOR is a "distance-based" method proposed by Opricović [18] for ranking and selecting from a discrete set of alternatives. The theoretical framework of this method is extensively investigated in [19, 20], while [21] presents a state of the art literature review.

Assuming that each alternative is evaluated according to each criterion, the compromise ranking is performed by a multi-criteria measure of "closeness" developed from the Lp-metric (*Equation 1*). When dealing with criteria which are not expressed in commensurable units, it is necessary to define their weighting coefficients and normalisation technique to ensure comparable data. Applying the linear max-min normalisation, the distance metric is rewritten as *Equation 2*:

$$L_i^p = \left\{ \sum_{j=1}^{n} w_j \left(\frac{f_j^* - f_{ij}}{f_j^* - f_j^-} \right)^p \right\}^{1/p}, \; i = 1,\ldots,m \tag{2}$$

where m is the number of feasible alternatives and n is the number of criteria; f_{ij} is the value of the j^{th} criterion for i^{th} alternative; f_j^* and f_j^- are the best and the worst values of the j^{th} criterion, respectively; w_j (j=1,…,n) are weights. *Figure 1* illustrates ideal and compromise solutions within a two-dimensional case, $F^*(f_1^*, f_2^*)$ and $F^c(f_1^c, f_2^c)$ respectively.

In the VIKOR method, ranking measures S_i and R_i are obtained as boundary Lp-metrics, L_i^1 and L_i^∞ respectively. The solution obtained by min S_i is based on the decision-making strategy with a maximum group utility capturing deviations in each dimension from the ideal point. The solution obtained by min R_i is based on the decision-making strategy with a minimum individual regret emphasising the maximal deviation from the ideal point. As these two decision-making strategies often result with ranking lists that differ from each other, the parameter v is used to aggregate these measures into the final compromise ranking metric.

Pareto efficiency

One of the key ideas in multi-criteria optimisation is the determination of Pareto-efficient solutions [22]. Within the Pareto concept, the efficient set of solutions (also known as Pareto front) refers to a set of solutions that are dominant to the rest of solutions in the search space but are mutually non-dominated. This implies that it is not possible to find a solution that is dominant to all other solutions in the search space with respect to all criteria. On the other hand, a solution s^* is dominated by another solution s if s is equally good or better than s^* with respect to all criteria. Determining a Pareto front is especially valuable in engineering and management. Focusing to the set of Pareto-efficient solutions, a decision maker can make trade-offs within this reduced set of solutions instead of

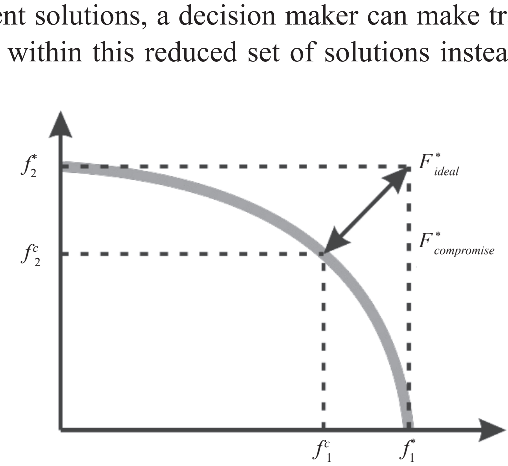

Figure 1 – Principal of compromise solutions

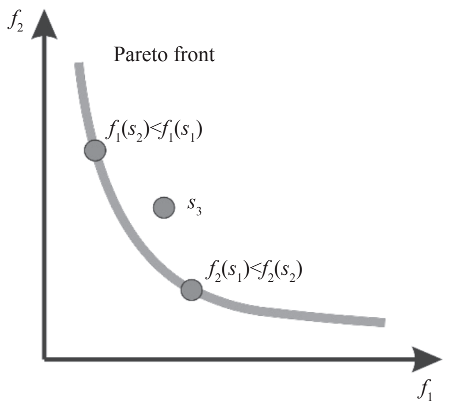

Figure 2 – Principal of Pareto efficiency

evaluating the full range of each criterion. *Figure 2* illustrates a trade-off within a two-dimensional case for minimising functions f_1 and f_2.

3. THE PROPOSED METHOD

The paper applies a two-phase model to evaluate track layout alternatives of a passenger rail station. In the first phase, we perform multi-criteria analysis evaluating predefined track layout alternatives only in terms of technological criteria. Applying the concept of compromise programming, the obtained distances from the ideal point are used to rank track layouts regarding the comprehensive technological performance. In the second phase, we incorporate a marginal analysis into the decision-making process considering trade-offs between the technological performance and required investments generated by each alternative. Favouring non-dominated alternatives, we focus trade-offs on the Pareto front within this two-dimensional space.

Phase 1: The evaluation of comprehensive technological performance

The proposed multi-criteria evaluation is based on the VIKOR method. Supposing the notation as already introduced under the preliminary definitions, the main steps could be summarised as follows.

Step 1.1: Form a set of potential track layout alternatives, select relevant criteria, and assess alternatives according to these criteria. With the aim of minimising potential bottleneck effects, a rail station has to establish technology that accomplishes smooth operations with trains as well as passengers. In order to achieve this aim, we propose the list of criteria encompassing the assessment of railway infrastructure capacity, safety, and passenger-pedestrian fluctuations.

The assessment of railway infrastructure capacity is performed based on the adopted measure of track layout complexity (TLC). As a measure of track layout complexity we propose the minimal number of sets of mutually compatible routes required to execute all predefined train movements through the station. From railway capacity theory, it is well-known that station capacity heavily depends on the number of routes that could be executed simultaneously. However, pure number of compatible routes is not an adequate indicator, since these routes could be executed simultaneously as different 2-tuples (couples), 3-tuples (triplets), or n-tuples of compatible routes. For that reason, we propose the usage of the abovementioned measure. This number of sets of mutually compatible routes could be optimally determined using the integer programming model that is originally developed in the paper [4]. The reason for using this measure does not lie only in the fact that it could be easily determined, but also in the fact that the obtained value guarantees the maximum theoretical station capacity. This criterion has a minimisation character, as the lower number of sets of mutually compatible routes explicitly provide a higher theoretical station capacity.

The safety criterion assessment is based on the train route collision analysis. In order to simplify the problem, we analyse only train movements neglecting collisions that potentially occur during shunting operations. Baring this in mind, a train collision can occur between two trains that arrive or depart the station only if their routes overlap both in time and space dimensions. For different pairs of train routes, we assign different collision rates mostly due to the different velocity values among arrival and departure train rides. The highest collision rate is assigned for the pair of arrival train routes. The combination of arrival and departure train routes is rated with lower value, while the lowest rate is assigned for the pair of departure train routes. The total sum of train route collision (TRC) ratings for all pairs of overlapping train routes at the station represents the assessment of the safety criterion for the observed track layout alternative (*Equation 3*). It is obvious that lower-rated alternatives are more preferable, so this criterion has a minimisation character.

$$TRC = \sum_{k} \sum_{l} c_{kl} \cdot x_{kl}, \quad k,l = 1,\ldots,r \tag{3}$$

The variable x_{ij} takes value 1 if conflict exists between two given train routes, and it takes value 0 if the two routes are compatible. The number of possible train routes is assigned with r. With $c_{kl} \in (c_1, c_2, c_3)$, we assign train route collision rates determined for the abovementioned three different pair possibilities.

To assess the impacts of station track layouts on passenger-pedestrian fluctuations, we consider pedestrian movements of transit passengers at the station. Movements of passengers are some of the key determinants of spatiotemporal fluctuations in every public transport mode, including rail stations. For the purpose of track layouts assessment, we measure longitudinal distances between the corresponding platforms in order to capture pedestrian distances that passengers pass through the station along their transit trip. Finally, we summarise pedestrian longitudinal distances (PLD) among all possible pairs of train routes that yield a transit trip connection (*Equation 4*). Station track layouts with lower *PLD* values are more preferable from the point of station throughput performances, so this criterion should also be minimised.

$$PLD = \sum_k \sum_l d_{kl} \cdot x_{kl}, \quad k, l = 1, \ldots, r \tag{4}$$

Variable x_{kl} takes value 1 if the two given routes yield a transit trip connection, and it takes value 0 if not. With d_{ij} we denote longitudinal distances between the corresponding platforms.

Step 1.2: Define weighting coefficients of criteria. To define weighting coefficients of criteria, we use both subjective and objective methods. Weighting coefficients are combined as follows:

$$w_j = kw_j^s + (1 - k) \cdot w_j^o \tag{5}$$

The parameter k takes the value from the interval [0, 1]. It is usually assumed that the value of this coefficient is 0.5 while its value could be varied as a part of the sensitivity analysis in both directions in order to test the stability of the obtained solutions.

The subjective weighting coefficients could be determined in numerous ways (e.g. survey of experts). They are based on expert opinions and judgments which are useful to fill the gaps in the existing data. In contrast, objective weighting is based on strict mathematical calculations performed over available data regarding the performances of alternatives with respect to the proposed criteria. The objective weighting coefficients are usually determined based on the well-known Shannon's entropy [23]. More details regarding this procedure for the determination of objective weighting coefficients could be found in [14].

Step 1.3: Calculate the best f_j^* and worst f_j^- values for each of the considered criteria. As all applied criteria have a minimisation character, these values are determined as $f_j^* = \min_i f_{ij}$ and $f_j^- = \max_i f_{ij}$.

Step 1.4: Calculate S_i and R_i using the following expressions due to the minimisation character of the adopted criteria:

$$S_i = \sum_{j=1}^{n} w_j \frac{f_{ij} - f_j^*}{f_i^- - f_i^*} \tag{6}$$

$$R_i = \max_j w_j \frac{f_{ij} - f_j^*}{f_i^- - f_i^*} \tag{7}$$

Step 1.5: Calculate the final ranking measure Q_i using the following expression:

$$Q_i = \frac{v(S_i - S^*)}{(S^- - S^*)} + (1 - v)\frac{(R_i - R^*)}{(R^- - R^*)} \tag{8}$$

where $S^* = minS_i$, $S^- = maxS_i$ and $R^* = minR_i$, $R^- = maxR_i$. The parameter v takes the value from the interval [0, 1] and is usually set to 0.5. As in the case of parameter k, its value could be varied in order to test the stability of the obtained solutions.

Step 1.6: Rank the alternatives in descending order by metrics S, R, and Q.

Step 1.7: Propose the compromise solution. The best ranked alternative by the metric Q could be proposed as a compromise solution only if it satisfies the following conditions:

- Acceptable advantage: The best ranked alternative has sufficient advantage over other alternatives if its Q metric exceeds others by the value $1/(m-1)$ where m stands for the number of predefined layout alternatives. In specific cases with small number of layout alternatives (i.e., $m<5$), the threshold level is fixed to value 0.25.
- Acceptable stability: The best ranked alternative by the metric Q also has to be the best ranked by metric S or R.

Phase 2: Marginal analysis

The assessment of track layout alternatives only in terms of technological criteria is not adequate because the complete evaluation process must further determine whether the proposed solutions are performance-efficient. Thus, we propose considering trade-offs between the distance ratings of comprehensive technological performance and required investments generated by each alternative. Note that ratings of comprehensive technological performance are obtained by the final Q metric in Phase 1.

The performance ratings express distances from the ideal point so that the lower distances indicate better performances. For a given Pareto front, we perform marginal analysis determining the condition in which extra costs gain sufficient performance improvements that justify additional investments. The following steps of the analysis are based on the applied procedure for solving cost-risk trade-offs within the bi-objective railway alignment optimisation problem presented in [24].

Step 2.1: Normalise estimated investment costs IC_i for each non-dominated solution applying a linear max-min normalisation to make them non-dimensional and comparable with values Q_i:

$$C_i = \frac{IC_i - IC_{min}}{IC_{max} - IC_{min}} \tag{9}$$

Step 2.2: Compute the positive and negative performance-benefit coefficients φ_i^+ and φ_i^- for each solution according to the following expressions:

$$\varphi_i^+ = \left| \frac{Q_i - Q_{i-1}}{C_i - C_{i-1}} \right| \tag{10}$$

$$\varphi_i^- = \left| \frac{Q_i - Q_{i+1}}{C_i - C_{i+1}} \right| \tag{11}$$

Step 2.3: Compute the final coefficients as the difference between the positive and negative performance-benefit coefficient:

$$\varphi = \varphi_i^+ - \varphi_i^- \tag{12}$$

Step 2.4: Rank all non-dominated alternatives in ascending order by the value of final coefficient φ and select the alternative with the highest value.

As illustrated in *Figure 3*, the coefficients φ_i^+ and φ_i^- indicate performance-increase and performance-reduction of the i^{th} solution compared to the lower-cost and higher-cost solutions in the neighbourhood, respectively. According to this figure, solutions are more performance-effective if φ_i^+ has higher and φ_i^- lower values. Therefore, the difference between values of φ_i^+ and φ_i^- is used to derive marginal benefits for a non-dominated solution.

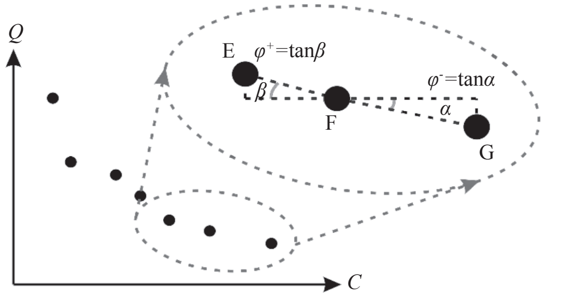

Figure 3 – Principal of marginal analysis

4. AN ILLUSTRATIVE EXAMPLE

To demonstrate the applicability of the proposed model for track layout evaluation, we employ an illustrative example of a passenger rail station. The example illustrates a node station on two double track lines A-B and C-D as shown in *Figure 4*. The intersection of these lines in the proposed node station enables trains to run through the station along the lines or to interchange lines in both directions allowing eight train running possibilities in total. The railway lines are used for mixed traffic with both passenger and freight train operations. The station is primarily used for passenger services. It is assumed to be equipped with eight platform tracks for passenger trains and two additional through tracks for freight trains to pass the station commonly with no stopping. Each alternative is equipped with four platforms for passengers boarding.

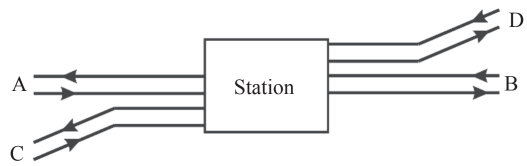

Figure 4 – Employed example illustration

Although we propose six track layout alternatives with the same number of tracks and platforms, they differ in: (i) the configuration of track connections, (ii) line services dedicated to platform tracks, and (iii) micro locations of platforms. In order to assess track layout performances with respect to railway capacity, safety, and passenger fluctuations, we made the following assumptions and calculations. Firstly, we determined potential overlapping occasions for each individual route with respect to all other predefined routes and constructed a route compatibility matrix to obtain the TLC measure as the minimal number of sets of mutually compatible routes for each of the layout alternatives following the procedure given in [4]. Secondly, we assigned collision rates as follows: 3 points for a pair of arrival routes, 2 points for a combination of arrival and departure routes, and 1 point for a pair of departure routes. Weighting the determined route compatibility matrix with the adopted collision rates, we derived the total sum of TRC ratings for all pairs of overlapping train routes at the station. Finally, in order to measure pedestrian distances of transit passengers at the station, the distance between track centres is adopted to 4.75 m and it is doubled for

Table 1 – The alternative assessments with respect to proposed criteria

	C1: Railway capacity TLC measure (# of route sets)	C2: Safety TRC ratings (points)	C3: Passenger fluctuations PLD distances (meters)	C4: Costs Initial investments (relative to A1)
Alternative 1	12	212	646	1.00
Alternative 2	10	153	646	1.05
Alternative 3	9	127	722	1.60
Alternative 4	9	133	541.5	1.60
Alternative 5	6	40	570	1.65
Alternative 6	12	140	741	1.45

the case of platform tracks to provide convenient train boarding and access to platform by stairways. Based on these unit distances we measured longitudinal distances between the corresponding platforms assessing PLD distances for all possible transit trip connections. The alternative assessments with respect to the proposed criteria are presented in *Table 1*. The cost criterion includes initial investments based on cost parameters that are given in [25] and are expressed relative to Alternative 1 as a base track layout.

Predefined track layout alternatives

Basic characteristics of predefined alternatives are described further in this text while their layouts are illustrated in *Figure 5*. In general, the first five alternatives are with symmetrical track arrangements according to the direction of train movements through the station where all train routes in the same direction on both lines are dedicated to adjacent station tracks. The last alternative is with the track arrangement according to the railway lines where all train routes that belong to the same line (no matter the movement direction) are dedicated to adjacent station tracks.

Alternative 1 presents a base track layout with the lowest investments due to the minimal number of switches used to connect tracks at the same level with no overpasses. The middle tracks are dedicated to freight trains passing through the station. The inner platforms are dedicated to serve passenger trains that operate without interchanging lines. The outer platforms are dedicated to serve passenger trains that interchange lines. Although proposed as a track layout with obvious cost advantages, Alternative 1 has negative consequences regarding railway capacity and safety issue. Due to the low track complexity there are no two routes of the same direction that can be executed simultaneously. All predefined routes are realised in enormous 12 sets influencing low railway capacity. High number of route overlapping manifests high train route collision ratings with a score of 212 points. The influences on passenger-pedestrian fluctuations are moderate as one part of transit trip connections could be realised with "cross-platform transfer" where transit passengers do not change a platform. On the other hand, the middle tracks for freight trains increase pedestrian distances for transit passengers who interchange lines in opposite directions. Therefore, the total longitudinal distances between corresponding platforms for all possible transit trip connections amounts to 646 meters.

Alternative 2 presents a slight variation of the base track layout with the same arrangement of tracks and platforms but upgraded track connections that enable simultaneous arrival of trains on both lines in the same direction. The upgraded layout provides improvement in railway capacity reducing the number of sets of compatible routes for 2. In addition, collision ratings are reduced due to the omitted overlapping of routes for a part of arriving trains. The provided changes have not influenced the layout performance regarding passenger-pedestrian fluctuations. The additional track connections cause insignificant higher investments, for about 5%, so it could be considered a fair trade-off.

Alternative 3 implements single-track overpasses of outbound track connections on both sides of the station. Keeping the track arrangement according to the direction of train movements, Alternative 3 brings some changes in line services dedicated to platform tracks. Consequently, platforms are strictly dedicated to a specific line omitting "cross-platform transfer". Inner platforms are dedicated to serve all arrival trains from the line A-B, while outer platforms are dedicated to serve all arrival trains from the line C-D. Therefore, all transit passengers have to change a platform to make their transfer. This

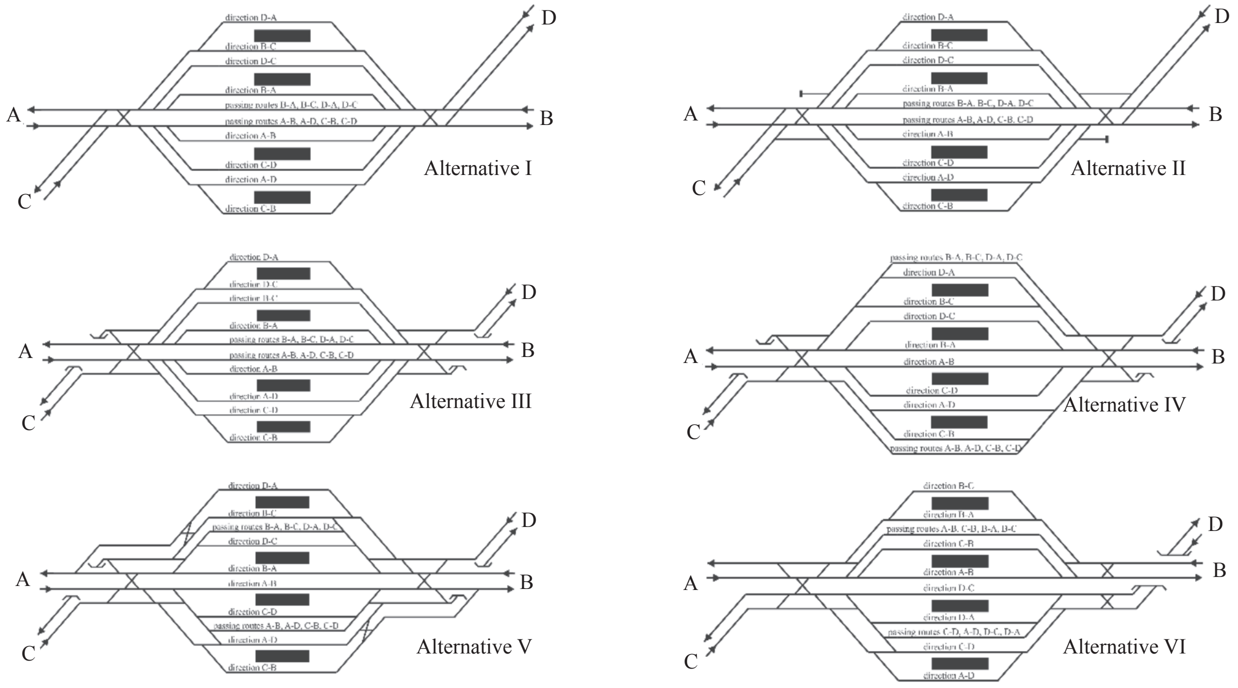

Figure 5 – Proposed layout alternatives

reduces the performance of this alternative regarding passenger-pedestrian fluctuations for more than 10%. The implementation of overpasses for outbound track connections positively influences capacity and safety issues. However, their positive effects are limited because freight train routes through middle station tracks overlap with multiple other routes. Applied track connections, additional switches, and track overpasses considerably increase the estimated investments for about 60% more than the base track layout.

Alternative 4 is characterised in dedicating outer tracks as by-pass tracks for freight trains. This track layout modification affects the capacity performance at the same level as in the case of Alternative 3. However, the displacement of freight dedicated tracks from the middle of the station significantly improves passenger-pedestrian fluctuations decreasing total distances between the corresponding platforms for all possible transit trip connections to 541.5 m. On the other hand, the negative impacts of this displacement refer to the increased number of overlapping routes compared to Alternative 3. The collision ratings increase to 133 points. Finally, total investments have not changed compared to Alternative 3.

Alternative 5 dedicates the 3rd and 8th track as through-tracks for freight trains and brings several additional track connections ultimately reducing the overlapping among train routes. The number of sets of mutually compatible routes is twice as low while collision ratings are more than 5 times as low compared to the basic track layout. As in the basic track layout, the inner platforms are dedicated to serve passenger trains running without interchanging lines, while the outer platforms are dedicated to serve passenger trains that interchange lines. The total longitudinal distances between the corresponding platforms for all possible transit trip connections is 570 meters. Due to additional track connections, Alternative 5 has significant investment costs. The investment requirements amount to about 65% more than the basic track layout.

Alternative 6, unlike all previous alternatives, has a layout with track arrangement according to the railway lines. The first half of the tracks is dedicated to the line A-B, while the second half is dedicated to the line C-D. The track layout is not symmetrical, one side is highly equipped with switches enabling track connections among all station tracks, while the other side is missing track connections between the lines and applies a double tracked overpass. It influences high investment requirements estimated to about 45% more than for the basic track layout. On the other hand, this layout is characterised with pure capacity, safety, and passenger fluctuation performances. The number of sets of mutually compatible routes amounts to 12, the same as for the basic layout. The total passenger distances are even

Table 2 – Criteria weighting calculations

		C1: Railway capacity	C2: Safety	C3: Passenger fluctuations
Subj. weights (w^s)	Initial	1	2	1
	Normalised	0.25	0. 50	0.25
Obj. weights (w^o)	Entropy	0.99	0.95	1.00
	Degree of divergence	0.01	0.05	0.00
	Normalised	0.21	0.73	0.06
Comb. weights (w)	Normalised	0.23	0.62	0.15

higher compared to the basic track layout and amount to 741 meters, while collision ratings are assessed to 140 points.

Model implementation

The proposed model is a two-phase approach. In the first phase, the VIKOR method is applied to rank alternatives with respect to technological criteria (railway capacity, safety issue, and passenger fluctuations). The assessed values of alternatives with respect to these technological criteria can be found in *Table 1*. After finishing the initial step, it is required to derive criteria weights. The criteria weighting combines both subjective and objective procedures as presented in *Table 2*.

For subjective weighting coefficients, we assume that weights of criteria regarding railway and passenger operations are equal while the weight of safety criterion is twice as high. The objective weighting coefficients are determined following the Shannon's entropy calculations with entropy attributes derived from the assessed values of layout alternatives. Within both subjective and objective weighting procedures, weights are normalised by applying the sum-based linear technique.

The following steps of the first phase determine extreme values among alternatives for each criterion, normalise and weigh distances of alternatives, and calculate S_i, R_i, and Q_i values (*Equations 6–8*) for all layout alternatives as shown in *Table 3*.

In the final steps of this phase, alternatives are ranked in descending order by metrics *S*, *R*, and *Q*. Alternative 5 is the best ranked alternative with respect to the first two criteria and by all three metrics. It easily satisfies the acceptable conditions regarding its advantage and stability over other alternatives. Alternative 5 is a superior layout regarding the comprehensive technological performance and the obtained objective weights influence which practically do not depend on subjective weights variations. However, the assessment of track layout alternatives only in terms of technological criteria is not sufficient for final decision making when it comes to financial considerations.

In the second phase, the decision making approach processes the marginal analysis considering trade-offs between the technological performance and the required investments generated by each alternative. Note that the performances are expressed as distances from the ideal point so that lower distances indicate better performances. Inputs for this calculations are presented in *Table 4* in the cost increasing order of alternatives.

Based on the data given in *Table 4*, the decision making problem is firstly reduced by removing dominated alternatives: Alternative 3 and Alternative 6. Alternative 3 is removed as it has a lower performance (i.e., higher distance from the ideal point) for the same investment costs compared to Alternative 4. Alternative 6 is also removed as it has a lower performance but higher investment

Table 3 – S, R, and Q distance metrics

	S	*R*	*Q*
Alternative 1	0.93	0.62	1.00
Alternative 2	0.64	0.40	0.66
Alternative 3	0.57	0.31	0.54
Alternative 4	0.45	0.33	0.50
Alternative 5	0.02	0.02	0.00
Alternative 6	0.74	0.36	0.68

Table 4 – Input data for marginal analysis

	Initial investments (relative to A1)	Technological performance (based on *Q* metric)
Alternative 1	1.00	1.00
Alternative 2	1.05	0.66
Alternative 6	1.45	0.68
Alternative 3	1.60	0.54
Alternative 4	1.60	0.50
Alternative 5	1.65	0.00

Table 5 – Normalised data for non-dominated alternatives

	C	Q
Alternative 1	0.00	1.00
Alternative 2	0.08	0.66
Alternative 4	0.92	0.50
Alternative 5	1.00	0.00

Table 6 – Performance-benefit coefficients for non-dominated alternatives

	φ^+	φ^-	φ
Alternative 1	-	4.38	-4.38
Alternative 2	4.38	0.20	4.19
Alternative 4	0.20	6.47	-6.27
Alternative 5	6.47	-	6.47

costs compared to Alternative 2. After removing all dominated alternatives, investment costs are normalised (*Equation 9*) in order to make them comparable with *Q* values (shown in *Table 5*).

The following steps of the second phase compute the positive and negative performance-benefit coefficients (*Equations 10 and 11*) and the final coefficients (*Equation 12*) as the difference between these performance-benefit coefficients (see *Table 6*). After that, we rank all non-dominated alternatives in ascending order by the value of final coefficient φ and select the alternative with the best value.

Alternative 2 has a high performance increase (φ_2^+=4.38) compared to Alternative 1 and low performance reduction (φ_2^-=0.20) compared to Alternative 4. Therefore, it could be stated as performance-effective comparing to neighbouring alternatives with the final performance-benefit coefficient φ_2=4.19. Alternative 5 is a high-cost alternative with a very high performance increase (φ_2^+=6.47) compared to Alternative 4. Alternative 5 has the best valued final performance-benefit coefficient so it could be stated as the most performance-effective alternative. Finally, based on the performed two-phase decision making approach, we can select Alternative 5 and propose it as the most favourable track layout of a passenger rail station.

Comparisons and discussions

As already mentioned, the proposed model is based on the two-phase approach combining the VIKOR model and marginal analysis. To further demonstrate the effectiveness of the proposed model, a traditional single-stage MCDM approach is considered for the comparison. As a part of the single-stage MCDM approach, we applied the traditional VIKOR model to evaluate predefined track layout alternatives with respect to all relevant criteria including investments. The criteria weighting calculations are presented in *Table 7* assuming that investment costs are just as important as all other technological criteria. The adopted criteria weights reflect the logic of the proposed two-phase model where financial considerations are extracted for the final decision making.

The obtained ranking metrics for the traditional VIKOR are presented in *Table 8*. In this case, Alternative 5 is a highly ranked solution just as in the proposed two-phase model. Alternative 5 has acceptable stability as it is highly ranked for all three metrics but it does not have acceptable advantage over Alterative 2. Therefore, the result of the traditional VIKOR model is the set of these two al-

Table 8 – VIKOR ranking metrics for traditional single-stage MCDM

	S	R	Q
Alternative 1	0.64	0.44	0.89
Alternative 2	0.46	0.29	0.25
Alternative 3	0.67	0.30	0.56
Alternative 4	0.61	0.30	0.48
Alternative 5	0.34	0.32	0.19
Alternative 6	0.72	0.25	0.50

Table 7 – Criteria weighting calculations for traditional single-stage MCDM

		C1: Railway capacity	C2: Safety	C3: Passenger fluctuations	C4: Costs
Subj. weights (w^s)	Initial	1	2	1	4
	Normalised	0.125	0. 25	0.125	0.5
Obj. weights (w^o)	Entropy	0.99	0.95	1.00	0.99
	Degree of divergence	0.01	0.05	0.00	0.01
	Normalised	0.18	0.63	0.04	0.15
Comb. weights (w)	Normalised	0.15	0.44	0.09	0.32

Table 9 –stability intervals for subjective weighting

	C1: Railway capacity	C2: Safety	C3: Passenger fluctuations	C4: Costs
Weight intervals	0.05 - 0.28	0.22 - 0.31	0.03 - 0.30	0.44 - 0.52

ternatives where Alternative 2 could not be rejected without performing additional calculations. *Table 9* presents weight stability intervals for each of the adopted criteria indicating one-dimensional subjective weighting variations for which the abovementioned track layout alternatives remain compromise solutions. In this paper we will discuss only investment criterion weighting variations while considerations regarding other criteria could be performed in a similar manner. As shown in *Table 9*, Alternative 5 and Alternative 2 remain the compromise solutions if the normalised value because the subjective weight of Criterion 4 varies in range from 0.44 to 0.52. Furthermore, Alternative 5 gains acceptable advantage over Alternative 2 if the normalised subjective weight decreases below 0.44. In contrast, Alternative 2 becomes the first ranked solution for weighting values above 0.52, while additional calculations show that it gains acceptable advantage and stability over Alternative 5 for the increase above 0.64.

5. CONCLUSIONS

Rail passenger station track layout design has to meet several conditions imposed by transport demand, safety and railway operating procedures. The selection of the station track layout is not simple decision-making based on pure cost criterion but a complex decision-making procedure that in addition to cost considerations should include railway capacity calculations, safety assessment, and evaluation of passenger-pedestrian fluctuations. In this paper, the railway capacity is calculated as a measure of track layout complexity, i.e., the minimal number of sets of mutually compatible routes required to execute all predefined train routes through the station. The safety assessment is based on the train route conflict analysis measuring collision ratings. The evaluation of passenger-pedestrian fluctuations refers to measuring longitudinal distances between corresponding platforms and summarises pedestrian distances among all possible pairs of train routes that yield a transit trip connection.

This paper proposes a two-phase approach for evaluating track layout alternatives of a rail passenger station. In the first phase, only technological criteria are used to assess different track layouts. Based on this assessment, layout alternatives are ranked regarding the technological performance leaving cost considerations for the final alternative selection in the second phase of the proposed decision making approach. In the second phase, trade-offs between technological performance and required investments are considered as a part of marginal analysis.

We tested the model employing an illustrative example of a passenger rail station. In order to illustrate the decision making procedure, we created six different track layout alternatives and evaluated them with respect to the above-mentioned criteria. The results of the first phase provided ranks of alternatives preferring Alternative 5 as the most favourable alternative with respect to technological criteria. In the second phase, performance-benefit coefficients were calculated in order to measure trade-offs between technological performance and required investments. The obtained values of performance-benefit coefficients were used for comparison and best alternative selection. The performance-benefit coefficient provided the relation among alternative track layouts in the way that Alternative 2 outperforms Alternative 1 and Alternative 4, while Alternative 5 outperforms Alternative 4. Finally, Alternative 5 was selected as the solution with the highest performance-benefit coefficient. Additionally, the proposed two-phase model was compared with traditional single-stage MCDM and the results were discussed. In light of these considerations, we conclude that the proposed two-phase model surpasses the traditional VIKOR providing a marginal analysis as an efficient decision making tool for performing final decisions.

Future research could go in several directions. Firstly, the stability of ranking results should be considered by analysing changes in parameter values and their influences on decision making. Deeper considerations regarding the criteria are highly recommended for the sensitivity analysis in order to explore the influences of trade-offs between criteria weights. Secondly, research studies regarding the application of different MCDM techniques are preferable in order to further investigate the effectiveness of the proposed two-phase approach. Finally, the application of fuzzy set theory could be of interests for further research as fuzzy sets are capable to mathematically define the uncertainties present in complex systems such as rail stations.

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DVOFAZNI VIKOR MODEL ZA VREDNOVANJE KOLOSEČNE SITUACIJE PUTNIČKIH ŽELEZNIČKIH STANICA

REZIME

Putničke stanice predstavljaju saobraćajna čvorišta gde se sustiče nekoliko železničkih pravaca. One imaju važnu ulogu u izvršavanju saobraćajnih operacija i pružanju usluge prevoza putnika. Zavisnost između projektovanih kolosečnih situacija i primenjenih tehnoloških procesa utiče na mogućnost postizanja usklađenosti rada stanica koja doprinosi eliminisanju efekata uskih grla i podizanju operativne efektivnosti čitave železničke mreže. U dosadašnjim istraživanjima, vrednovanje kolosečnih situacionih rešenja nije vršeno uzimajući istovremeno u obzir različite saobraćajno-tehnološke aspekte poput tehnoloških operacija, bezbednosti i pružanja usluge putnicima već primenom jednostavne analize nekog od prethodno pomenutih aspekata. U ovom radu predložen je nov dvofazni model odlučivanja namenjen kompleksnom vrednovanju kolosečnih varijantnih rešenja stanica. Prva faza modela zasniva se na VIKOR metodi rangiranja kolosečnih varijantnih rešenja uzimajući u obzir kriterijume kapaciteta, bezbednosti i fluktuacije putnika. Zatim, druga faza modela, zasnovana na marginalnoj analizi Pareto fronta, poredi dobijene rang vrednosti varijanata na osnovu proračuna koeficijenta performanse. Primenljivost predloženog modela prikazana je na ilustrativnom primeru putničke železničke stanice sa šest varijantnih rešenja. Efikasnost predloženog modela je potvrđena njegovim poređenjem sa tradicionalnim VIKOR postupkom.

KLJUČNE REČI

višekriterijumsko odlučivanje; kompromisno programiranje; VIKOR; pareto efikasnost; železničke stanice; kolosečna situaciona rešenja.

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