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MULTIPLE-CRITERIA DECISION SUPPORT SYSTEM IN HIGHWAY INFRASTRUCTURE MANAGEMENT

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Abstract. Highway infrastructure represents a significant part of the public assets, and through its lifetime, is exposed to various deterioration processes leading to the depreciation of its value. It is therefore of vital importance to manage these assets aiming to reduce the loss of their value with time to a minimum. A typical task of road managers is making decisions related to maintenance, repair and rehabilitation based on data regarding the existing condition, risk of its use, life cycle costs and age. Road infrastructure is complex, and therefore the optimal choice of planned interventions is a delicate task often left to the road managers' subjective judgment. The main goal of research work presented in the paper is the development of a multiple criteria decision support system to determine the priority ranking of asset rehabilitation projects. Results are presented for a selected case study that consists of 27 overpasses for a highway section. The data on the condition of crossovers obtained by regular inspection along their contribution to a structured database are essential. The selection of the set of asset rehabilitation projects is carried out by using the developed decision support system that includes the budget constraint option. The selected set of asset maintenance/rehabilitation projects meets best the pre-defined combination of several criteria and therefore yields the maximized overall benefit. The results showing the selection criteria employed in the decision process and relative importance are crucial in obtaining the targeted goals. The selected criteria should therefore reflect the needs of the users and the actual conditions related to the assets.

Keywords: asset management, multiple criteria decision methods, highway overpass, maintenance, rehabilitation, infrastructure management systems.

1. Introduction

Public infrastructure, as one of the key elements enabling the development of every national economy represents a major part of the existing publicly owned assets. This large public capital is diverse and consists of electrical network, power related facilities and supply systems, water supply networks, waste water systems, communication systems and transport systems. In contemporary world, highway infrastructure has a special role as it ensures the mobility of citizens and eases the transport of goods. Special attention should be therefore placed to construction, maintenance and upgrading this particular infrastructure system (Bi and Ruan 2006; Hallberg and Racutanu 2007; Hegazy 2006; Frangopol and Liu 2007; Ugwu *et al.* 2006a, b; Leonovič and Kaševskaja 2007).

When using it, the performance of any facility decreases with time due to aggressive environmental conditions and different inherent factors as schematically presented in Fig. 1. In the past, maintenance, repair and rehabilitation (MR&R) planning were limited to contingency planning in the event of an emergency leading to excessively high costs of maintenance (Miyamoto *et al.* 2000, 2006).

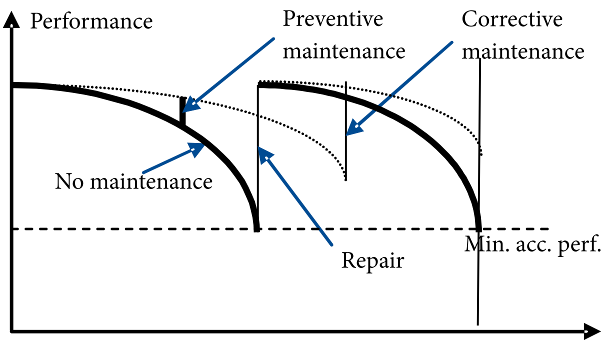

Fig. 1. Changes of performance with time for different MR&R scenarios

To prevent the loss of capital value at a reasonable cost, the MR&R actions are required throughout the planned service life of the facility. The efficient and

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planned execution of the MR&R actions also contributes to a sustainable built environment as the need for constructing the new facilities is reduced and the engaged resources are rationally used. Furthermore, the planning and execution of these actions have to be cost effective without compromising the safety and comfort of the users, and the MR&R program has to be established on short, medium and long-term basis.

Asset managers must make decisions on maintenance and renewal alternatives based on scarce data about the current state of their infrastructure assets, the relative risk of failure and the life cycle costs of proposed interventions.

The funding allocated for MR&R is always limited, and therefore it is necessary to prioritize and select the options that are best aligned with the asset managing company's objectives, which, in case of infrastructure, should also reflect the needs of society.

The criteria used in this process are often uncertain, conflicting and sometimes subjective, including the type of maintenance intervention, risk and reliability, overall network performance, life cycle costs, desired levels of service, budgetary concerns and construction and social costs.

The optimal selection of intervention projects across a broad spectrum of assets is therefore a challenging task, and in practice, is often carried out in a subjective manner. To overcome this current practice, a rational decision model has to be established.

The paper presents a systematic approach to MR&R management based on a multiple criteria decision model. The main objective is to establish a model able to support the decisions regarding the selection and priority of the MR&R projects within a given set of facilities. The applicability of the model is presented on a case study of 27 overpasses that bridge a selected highway section in Slovenia.

In many countries, it can be observed that current MR&R spending is considerably less than the amount required to keep the publicly owned infrastructure in acceptable conditions (Miyamoto *et al.* 2000). The estimate for the annual budget for MR&R in the EU that would ensure adequate functioning of road infrastructure ranges between 1 and 2% of the total asset value. Considering the monetary value of road infrastructure, it is clear that the available annual budget for maintenance, repair and rehabilitation is always limited and this should be accounted for in the decision model. Therefore, the main purpose of the proposed model is to obtain maximum total utility or the benefit of the selected set of the MR&R projects or facilities associated with these projects while their total cost does not exceed the allocated budget.

2. Road Infrastructure Management Methodology

Efficient road asset management is based on a structured methodology schematically presented in Fig. 2. A sequence of several steps has to be carried out in order to maintain the adequate performance and functionality of the assets. The first step is creating an asset inventory system where all diverse assets are identified and described by the pre-defined indicators.

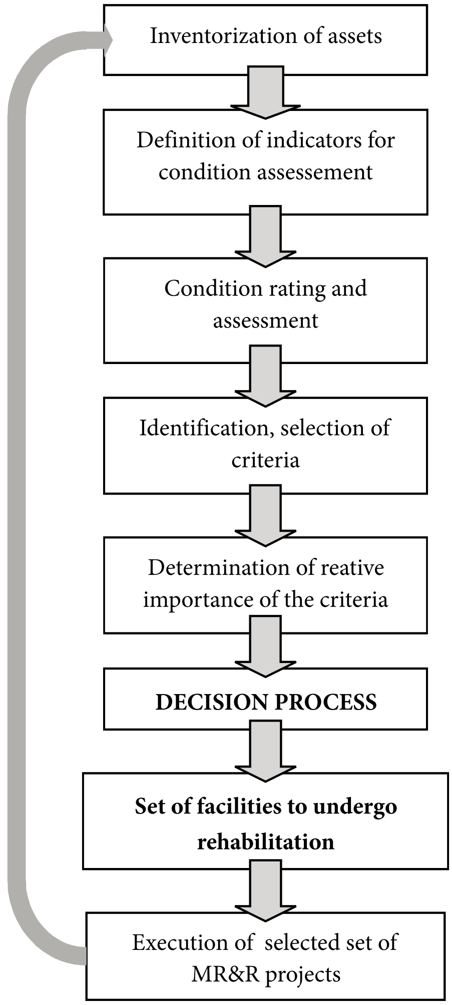

Fig. 2. Schematic presentation of the infrastructure management methodology

As the second step, field inspection, condition assessment and consequent rating of all assets have to be carried out. The rating is based on the asset's physical and functional condition as well as on its structural and overall safety. The indicators have to be established prior to field inspection. The final result of the rating process is a set of scores for each indicator and, if desired, an aggregated total score for each asset.

The rating phase in asset management is followed by the decision process where different criteria can be employed. The criteria and relative importance have to be determined prior to the decision process. The result of the decision process is a set of assets selected for the MR&R actions. After these projects are completed, the performance of the asset is increased (Fig. 1). The cycle is completed by the re-inventarization of the upgraded assets where the new performance level has to be recorded for each facility.

The focus of the present paper is the decision process that supports the selection of a set of assets to be rehabilitated within a given time period. In order to ensure rational decisions that result in maximum benefit for the users as well as for the asset manager, the proposed multiple criteria decision support tool should be embedded into a comprehensive computer-supported asset management system that includes all described elements and is capable of handling large amounts of information that also encompass the tools for condition rating, service life performance analysis and project management.

3. Mathematical Formulation of the Multiple Criteria Decision Model

Multiple Criteria Decision Methods are frequently employed in the evaluation and selection of various constructed assets and their designs, as presented by e. g. Brauers *et al.* 2008; Kaklauskas *et al.* 2007; Kaplinski and Janusz 2006; Jakimavičius and Burinskiene 2007; Lin *et al.* 2008a; Morkvėnas *et al.* 2008; Šaparauskas and Turskis 2006; Viteikienė and Zavadskas 2007; Vaidogas 2007; Tanczos and Torok 2007; Turskis *et al.* 2006; Zagorskas and Turskis 2006; Zavadskas and Antuchevičiene 2007; Zavadskas and Vilutienė 2006; Zavadskas *et al.* 2006, 2007, 2008). The model proposed in this work also includes the budget constraint option which can be mathematically described by the knapsack problem.

For a given set of n facilities requiring a MR&R project, decision variables are labeled as

$a_1, a_2, \ldots, a_i, \ldots, a_n$,

where: $a_i \in \{0,1\}$. $a_i = 1$ if MR&R project for the facility i is selected for execution, else $a_i = 0$.

S_i is the utility score achieved by selecting the facility i to undergo the MR&R project.

Total utility score, S_{tot}, is defined by the expression

$$S_{tot} = \sum_{i=1}^{n} (a_i S_i). \tag{1}$$

All selected MR&R projects within a given time period should result in maximum total utility score, therefore the function

$$\sum_{i=1}^{n} (a_i S_i) \tag{2}$$

is the objective function of the problem to be solved. The problem solution is subject to constraint

$$\sum_{i=1}^{n} a_i C_i \le C_{\max}, \tag{3}$$

where: C_i is the cost of the MR&R project i, and $C_{\max}$ is the available budget for the given time period.

Depending on the criteria employed, the problem may be subject to several other constraints.

The importance of different criteria used in the selection of actions can be captured by assigning criteria weights, w_j, to indicate their relative importance, where the sum of all criteria weights equals to 1 as presented in Eq.(4); m is the number of criteria employed in the decision process.

$$\sum_{j=1}^{m} w_j = 1. \tag{4}$$

Assigning the importance to individual criteria has to be performed prior to the selection process. One of the ways to achieve realistic relative importance between the criteria used and eliminate the subjective influence of the decision maker is to use the analytical hierarchy process (AHP) as proposed by Saaty (1990). This method requires decision-makers to perform the pair-wise comparisons of the relative importance of goals and objectives as well as the relative desirability of competing alternatives (Skibniewski and Chao 1992; Su *et al.* 2006; Lin *et al.* 2008b).

Utility score associated with carrying out the MR&R project on facility i, S_i, can be seen as the value that can be expected when selecting the project/facility. Project/facility i is assigned a utility value S_{ij} with respect to the individual criterion j used in the analysis.

$$S_i = \sum_{j=1}^{m} w_j S_{ij}. \tag{5}$$

A total utility score of a set of the selected projects/facilities, S_{tot}, is the sum of the utility values of all separate projects/facilities selected (Eq. 1). The objective of the decision process is to select a set of the MR&R projects/facilities that results in maximum total utility score (Eq. 2) according to the criteria by taking into account the financial constraint (Eq. 3) and compatibility constraints that depend upon the case being considered. The problem can be solved numerically by using the SOLVER function of MS Excel software.

The cost of the selected portfolio of the MR&R projects, C_{tot}, is the sum of separate projects.

$$C_{tot} = \sum_{i=1}^{n} a_i C_i. \tag{6}$$

4. Case Study

Highway infrastructure consists of various facilities including roads, bridges, tunnels, connections etc. Their properties are diverse and priority ranking of all facilities requires identifying all relevant criteria (different for each facility type) and a comprehensive multiple criteria model.

One of the most frequent facilities within highway infrastructure is overpasses that allow crossing local roads over the highway. Their number is large and their condition can crucially affect the traffic safety on the highway. In addition, the driving conditions on the highway are impaired by overpass rehabilitation work. It is clear that the efficient MR&R management of this particular group of facilities also leads to a better management of highways.

The applicability of the proposed methodology to select a portfolio of overpassing rehabilitation projects with the highest total utility value is presented for a group of 27 overpasses for a selected highway section of 59 km in Slovenia. As already discussed, due to the close interaction between the highway and the overpass, the selection of the criteria used in the decision model has to reflect the changes in highway traffic conditions.

The following criteria are therefore identified and considered:

- ***Facility rating (R).*** Rating or scores assigned to an individual facility as a whole stem for the last regular condition assessment carried out in 2004.
- ***Facility age (A).*** Implicitly, this criterion also includes the functional performance of the facility under consideration.
- ***Overpass grouping (G).*** When a MR&R project is carried out for a particular overpass, one lane on the highway underneath has to be closed for the traffic. The closure of one highway lane yields additional costs to the highway management. Moreover, it can be carried out between two consequent openings in the midline barrier between two highway lanes. If there are several overpasses between two consequent openings in the midline barrier, a rational approach simultaneously requires the execution of their MR&R actions.
- ***Indirect costs (IC).*** The indirect costs of a MR&R project carried out on the overpass are incurred due to highway traffic travel speed decrease. For the purpose of the study, the first estimate for IC was calculated as the financial value of the additional travel time due to speed reduction from initial travel speed (from v_0 to v_1) by using the *ad hoc* expression

$$IC = \left(\frac{d_{c1}}{v_1} - \frac{d_{c1}}{v_0} \right) \cdot DTV \cdot c_{aver} \cdot t_R, \tag{7}$$

where: d_{cl} is the length of the closed lane or the length between two consequent openings in the

Table 1. Values and normalized utility values for the selected set of overpasses for the criteria considered

Facility code *i*	Actual values (f_{ij}) *j* R	A	G	IC	PC	Utility values (S_{ij}) *j* R	A	G	IC	PC
	/	(years)	/	(EUR)	(EUR)					
1	4.29	33	1	199 909	401 370	1.00	10.00	1.00	10.00	9.38
2	9.02	33	3	393 749	411 916	4.09	10.00	10.00	2.05	9.30
3	6.61	31	3	393 749	454 886	2.52	1.00	10.00	2.05	8.95
4	9.03	32	3	376 799	481 644	4.10	5.50	10.00	2.74	8.73
5	9.92	32	1	258 441	387 686	4.68	5.50	1.00	7.60	9.50
6	6.78	31	1	382 792	401 370	2.63	1.00	1.00	2.49	9.38
7	5.45	31	2	394 179	339 922	1.76	1.00	5.50	2.03	9.88
8	12.57	31	2	394 179	385 245	6.42	1.00	5.50	2.03	9.52
9	11.61	31	1	203 428	385 245	5.79	1.00	1.00	9.86	9.52
10	12.57	31	1	214 892	339 922	6.42	1.00	1.00	9.39	9.88
11	9.51	31	1	214 188	560 218	4.41	1.00	1.00	9.41	8.10
12	13.74	31	2	215 696	325 541	7.18	1.00	5.50	9.35	10.00
13	4.77	31	2	215 696	401 370	1.31	1.00	5.50	9.35	9.38
14	11.89	31	2	212 451	481 644	5.97	1.00	5.50	9.49	8.73
15	15.01	31	2	212 451	401 370	8.01	1.00	5.50	9.49	9.38
16	6.29	31	1	282 095	339 922	2.31	1.00	1.00	6.63	9.88
17	10.17	31	3	252 339	454 886	4.85	1.00	10.00	7.85	8.95
18	9.87	31	3	312 420	476 292	4.65	1.00	10.00	5.38	8.78
19	5.27	31	3	312 420	375 222	1.64	1.00	10.00	5.38	9.60
20	6.96	31	1	269 505	375 222	2.75	1.00	1.00	7.14	9.60
21	7.37	31	1	275 051	411 916	3.01	1.00	1.00	6.92	9.30
22	9.11	31	2	295 518	428 128	4.15	1.00	5.50	6.08	9.17
23	9.83	31	2	295 518	470 069	4.62	1.00	5.50	6.08	8.83
24	11.84	31	2	350 463	806 091	5.94	1.00	5.50	3.82	6.10
25	14.89	31	2	350 463	1 434 266	7.93	1.00	5.50	3.82	1.00
26	18.05	31	1	337 523	473 799	10.00	1.00	1.00	4,35	8.80
27	10.07	31	1	419 215	473 799	4.78	1.00	1.00	1.00	8.80
MAX	**18.05**	**33**	**3**	**419 215**	**1 434 266**					
MIN	4.29	31	1	199 909	325 541					
Σ				8 035 127	12 678 961					

Shaded fields indicate the overpasses that can be grouped by joint lane closure highway midline barrier; *DTV* is the average daily traffic volume for a particular location (overpass) on a highway section under consideration; t_R is the average expected duration of rehabilitation work (60 days); c_{aver} is the Slovenian average net hourly wage taken as 4.72 EUR/h as reported by the Statistical Office of the Republic of Slovenia (2007).

- ***MR&R project cost (PC).*** This criterion is composed of rehabilitation work costs (*RWC*) and the lane closure costs (*LCC*),

$$PC = RWC + LCC. \tag{8}$$

Values for the above described criteria for the selected group of 27 overpasses ($f_{i,j}$) are presented in Table 1. These values are normalized in order to obtain utility values S_{ij} for each overpass *i* and criterion *j* presented in Table 1 as well.

For determining utility values for criteria *R*, *A* and *G* (j = 1, 2, 3), the expression

$$S_{ij} = 1 + 9 \cdot (f_{i,j} - f_{min,j}) / (f_{max,j} - f_{min,j}) \tag{9}$$

is used while utility values for criteria *IC* and *PC* (j = 4, 5), where the utility value increases when the cost increase, are determined by the expression

$$S_{ij} = 10 - 9 \cdot (f_{i,j} - f_{min,j}) / (f_{max,j} - f_{min,j}). \tag{10}$$

The actual values belonging to the set of overpasses under consideration (Table 1) show that the age of overpasses ranges from 31 to 33 years. Rehabilitation project costs range from 325 541 to 1 434 266 EUR. Despite the simplified methodology employed in the determination of indirect costs, which is likely to underestimate the real value, it can be observed that for many overpasses under consideration, the indirect costs are in the same range as the project costs.

The weights assigned to the employed criteria are determined by AHP as described in detail by Kne (2007). Their values are presented in Table 2. It can be seen that facility rating is considered the most important factor to be taken into account in the decision process.

Table 2. Weight values, w_j, assigned to the employed criteria and determined by AHP.

j	label	w_j
1	R	0.653
2	A	0.061
3	G	0.112
4	IC	0.061
5	PC	0.112

5. Results and discussion

By taking into account the budget constraint in a given time period of 1 year, the proposed multiple criteria decision model results in a set of the MR&R projects/facilities that yields the maximum total utility value (S_{tot}).

In order to study the importance and influence of the selected criteria upon the selected set of facilities, 4 alternative scenarios regarding a combination of various criteria are taken into account:

- **A.** neither indirect costs (*IC*) nor grouping (*G*) are considered;
- **B.** *IC* are not taken into account as a decision criterion;
- **C.** grouping is not considered as a criterion;
- **D.** all criteria listed in the previous section are taken into account.

The results of the proposed multiple criteria decision model for these scenarios are presented in Table 3. Total budget for all selected MR&R projects (Σ *PC*) is limited to 8 million EUR. The height of allowable indirect costs (Σ *IC*) added to the total budget should not exceed 2 million EUR.

Table 3. Results (sets of selected overpasses) of the 5-criteria decision model.

Scenario	A	B	C	D
IC included	no	no	yes	yes
G included	no	yes	no	yes
Facility code, *i*	Decision vector, a_i			
1	1	1	0	0
2	1	1	1	1
3	1	1	0	0
4	1	1	1	1
5	1	1	1	1
6	1	1	0	0
7	1	1	0	0
8	1	1	1	1
9	1	1	1	1
10	1	1	1	1
11	0	1	0	0
12	1	1	1	1
13	1	1	0	0
14	1	1	1	1
15	1	1	1	1
16	1	1	0	0
17	1	1	1	1
18	1	1	1	1
19	1	1	0	1
20	1	1	0	0
21	1	1	0	1
22	1	1	1	1
23	1	1	1	1
24	0	0	0	0
25	0	0	0	0
26	1	1	1	1
27	1	1	0	0
Σ	**24**	**25**	**14**	**16**
S_{tot}	**118.0**	**122.6**	**83.5**	**90.7**
Σ PC (10^6 EUR)	**9.87**	**9.68**	**9.88**	**9.44**

(0 = project not selected; 1 = project is selected)

The results show that grouping overpasses, when possible, results in a larger number of selected facilities and associated larger total utility score. When indirect costs are considered as a criterion, priority is shifted towards overpasses on locations where highway traffic volume is lower. It should be noted, however, that the relative weight for indirect costs is relatively low; therefore their consideration cannot significantly affect the selected set of overpasses to be repaired.

6. Conclusions

After being built and opened for public use, highway infrastructure is exposed to various deterioration processes throughout its service life. The performance of facilities decreases at different rates and due to various causes. As a consequence, maintenance, repair and rehabilitation projects have to be carried out on several facilities. The budget allocated for these project actions is frequently not sufficient to keep the infrastructure in an adequate condition.

In order to maintain the required performance of the system and consequently ensure its efficient service, the management of this large asset value needs to be rational and should provide the largest benefit to the users. One of the main elements of an adequate database management system that supports highway infrastructure management is a decision support tool which facilitates the process of selecting facilities to undergo a MR&R project. The multiple criteria decision model that takes into account the budget constraint option presented in this paper provides the solution with the highest cumulative utility score. The case study consists of 27 overpasses over a highway section. 5 different criteria are taken into account: condition rating, age, possibility of facility grouping, indirect costs and MR&R project costs. To eliminate the subjectivity of decision makers, their relative importance is determined by the analytical hierarchy process.

The obtained results show that indirect costs, when compared to the MR&R project costs, are significant even when the employed methodology is simplified and the actual indirect costs are underestimated. If indirect costs are not taken as a criterion, the set of overpasses selected to be rehabilitated is significantly changed. The presented decision tool has the potential to facilitate work and rationalize the decisions of the highway network manager. Ideally, it should be embedded in a comprehensive information system that should also contain all types of facilities with all related data, i.e. condition rating and a pictorial database of facilities.

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