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A multi-criteria decision making approach for the evaluation of roads and streets system in Gniezno

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Abstract: The article presents the application of the MCDM methods, belonging to the PROMETHEE family, for the evaluation of potential solutions of the road system (RS) in the selected area located in Gniezno, historical capital of Poland. The proposed set of heuristics variants of RS were assessed by a coherent family of criteria taking into account different groups of stakeholders. The decision problem was defined as an issue of prioritising a finite number of variants of road-rail system reconstruction. The proposed model of decision-maker's preferences was developed based on the results of surveys conducted during public consultations with the residents of the area. The originality of the study consists in that the model became the basis for the final variants ranking that was subsequently compared with the results obtained using another MCDM method – ELECTRE III, where the decision-maker's preference model was developed on the basis of information obtained from independent experts.

Keywords: road and rail traffic, MCDM, sustainable transport, streets system, railroad crossings.

1. Introduction

The processes of urbanisation and de-urbanisation occurring in Poland, as well as the increase in the number of travels for various motivations entails the need to adapt and change the transport infrastructure. Significant for this fact is the growing number of motor vehicles in Poland, which almost doubled in 2017 as compared to 2003 (Table 1). This results in traffic congestion observed both in agglomerations and in smaller towns.

Table 1. Number of vehicles in Poland 2003-2017 [8].

Year	2003	2005	2007	2009	2011	2013	2015	2017
[millions vehicles]	15.90	16.82	19.47	22.02	24.19	25.68	27.41	29.63

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The above mentioned changes in infrastructure may concern both linear elements, including the construction or modernization of roads and railway lines or point elements, such as the construction/modernisation of fuel stations, public transport stops and stations, construction/ modernisation of road hubs, etc. The introduction of changes in the road system, especially in urban areas and due to different stakeholder groups, is a major challenge in many Polish local government units. This is due to the limited amount of funds allocated to such investments. Therefore, one of the possible solutions is to look for external sources of funding, including those from the European Union, for road and rail investments. The scale of the problem depends, on the one hand, on the size of the project (investment) itself, but also on its potential location where one may take into account geographical location (terrain, the existing infrastructure) or legal aspects – the location in relation to various local government units.

In view of the above, the authors defined a research problem involving the impact of evaluations obtained from public consultations on the choice of a variant of reconstruction of the road-rail system in the region of Gniezno, historically the first capital of Poland.

2. Road infrastructure investments and supporting the decision-making process

Making all investment decisions, including those relating to transport infrastructure, involves a large number of aspects. As in the case of complex socio-economic systems [1], a certain minimum set of criteria should be taken into account, e.g. the technical, economic, social, environmental and legal aspects [4, 5, 7, 11, 13, 14, 15, 17, 18, 19, 20].

Making investment decisions related to transport infrastructure is an issue that needs to be considered by numerous stakeholders [23]. The specific character of introducing certain changes into road systems requires that decision-makers have a broad and holistic approach to their task. As a consequence, it is advisable to apply a multi-criteria decision making (MCDM) methodology that takes into account many, frequently opposing, points of view [12, 21]. This approach is often used to tackle transport decision-making problems, including: those involving infrastructure [1, 9, 13, 14, 16, 24].

Project development process (PDP) related to transport infrastructure needs to account for numerous elements such as [18]:

1. Evaluation of alternative facility plans and policies (review of network – level plan).
2. Evaluation of alternative facility locations (project identification, mitigation, ROW studies).
3. Evaluation of alternative facility designs.
4. Evaluation of alternative project delivery practices (facility construction).
5. Evaluation of alternative operational policies and regulations.
6. Evaluation of alternative preservation practices.

Individual elements require, on the one hand, specific human resources, and tools and methods on the other. In this article, the authors, based on Sinha & Labi's [18] guidelines, presented a case study of transport infrastructure investment planning for a selected part of the town of Gniezno.

2.1. Gniezno case study. The characteristics of transportation problems

The region under consideration is located in the Wielkopolskie Voivodeship. It covers the south-western part of the Gniezno County (Figure 1) and, to be more precise, the urban area (the municipal commune – the city of Gniezno), as well as the rural area (the rural commune of Gniezno). The area of the county covers 1255 km^2 and the number of inhabitants as of the end of 2017 amounted to 145,333 [8]. The average population density of the area at the end of 2017 was almost 116 inhabitants per square kilometre, which is slightly lower than the Polish average of 123 inhabitants per square kilometre. In the case of the town of Gniezno, this figure is about 1700 inhabitants per square kilometre. In the central part of the district, both the national and international roads intersect (from Prague via Wrocław, Poznan to Bydgoszcz and Gdansk. Administratively, the Gniezno County is made up of 10 independent communes (Figure 1). The region is intersected by two railway lines (No. 353 Poznan East – Gniezno – Skandawa) Gniezno and No. 281 Olesnica – Gniezno – Milicz), which are crossed by county roads. The railway and road crossings considered ("I" and "II" Figure 2) in the analysed area are crucial for the transport system of both the City of Gniezno, the Gniezno Commune and, naturally, the Gniezno County. Due to their location, these railway crossings significantly limit the road capacity. This results in poor accessibility of the area and low level of safety for all inhabitants i.e.

obstacles for emergency services like fire brigade, etc. Due to the scale of the problem, the area of the analysis was additionally extended by several socio-economic conditions, which are closely related to Poznan, the capital of Wielkopolska, and the neighbouring county capitals.

Figure 1. Gniezno County with the area of potential changes in the road system ("X")

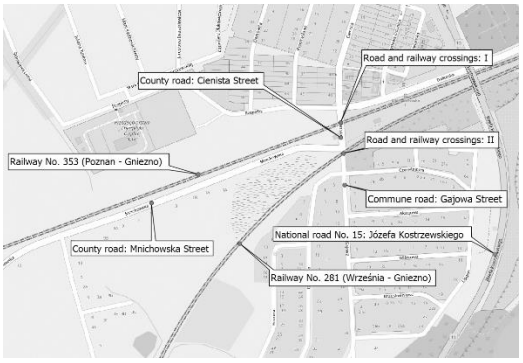

Figure 2. The current road system of the analysed part ("X") of the town of Gniezno.

According to the Polish regulations, the above mentioned road-rail crossings are classified as category A, which means that the traffic must be directed by authorized employees of the railway manager or railway carrier who have the required qualifications. At the same time, manual signals or systems or crossing devices equipped with gates closing the whole width of the road must be used (Figure 3, Figure 4). Taking into account the geographical location of the analysed area, it is a transit point for the inhabitants of the commune and the town of Czerniejewo who travel from or to Gniezno on the local road. This distance is less than 15 km, and the time needed varies from about 15 to about 30 minutes and it depends mainly on the day of the week, the time of day (during the peak traffic time decreases) and the time of raising the gates mainly rail-road crossing No.I (Figure 2). In the case of the residents of the town of Gniezno, or more precisely of the Dalki housing estate, the additional accessibility restriction is related to the latter of the above mentioned railway-road crossings. Due to the smaller use of line 281 for the needs of transport, the inconveniences related to closing the crossing are smaller. The measurements of traffic intensity showed that the average daily traffic at the railway-road crossing I varied between 6000 and 7000 vehicles per day – for most of the day, i.e.13-14 hours, traffic remained at the level of over 300 vehicles per hour. On the other hand, the average daily traffic of vehicles in the second crossing oscillated between 3000 and 4000 vehicles per day – on average during the greater part of the day there were about 200 vehicles per hour.

Figure 3. Railway and road crossing I.

Figure 4. Railway and road crossing II.

The analysed rail-road crossings play an important role, especially in journeys between the town of Gniezno and the communes of Gniezno and Czerniejewo. Taking into account the de-urbanisation

processes of the town of Gniezno and comparing the individual years between 2013 and 2017, it is evident that in the selected areas the number of inhabitants of Dalki, Mnichowo and Skiereszewo increased significantly [7]. Therefore, in the authors' opinion, there is a high probability that in the coming years the number of people using level railway crossings will increase due to the expansion of areas intended for housing developments. Due to the increasingly frequent traffic congestion outside the strict centre of Gniezno as well as threats related to the impact of road transport on the environment, it was necessary to introduce changes to the existing infrastructure.

Stakeholders of the decision problem: In order to assess the proposed variants of changing the road system in the analysed area, it is necessary to define the participants of the decision-making process. The choice of the investment option as a compromise solution, according to the MCDM methodology, should take into account the interests of different stakeholders (Table 2). It should be stressed that the interests of a person may vary according to their current needs.

Table 2. Stakeholders of the decision problem.

Decision makers	Interveners

• Railway infrastructure manager – PKP PLK S.A.
• Road infrastructure manager:
  ○ County Authorities in Gniezno (through Zarząd Dróg Powiatowych w Gnieźnie),
  ○ The Communal Authorities in Gniezno,
  ○ Municipal Authorities in Gniezno.
	• Road users in the analysed region: drivers, passengers of public transport, cyclists and pedestrians.
	• Residents of the immediate vicinity of the analysed road system who, apart from using the possible changes, are also exposed to the negative impact of traffic, including the emission of noise and air pollution.
	• Enterprises (businesses) located in the analysed area and in its immediate vicinity
	• Railway carriers providing passenger and freight services in the area under analysis on lines No. 281 and No. 353
	• Organizers and public transport companies using road infrastructure in the area under analysis.
	• Residents of neighbouring communes, e.g. Łubowo, Czerniejewo

Variants of road system: The analysis took into account the following four variants: alternative A0 – the current state and three other variants (alternative A1, alternative A2 and alternative A3), which were suggestions for potential changes. A number of conditions which were relevant from the point of view of major stakeholders were considered, including:

1. Eliminating a rail-road crossing on one of the railway lines.
2. Proposing a (rational) alternative road connection for motorised and non-motorised inhabitants of the area under consideration.
3. The technical feasibility of including the proposed changes into the existing road system.
4. Ensuring compatibility of the proposed road system solutions with local and regional planning documents.

The first of the investment options – alternative 1 (A1) involves (Figure 5):

1. The viaduct connecting the existing district road with the national road No.15.
2. A change in the route of the public transport line, i.e. public transport provided by Miejskie Przedsiębiorstwo Komunikacyjne Gniezno Spółka z o.o. (MPK Gniezno) buses and extra-municipal transport provided by regional carriers.

The elimination of the rail-road level crossing on railway line No.353, including the limitation of pedestrian and bicycle traffic.

Interestingly, alternative 1 has a number of disadvantages resulting from the location of railway lines No.353 and No.281 in relation to each other (these lines are connected under the national road No.15 railway viaduct and the distance between them is approximately 16 m). In addition, it is necessary to build another intersection at road No.15, which may reduce the capacity of this road.

Furthermore, it is essential to rebuild the energy infrastructure which is currently located along the viaduct next to road No.15 (Figure 6).

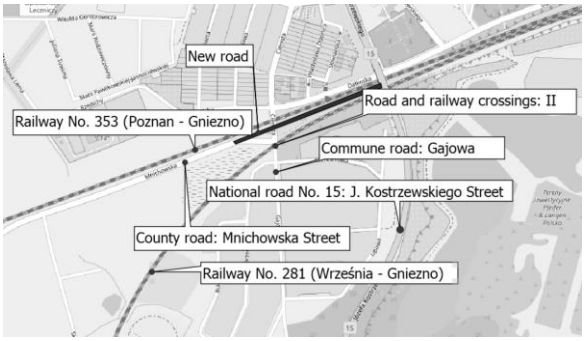

Figure 5. Alternative A1.

Figure 6. View of the energy installation near the railway viaduct – national road No. 15 over lines No. 353 and No. 281

The second investment variant, alternative 2 (A2), assumes the construction of a crossing under the railway line 353, which means closing the railway crossing on the line 353 and extending one of the local roads in the western direction parallel to the line 353, followed by a collision-free crossing under the tracks of the line 353 This alternative requires a change in the course of the public transport line and the buyout of land on which the road is planned, both on the northern and southern side of the railway line 353. The concept of solving the road system is presented in Figure 7.

The last alternative (A3) – Figure 8 is similar to alternative 2, assuming that the passage under the tracks would be located a bit further away. A characteristic feature of this variant is the location of a collision-free crossing under railway line no. 353 near the former railway-road crossing. At present, there is an unpaved road leading to the surrounding buildings on the southern side of the 353 railway line

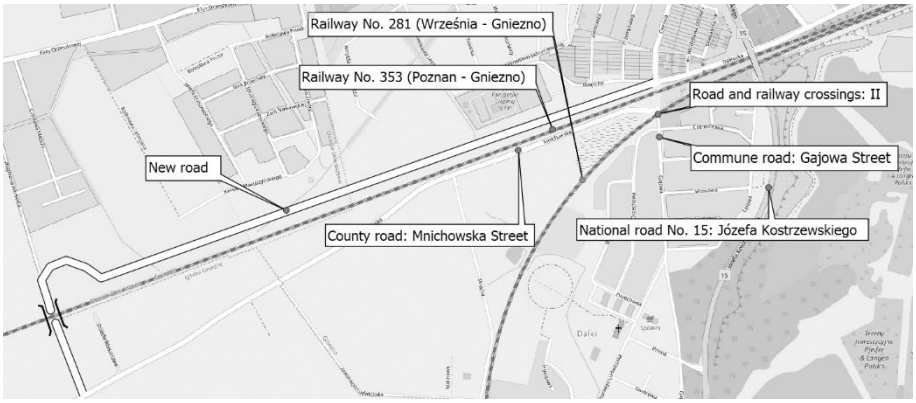

Figure 7. Alternative A2.

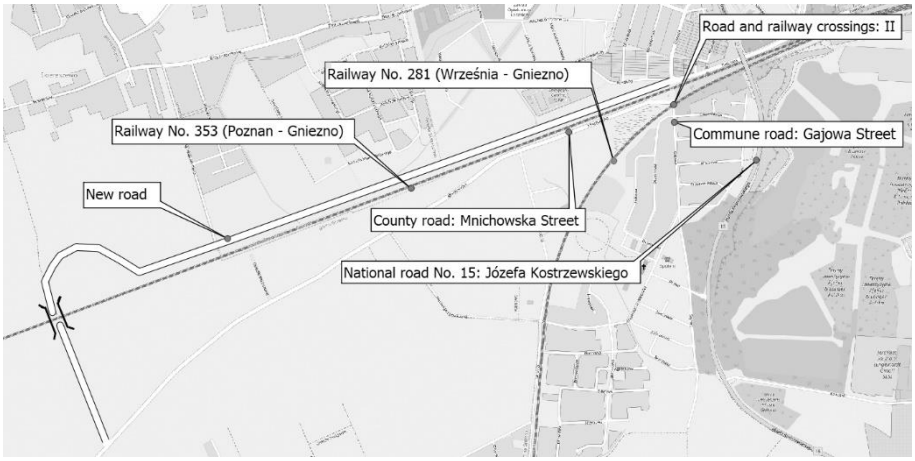

Figure 8. Alternative A3.

Choosing Criteria of Evaluation. The proposed variants were assessed by a coherent family of criteria taking into account different stakeholder groups, i.e. the inhabitants of the area, the entrepreneurs, the municipal and commune authorities, public transport, the investors. Thus, the following factors were taken into account [Kiciński et al., 2018]:

Criterion 1 – the costs of road system reconstruction. Within this criterion, the elements taken into account included carrying out design work, purchase of plots of land on which the new road system is to be built, construction work on roads, paths, pedestrian and bicycle paths of viaducts and culverts, as well as design work. This criterion expressed in PLN (4.25 PLN ≈ 1.00 Euro) is minimized.

Criterion 2 – average time of car ride. The method of determining this criterion takes into account the journeys between two selected starting points and four destinations. These points reflect the diversified directions of travel of the inhabitants of various communes of the Gniezno County, including those connected with access to
a hospital or a railway station. This criterion is expressed in minutes and it is minimised.

Criterion 3 – average distance between selected points of the city and municipality of Gniezno. This criterion takes into account the same set of starting points and destination points as when determining criterion 2. Only paved roads on which vehicles of at least 3.5 tonnes maximum permissible weight can be driven are included in the calculation. This criterion is expressed in kilometres and it is minimised.

Criterion 4 – the number of residential buildings located in the vicinity of the road. Only residential buildings located within 50 m from the edge of the roadway were taken into account in this criterion. This criterion is a measure of the disruption posed by the noise and pollution generated by traffic on this road. Nevertheless, it needs to be taken into account that the potential solutions of the road system do not affect the changes of the railway route. This means that the distance between the existing residential buildings and railway lines does not change. This criterion is expressed in units and it is minimised.

Criterion 5 – the size of changes in the transport work of rolling stock in a single course in regional and local public transport. When determining this criterion, the transport of the two largest public transport carriers operating in this region, i.e. MPK Gniezno (the urban public transport operator in Gniezno) and Przedsiębiorstwo Komunikacji Samochodowej w Gnieźnie Spółka z o.o. (the regional public transport company), was taken into account. The values were determined on the basis of business day data. It should be borne in mind, however, that in case of changes in the road system, the whole PTZ network may need to be adjusted, which was not considered in this criterion, as the very design of the public transport network is already a different decision-making problem. This criterion is expressed in vehicle-kilometres and it is minimised.

Criterion 6 – the changes in the length of bicycle or walking/cycling paths. It takes into account the interests of the most vulnerable road users – pedestrians and cyclists. This criterion is expressed in units of length (km) and it is maximised.

Criterion 7 – the accessibility of travels between selected points in the network. This criterion was defined for the time frame between 6 a.m. and 10 p.m. In this case, it was based on the closures of railway crossings, estimating the actual time of inability to cross the road-rail crossing of line 353. The criterion is maximized.

The matrix of assessments of all options on the basis of particular criteria is presented in Table 3.

Table 3. The matrix of assessments of the alternatives of road system.

No.	Name of criterion	Direction of preferences	Unit	Alternatives			
				A0	A1	A2	A3
1	The costs of road system reconstruction	Min	[PLN million]	0	19.2	23.5	25.3
2	Average time of car ride	Min	[min]	16	13	22	24
3	Average distance between selected points of the city and municipality of Gniezno	Min	[km]	9.5	9.2	10.3	11.4
4	The number of residential buildings located in the vicinity of the road	Min	[No.]	47	8	16	20
5	The size of changes in the transport work of rolling stock in a single course in regional and local public transport	Min	[vehicle-kilometres]	0	0.32	2.76	3.92
6	The changes in the length of bicycle or walking/cycling paths	Max	[km]	0	0.27	2	2.8
7	The accessibility of travels between selected points in the network	Max	[-]	0.67	1	1	1

Model based on decision makers' preferences. The way of defining the model of decision-makers' preferences in multi-criteria methods of prioritising variants depends on the method used. In this case, the multi-criteria methods of the Promethee family were used to determine the final rankings: I and II [2, 3, 10]. Similarly to the ELECTRE methods, they belong to the group of approaches based on the outranking relation. [12].

The model of the decision-makers' preferences, i.e. the values of indifference thresholds (q) of preferences (p) and the significance of the criteria were estimated on the basis of surveys conducted during public consultations. The set of questions presented to stakeholders included, among others [7]:

- the degree of inconvenience perceived in connection with the closure of level crossings;
- the most frequent motivation to travel when crossing railway lines;
- the frequency of use of railway crossing;
- the manner of crossing railway crossings.

The model of decision-makers' preferences adopted in the computational experiment is presented in Table 4.

Table 4. The model of decision-makers' preferences adopted based on public consultations.

No.	Name of criterion	Criterion relevance	thresholds *	
			q	p
1	The costs of road system reconstruction	5	0	19.2
2	Average time of car ride	10	16	13
3	Average distance between selected points of the city and municipality of Gniezno	10	9.5	9.2
4	The number of residential buildings located in the vicinity of the road	9	47	8
5	The size of changes in the transport work of rolling stock in a single course in regional and local public transport	3	0	0.32
6	The changes in the length of bicycle or walking/cycling paths	7	0	0.27
7	The accessibility of travels between selected points in the network	10	0.67	1
(*) q – indifference threshold, p – preference thresholds				

Computational experiments. The computational experiments were performed using Visual Promethee – version 1.4.0.0 [22]. The order of variants in the PROMETHEE I method is presented in Figure 9, where the so-called Phi+ output dominance flow and the Phi- output dominance flow are shown. Taking into account these rankings, it is possible to perform a final ranking of the variants from the best to the worst in terms of net dominance flows, which is presented in graphic form in Figure 10.

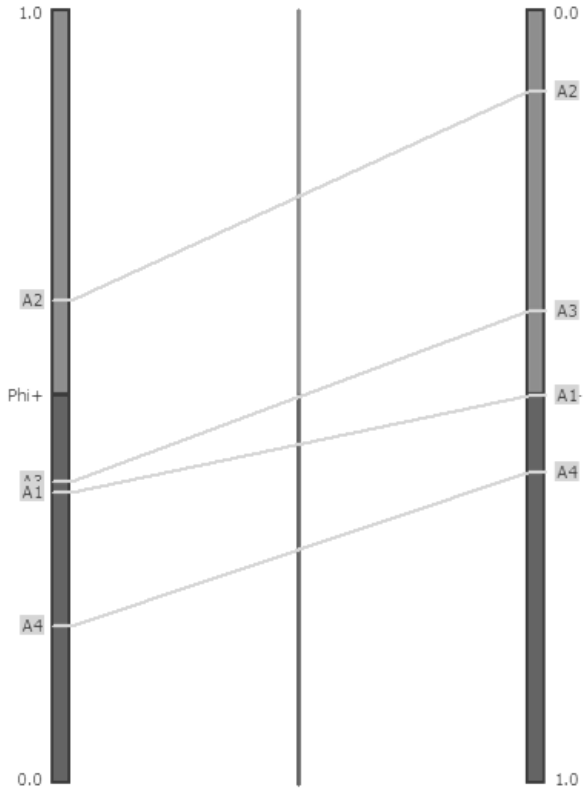

Figure 9. PROMETHEE I Partial Ranking

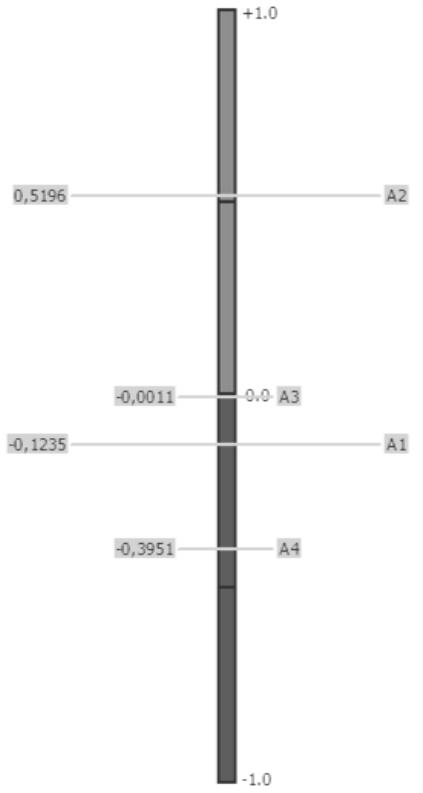

Figure 10. PROMETHEE II Complete Ranking

As can be seen from the adopted preference model, the highest ranked option is the option identified as alternative 1, which prevails over the others on four out of seven criteria. It is also characterised by the fact that it is not the worst in any of the other criterion functions.

3. Conclusions

The example of the approach to the problem of choosing a compromise investment option related to the reconstruction of railway and road infrastructure in the area of the city of Gniezno presented in this article confirms the usefulness of multi-criteria decision making methods. Comparing the approach described in the article Kiciński et al. [6], where another MCDM method – ELECTRE III – was used, it may be concluded that the direction of development of the road system in this part of the city should first consider alternative A1 which was the best alternative in both experiments. In both methods, despite the fact that preferences were expressed by different stakeholder groups:

1. PROMETHEE I and II: the inhabitants of the area (based on public consultations),
2. ELECTRE III: opinions of independent experts on transport and traffic organization,

the position of variant A1 in the rankings did not change. The situation was similar in the case of the worst option, i.e. alternative A3. As for the other options (alternative A0, alternative A2), the situation was no longer conclusive due to the discrepancies in the rankings observed when using particular methods.

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