Decision support system to urban infrastructure maintenance management

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Life-cycle management of urban infrastructure projects is very complex process from both management and economic aspects. Focus of this research is on urban infrastructure maintenance phase of a life-cycle, especially on decision making in maintenance problems. Urban infrastructure maintenance management deals with complex decision making process. The reasons for a complexity are: lots of participants, multidisciplinarity, huge quantity of information, limited budget, conflict goals and criteria. These facts indicate that decision making processes in urban infrastructure management undoubtedly belong to ill-defined problems. In order to cope with such complexity and to help project managers during decision making processes this research proposes an application of multicriteria methods. Multicriteria methodology proposed herein is applied on priority setting problem. It starts with goal analysis followed by definition of urban infrastructure elements and development of adequate criteria set. Evaluation of criteria importance (weights) is based on a set of experts' opinions processed by AHP method. An assessment of maintenance conditions of urban infrastructure elements is provided trough monitoring process. The way of using proper forms and procedures for data collection is presented as well. All collected data are processed by PROMETHEE multicriteria methods. The main result of a multicriteria process is priority maintenance list for urban infrastructure elements. The methodology is tested on road infrastructure of town of Split.

Keywords
maintenance management, decision support, urban infrastructure, multicriteria methods

INTRODUCTION

Ever growing urban infrastructure systems, such as water supply systems, traffic systems, sewage systems and others, contribute to the difficulty within a decision making process as regards their management that is very complex and social sensitive. City councils face the problem of managing big infrastructure projects, especially when is necessary to find solution which can meet requirements of all stakeholders and, at the same time, be a part of sustainable development concept. Maintenance phase of life-cycle management of urban infrastructure projects are not exception.

Infrastructure maintenance process becomes even more both complex and demanding task in a case of its long-term planning. Therefore, long-term planning tasks should be supported by decision tools such as multicriteria methods or other operational research models thus becoming more efficient. Lots of authors research in the field of decision support to urban infrastructure management. In his work Bielli (1992) demonstrates DSS approach to urban traffic management. Its aim is the achievement of maximum efficiency and productivity for the whole urban traffic system. Cost and benefits evaluation aspect of potential infrastructure investments is also introduced in literature and several decision support models could be indicated (Guisseppi, A., Forgionne, G.A, 2002.). Quintero et al. 2005 described an improved DSS named IDSS (Intelligent Decision Support System) that coordinates management of urban infrastructures, such as sewage and waterworks. Authors introduce IDSS as a solution for future urban infrastructure management. Similar approach can be found in publications of other authors (Afraim, T., Jaye, A., 1995.; Burstein, F., 1995.; Leclerc, G. et al., 2001.; Pomerol, J. et al., 1996.).

This research is focused on routine and periodic (resealing and rehabilitation) maintenance activities which are either an integral part or a phase of infrastructure project life-cycle. Emergency and extraordinary maintenance activities like repairs of sudden and accidental damages and failures are not taken into account. Several authors research in various aspects of infrastructure maintenance. Maintenance technologies, types and approaches are some of researchers' topics. Rouse, P., Chiu, T. 2008. describe optimal life-cycle management in road maintenance setting in New Zealand. Their paper focuses on local road aspects of the highway system and aim to assess

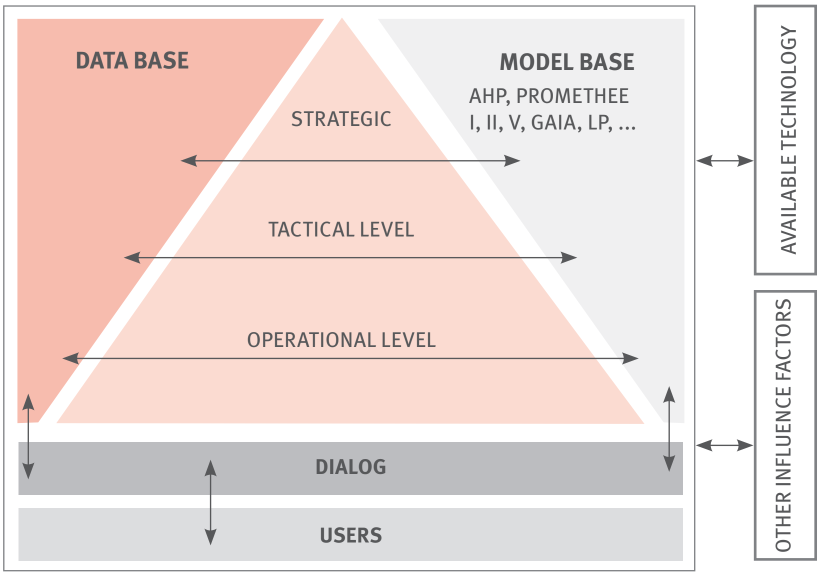

Figure 1: **Architecture of the DSS for urban infrastructure management (Jajac, N., 2007).**

how local authorities have maintained their respective local road networks from a life-cycle perspective. Finally they provide a best practice indication of the optimal maintenance activity that must be undertaken. Development of a life cycle assessment tool for construction and maintenance of asphalt pavements was in focus of Yue Huang, Roger Bird and Oliver Heidrich, 2009 research. During maintenance decision making process it is important never to forget environmental assessments of maintenance activities impacts. A comparative study of the emissions by road maintenance works and the disrupted traffic using life cycle assessment and micro-simulation was elaborated in paper of Yue Huang, Roger Bird and Margaret Bell 2009.

A structure of the proposed urban infrastructure maintenance management system is based on the previous research (Jajac, N. et al, 2008), where "three decision levels" concept for an urban infrastructure management (strategic, tactical, and operative) is proposed (Figure 1). The modular concept is based on DSS basic structure: data, dialog, models. Interactions between modules are realised trough decision making processes at all management levels which serve as meeting points of adequate models and data. First management level supports decision-makers at lowest, operative decision level. It has three basic functions. The first is to support of decision making at the operative level, the second is to process data and information, and the third to provide information flows for higher decision levels. Likewise, the second level delivers tactical decisions and creates information basis and solutions or models for a strategic decision level. The decisions throughout the system are based on the generated knowledge at the first decision level. The aquatinted knowledge is structured in an adequate knowledge based system. At the second level, decisions are made by individual experts and expert teams as well as by employees from local political bodies and public companies with certain responsibilities. At the third level, based on the expert deliverables from the tactical level a future development of the system is carried out. Delivered strategies have to be sound with existing global development and urban plans for the city or a region. These strategies are frameworks for lower decision and management levels thus ensuring continuity of decision making processes throughout decision and management systems. Both strategic and tactical level uses more complex techniques and knowledge then operative one.

Many outside factors influence an urban infrastructure system as it is shown on Figure 1. Besides technology, which obviously influences the system at all levels through diverse innovations and solutions, other factors like local behaviour (actual and traditional styles of management and decision making, local mentality, etc.) have huge influence to both decision making and management processes. (Jajac, N. et al, 2008). The described DSS is found to be adequate for an urban infrastructure projects because its structure easily supports all phases of project life-cycle. Since this research is focused only on maintenance phase, this concept is used to support urban infrastructure maintenance management system.

1. DSS for urban infrastructure maintenance management

Using previously described generic architecture of the DSS for urban infrastructure management, a concept of DSS for urban infrastructure maintenance management is developed. DSS for urban infrastructure maintenance management deals with lots of stakeholders and constrained resources. Since limited finances are usual main restriction, decision making problems at tactical level are generally priority setting. There are some crucial problems of maintenance decision making process that are recognised and modelled in the DSS. Herein, a step by step approach for maintenance priority setting and strategy selection is proposed (Figure 2).

The decision making process starts at strategic and tactical levels with a selection of both study area and type of infrastructure. At the first step, decision makers usually face a problem of the stakeholders selection. In order to provide good basis for efficient decision making process, stakeholders are divided into three groups: experts, local government and citizens representatives. Citizens group is generally formed from representatives of districts or similar city formations.

After the decision is made about the type of infrastructure and stakeholders, the next step is to define a maintenance model of an infrastructure system. The model consists of an infrastructure register and key characteristics of each infrastructure element. The infrastructure register requires decomposition of the system into manageable pieces herein called infrastructure elements. Definition of key characteristics for each element is very important for setting up criteria and their weights in the priority setting process and therefore directly influence final decisions. In further decision phases, the characterises are directly incorporated in hierarchy of objectives and criteria. Assessed values of the elements' characteristics are input data for multicritera priority setting.

In order to assess the characteristics a comprehensive monitoring program should be carried out. The program includes design of monitoring forms, monitoring scheduling (timing) and definition of an inspection process. Several monitoring forms for data acquisition are designed. Each form deals with one or more aspects of an element condition. Final form (Figure 3) represents summary of element condition for any kind of infrastructure. It consists of different aspects of element condition assessments. The most common are: equipment, element cross section and structures' characteristics. Inspection of infrastructure elements is a combination of a visual inspection and measurements methods resulting in element condition evaluation. Inspections and elements' conditions reassessment are repeated in periods from four months to one year in accordance with size of a city. For cities with over one million inhabitants

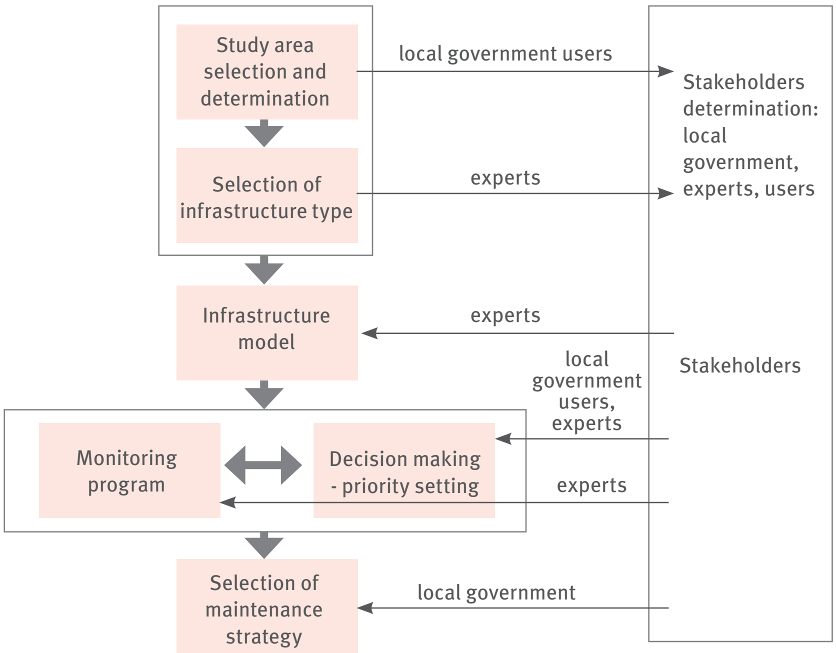

Figure 2: **Maintenance decision making process flow diagram**

it is continuous process. Monitoring plans must include re-inspection time schedules.

In parallel to preparation of a monitoring program, at tactical level of the DSS, a priority setting model is carry out. Due to ill-structured nature of the problem that emerges from incomparable data and conflict stakeholders' demands, multicriteria models are proposed. Therefore, a decision making model is multicriteria priority setting process that starts with goal analysis resulting in hierarchic structure of the goals, a goal tree. Since the goal analysis is the basis for a criteria definition, criteria are seen as an integral part of the goal tree. Criteria setting up process involves local government and experts' representatives while setting up of criteria weights involves opinions from all stakeholders groups. Using Analytic Hierarchic Processing (AHP) method (Saaty, T.L., 2001.) it is easy to assign weights through group decision making process by interviewing all stakeholders groups. Based on the authors' experience, in this research, among various multicriteria methods, the method PROMETHEE II (Brans, J.P., Vincke, Ph., 1984.) is proposed. Infrastructure elements act as actions in a multicriteria model. Data from monitoring/inspection process are input for multicriteria priority setting process. Multicriteria decision making is supported by several strategies i.e. scenarios. Each scenario consists of different combination of criteria weights values.

Priority setting decision making model and setting up of monitoring program are both parallel and interrelated processes. Precisely, design of monitoring forms include elements' characteristics that serves as criteria in mulitcriteria decision model. Furthermore, data acquainted during inspections are using adequate forms serves as input for priority setting process. Local government selects the most compromised strategy according to multicriteria analysis results and actual policies. The proposed DSS concept is tested on maintenance problem for road infrastructure in town of Split.

Evaluation of urban road infrastructure element conditions	
Traffic signs and signals	**Element condition**
Vertical signs	o
Horizontal signs (road markings)	o
Traffic signals	o
Road equipment	o
Pavement edge marking equipment	o
Fence	o
Traffic calming equipment	o
Lightening	o
Cross section elements	o
Pavement	o
Gutter and Drain	o
Curb	o
Pedestrian path	o
Traffic flow canalization elements	o
Shoulder	o
Side slope	o
Pipe man hole	o
Traffic structures (objects) characteristics	o
Fracture	o
Other damages	o
Concrete armature cover	o
Displacement of main structure elements	o
Bearing	o
Installation	o
Fire protection	o
Structural elements appearance	o

Figure 3: **Final monitoring form for maintenance status evaluation**

2. Application of the model to road infrastructure in town of Split

Urban expansion as well as huge growth of vehicles on the roads raises the problem of maintenance of the road transportation infrastructure, especially in the densely populated centre of the town of Split. The study area is wider city centre with high concentration of both public facilities and pedestrian flows. The area was surveyed in detail and classification of infrastructure elements was established (infrastructure register). At the same time, an assessment of conditions of urban infrastructure elements is carried out during monitoring process. Monitoring includes inspection of urban road infrastructure elements like: road segments, parking places, bus stations, gas stations, crossroads and may other urban traffic structures (bridges, viaducts, overpasses, underpasses, tunnels, terminals, parking garages).

Monitoring process starts with on site inspection of elements in the study area during which inspectors are filling forms with perceived facts about conditions of elements. There are a several forms which need to be completed. Through specified process data is arranged and presented in final monitoring form of maintenance status showed on Figure 3. Maintenance status is defined as a evaluation of infrastructure element condition and its aim is the estimation of maintenance requirement. Form presented in Figure 3. expresses a finite summarized evaluation of one element condition. Monitoring process must be repeated every 6 months.

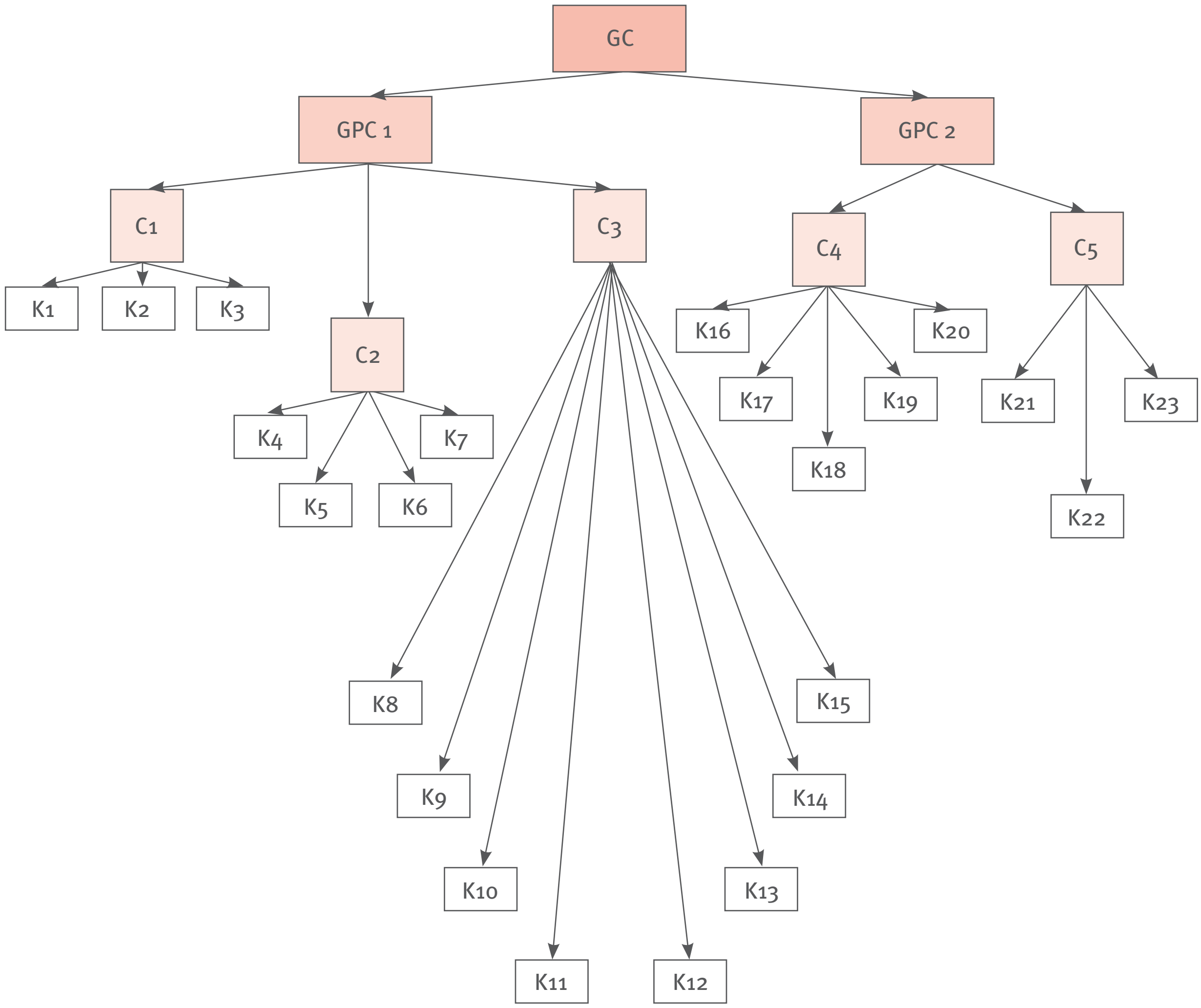

Figure 4: **Hierarchy of the objectives as well as criteria for maintenance priority setting problem for road transportation infrastructure in town of Split**

Both Figure 4 and Table 1 describe the goal hierarchy for the defined problem. As the main goal is "Sustainable maintenance of urban road infrastructure in the city of Split", the solution is based on the stepwise approach to maintenance activities taking place on 392 road infrastructure elements. During the definition of the lower goals' levels all stakeholders were involved and the objective tree is defined. As criteria for multicriteria analysis emerge form an objective tree, last hierarchic level of this particular tree represents the criteria set (Figure 4).

Criteria weights for the PROMETHEE method were evaluated by AHP method involving all stakeholders. According to the main goal of the stakeholders, three scenarios were developed (Table 2). The first scenario describes preferences of citizens (users), the second one of the transportation experts, and the third scenario represents how city authorities (local government) see the problem. The fourth scenario is an average value and stands as a compromised view to the problem.

Multicriteria model for ranking urban road infrastructure elements according to their "maintenance status" was created. Multicriteria model consists of 23 criteria and 392 alternatives. Regarding conflicts between the scenarios, compromised weights are set up by calculating simple average of scenarios' weights, thus giving equal importance for all groups of stakeholders. Table 3 shows the final compromised rank of (top 10) infrastructure elements for maintenance activities. Following this results a maintenance strategy will be delivered.

CONCLUSION

Supporting complex and sensitive decision-making processes such as maintenance priority set up for urban infrastructure achieved without using DSS principles of connection of appropriate methods and data. Previously developed DSS for infrastructure management and project life-cycle meth-

Hierarchy level	Code	Goal, objectives, criteria description	
0	GC	Goal	Sustainable maintenance of urban road infrastructure in the city of Split
1.	GPC1	Objectives	Maximization of maintenance quality for main urban road infrastructure elements
1.	GPC2		Maximization of maintenance quality for specific urban road infrastructure elements and their structure characteristics
2.	C1		Maintenance improvements of traffic signs and signals
2.	C2		Maintenance improvements of road equipment
2.	C3		Maintenance improvements of cross section elements
2.	C4		Maintenance improvements of structure stability characteristic elements
2.	C5		Maintenance improvements of structure nonstability characteristic elements
3.	K1	Criteria	Vertical signs - maintenance status
3.	K2		Horizontal signs - maintenance status
3.	K3		Traffic signals - maintenance status
3.	K4		Pavement edge marking equipment - maintenance status
3.	K5		Fence - maintenance status
3.	K6		Traffic calming equipment - maintenance status
3.	K7		Lightening - maintenance status
3.	K8		Pavement - maintenance status
3.	K9		Gutter and drain - maintenance status
3.	K10		Marginal strip - maintenance status
3.	K11		Pedestrian path - maintenance status
3.	K12		Traffic flow canalization elements - maintenance status
3.	K13		Shoulder - maintenance status
3.	K14		Side slope - maintenance status
3.	K15		Pipe man hole - maintenance status
3.	K16		Fracture - maintenance status
3.	K17		Other damages - maintenance status
3.	K18		Concrete armature cover - maintenance status
3.	K19		Displacement of main structure elements - maintenance status
3.	K20		Bearing - maintenance status
3.	K21		Installation - maintenance status
3.	K22		Fire protection equipment - maintenance status
3.	K23		Structural elements appearance - maintenance status

Table 1: **Hierarchy, code and description of goal, objectives and criteri**

odology were a good starting point for considering such approach and solution concept. The DSS for urban infrastructure maintenance presented in this paper is a unique system for the priority setting strategy for infrastructure maintenance conceptualized as a conjunction of operational models and multicritera models. Applied to the road infrastructure of town of Split it seems to function well and it can be used for any other type of infrastructure. The DSS concept is applied to the problem of maintenance priority ranking for the selected road infrastructure elements in the town of Split. It was shown that maintenance decision making processes can be supported at all hierarchy levels by interaction of DSS modules. Monitoring program determination provide uniformed and scheduled data acquisition and evaluation processes for urban infrastructure element's maintenance status

Criteria	Description of criteria	Scenario 1	Scenario 2	Scenario 3	Average weight	MIN/ MAX
K1	Vertical signs maintenance status	0.04	0.059	0.08	0.060	MAX
K2	Horizontal signs - maintenance status	0.068	0.058	0.041	0.056	MAX
K3	Traffic signals - maintenance status	0.027	0.06	0.083	0.057	MAX
K4	Pavement edge marking equipment - maintenance status	0.033	0.038	0.042	0.038	MAX
K5	Fence - maintenance status	0.042	0.039	0.038	0.040	MAX
K6	Traffic calming equipment - maintenance status	0.025	0.042	0.065	0.044	MAX
K7	Lightening - maintenance status	0.041	0.043	0.048	0.044	MAX
K8	Pavement - maintenance status	0.1	0.09	0.11	0.100	MAX
K9	Gutter and drain - maintenance status	0.032	0.06	0.07	0.054	MAX
K10	Marginal strip - maintenance status	0.037	0.045	0.038	0.040	MAX
K11	Pedestrian path - maintenance status	0.012	0.01	0.008	0.010	MAX
K12	Traffic flow canalization elements - maintenance status	0.047	0.032	0.021	0.033	MAX
K13	Shoulder - maintenance status	0.023	0.012	0.008	0.014	MAX
K14	Side slope - maintenance status	0.035	0.025	0.015	0.025	MAX
K15	Pipe man hole - maintenance status	0.082	0.063	0.041	0.062	MAX
K16	Fracture - maintenance status	0.041	0.045	0.05	0.045	MAX
K17	Other damages - maintenance status	0.039	0.04	0.042	0.040	MAX
K18	Concrete armature cover - maintenance status	0.027	0.043	0.053	0.041	MAX
K19	Displacement of main structure elements - maintenance status	0.047	0.049	0.051	0.049	MAX
K20	Bearing - maintenance status	0.027	0.037	0.046	0.037	MAX
K21	Installation - maintenance status	0.047	0.039	0.027	0.038	MAX
K22	Fire protection equipment - maintenance status	0.055	0.029	0.02	0.035	MAX
K23	Maintenance status of structural elements appearance	0.069	0.04	0.02	0.043	MAX

Table 2: **Criteria values and scenarios**

Ranking	Φ	Code	Alternatives	Infrastructure element
1.	0.3191	R5	Domovinskog rata – Vukovarska ulica	crossroad
2.	0.2147	GUC3-1	Put Plokita	street segment
3.	0.2143	GM1-1	Domovinskog rata	street segment
	0.1794	AP-GM1-3	Domovinskog rata	bus station
4.	0.1759	R12	Mažuranićevo šetalište - Dubrovačka	crossroad
5.	0.1583	GM1-3	Domovinskog rata	street segment
	0.1538	AP-GM1-1	Domovinskog rata	bus station
6.	0.1389	GGU3-2	Ulica Slobode	street segment
7.	0.0931	R7	Put Supavla – Hercegovačaka – Put Stinica	crossroad
8.	0.0697	GGU3-1	Ulica Slobode	street segment
9.	0.0584	R10	Velebitska - Dubrovačka	crossroad
10.	0.0408	P5	Kragićeva	parking

Table 3: **Preference flows and PROMETHEE II complete ranking for the compromised scenario**

establishment. In addition, application of multicriteria analysis points out several methodological and sociopolitical advantages of this approach in resolving complex problems such as infrastructure elements maintenance priority ranking, regardless of decision level. Stakeholders are divided into three significantly different groups (citizens, transportation maintenance experts, city authorities) and are directly involved in a decision making process. Their opinions are expressed by criteria weights thus making a maintenance strategy selection process as well as its implementation much easier and clearing all mistrust and bias situations. Obtained solution, expressed in form of list of the highest ranked infrastructure elements according to the maintenance criteria serve as possible strategic alternatives in urban infrastructure maintenance management. Further research will focus on finding appropriate models at operative level like knowledge based tools for substitution of experts involvement (introduction of neural networks to maintenance management).

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