Primljen / Received: 10.3.2014.
Ispravljen / Corrected: 4.8.2014.
Prihvaćen / Accepted: 4.9.2014.
Dostupno online / Available online: 10.11.2014.

Optimisation and ranking of permanent way types for light rail systems

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Subject review

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Optimisation and ranking of permanent way types for light rail systems

The evaluation process proposed in the paper is aimed at enablingall interested parties to select the best permanent way type for light track systems, taking into account particular features of every urban area. To this effect, various solutions were studied and ranked by means of the multicriteria evaluation theory in order to determine which specific type can be recommended. The authors do not wish to favour neither the light rail system as a type of public passenger transport nor any particular type of permanent way.

Key words:
light rail system, track structure, evaluation criterion, alternatives, optimization process, ranking, multicriteria evaluation theory

Pregledni rad

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Optimizacija i rangiranje tipova gornjeg ustroja lakog tračničkog sustava

U radu predloženi proces procjene ima cilj osigurati odluku o izboru najboljega gornjeg ustroja lakog tračničkog sustava za sve zainteresirane, uzimajući u obzir okolnosti određenog grada. U tu svrhu istraživana su različita rješenja i rangirana su pomoću teorije višekriterijskog vrednovanja da bi se odredilo koji tip se može preporučiti. Autori nemaju namjere popularizirati niti laki tračnički sustav kao vrstu javnog putničkog prijevoza niti tip gornjeg ustroja.

Ključne riječi:
laki tračnički sustav, konstrukcija kolosijeka, kriterij procjene, alternative, proces optimizacije, rangiranje, teorije višekriterijskog vrednovanja

Übersichtsarbeit

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Optimierung und Einordnung von Oberbautypen leichter Eisenbahnsysteme

In der vorliegenden Arbeit wird ein Bewertungsverfahren vorgeschlagen, das anstrebt unter Berücksichtigung gegebener Stadtverhältnisse Entscheidungen bezüglich der Auswahl eines für alle Interessenten optimalen Oberbaus für leichte Eisenbahnsysteme zu ermöglichen. Dazu sind verschiedene Lösungen durch die Theorie der Multi-Kriterien-Analyse rangiert, um zu ermitteln, welcher Typ empfehlenswert ist. Die Autoren haben nicht die Absicht leichte Eisenbahnsysteme im öffentlichen Personenverkehr oder bestimmte Oberbautypen zu popularisieren.

Schlüsselwörter:
leichte Eisenbahnsysteme, Gleisstruktur, Bewertungskriterien, Alternative, Optimierungsprozess, Einordnung, Theorie der Multi-Kriterien-Analyse

1. Introduction

The light rail system ("Light rail" or "Light Rail Transit" - LRT) as a particular class of urban public passenger railway is an integral part of public transport systems in many cities. As a hybrid form of public transport, i.e. a synergetic combination of aspects of an urban tram and a conventional train, it can hardly be defined in one sentence. The most appropriate definition of LRT is given in ref. [1]: *Light Rail Transit (LRT) is a light capacity transit mode utilizing predominantly semi-exclusive right-of-way and electrically propelled rail vehicles capable of multiple unit operation.*

The LRT's proximity to neighbouring buildings, the need to share the route with motor traffic, and environmental hazards (vibration and noise), are the main limitations with regard to track design and construction [2].

The Light rail system is actually either a new railway for local transit or, more frequently, a system developed from tram lines (Figure 1). Many cities are striving to improve the prestige and image of their cities and policies by using the new term "light rail"[3].

Figure 1. Light rail developed from tram system in Belgrade

The design and construction of LRT projects is both a multidisciplinary and interdisciplinary effort. Selection of the best track superstructure type is a difficult and complex task because of many factors that must be taken into consideration. The situation is further complicated by many different track system alternatives currently available on the market. The factors of influence (assessment criteria or attributes) can be technical and relate to the design and construction, while others are operation and maintenance specific; the third issue is environment, and the final one is safety. All these factors are specific to a particular set of circumstances, and need to be evaluated for such circumstances. On the other hand, the affordability is different for each LRT infrastructure provider, depending on its needs, preferences, available budget and local situation. Every provider attempts to reach the best solution, i.e. to gain maximum benefit with most criteria satisfied, all within the available budget.

The main decision-making problem involves selection of the most favourable solution for building the light rail track superstructure, based on the analysis of many influential parameters. The multi-attribute value theory (MAVT) has been selected in this paper for solving this multi-criteria decision making problem.

2. State of the art

As the legislation, standards, and even consistent information on applicable design practices, are still difficult to obtain and often unavailable, many LRT projects have been designed using a mixture of criteria, derived from widely disparate sources. LRT designers have been mostly compelled to rely on practices developed for trams (like BOStrab regulations in Germany), heavy rail transit, and conventional railway operations, although these are not necessarily well suited for light rail systems. This has resulted in design criteria that are often internally inconsistent. Moreover, many of the already realized projects have had maintenance problems due to disparity between the tracks and vehicles utilising such tracks.

The Track Design Handbook for LRT, TCRP Report 57 from 2000, and its second edition, TCRP Report 155 from 2012 [4], provide a single source of information and an up-to-date guide for the design of light rail tracks. However, the editors emphasize that the data and discussions presented are for guidance only, and that the users themselves assume the entire responsibility for the selection, design and construction based on such guidelines.

The vast majority of the reviewed studies on light rail systems focus on the economic or traffic analysis of such systems, while none of them places emphasis on the assessment of track superstructure.

Gunduz, Ugur and Ozturk [5] have developed multivariable regression and artificial neural network models for estimating construction costs of LRT track works in Turkey at the decision-making phase of such projects.

Kim et al. [6] conducted a research in which they estimated approximate construction costs of LRT structures (e.g. bridges, tunnels, etc.) and developed an economic feasibility analysis system for LRT structures as a support to a reasonable decision-making process.

De Bruijn and Veeneman [7] present a multi-actor decision-making process for making the right decision. They show that the LRT linking to various technical systems increases its technical and social complexity. The choice may change over time and there is no "one right choice".

De Brucker, Macharis and Vebeke [8] demonstrate that multi-criteria analyses can be usefully applied in the context of the stakeholder-driven to transport project evaluation. The decision hierarchy for prioritization is made at several levels.

Litman [9] summarizes the findings of a detailed analysis of transit benefits. Li and Yin [10] provide a basis for accurate calculation of total costs of the urban rail transit. Based on the chain theory, the internal cost is divided into preliminary planning and design cost, construction cost, and operating cost. The external cost is classified into the air pollution costs, traffic accident costs, and noise pollution costs, and an appropriate quantification is made.

Huang and Xia [11] analyse social and economic properties of urban rail transit, and they point to direct and indirect effects the urban rail transit construction has on economic development.

Jha and Samanta [12] use the genetic algorithm and geographic information system approach for rail transit line optimization. Two types of costs are formulated: operator costs and user costs.

Hoback [13] makes a rough estimate of light rail construction, which is solely based on the mileage and type of right-of-way. This finding is often used as an indicator of whether the project meets the budget requirements.

In their study, Zhao and Wei [14] develop a model using the multilevel fuzzy comprehensive evaluation method. The following objectives are considered significant: traveller attraction, environmental protection, project feasibility, and operation. The consistent matrix analysis method is used to determine the weights of individual objectives. The results show that this model can deal with the multivariable and multilevel decision process, which is useful for solving urban rail transit planning problems.

The comparative analysis of the light rail track structures, with respect to technical, economic, operating and ecology requirements, was conducted by Brankovic V. [15] and also by Tomicic-Torlakovic M., Brankovic V. [16].

At the latest TRB 2014 Annual Meeting, only two papers actually dealt with the light rail track issue, but both focus on traffic problems. Jha et al. [17] examine available analytical models for the route and station optimization, with regard to various design and operational constraints. Zlatkovic and Stevanovic [18] evaluate combined effects of increased LRT vehicle frequencies and predictive priority strategies on traffic operation along the corridor, and recommend possible improvements at critical locations by means of the microsimulation software and traffic controllers.

The previously presented literature shows that the assessment and ranking of track superstructure is not considered in papers, and is still based on experience and empirical relations, rather than on numerical optimization techniques.

3. LRT track superstructure options/alternatives

The assessment and optimization process for selecting the best LRT track option is carried out for twelve types of superstructure. They are chosen on the basis of frequency of their implementation in European cities. The track superstructures for LRT can be divided depending on the track bed material:

- Ballasted tracks, and
- Ballastless or so-called slab tracks resting on solid bed (concrete or asphalt).

According to rail support solutions, the ballastless track superstructures are those with: discrete supports and continuous support, [15, 19, 20]. A special solution is the so-called "mass-spring" track structure. The track with a discrete rail support can be either with or without sleepers. According to their design, tracks with sleepers can be characterized by:

- Compact design with the sleepers incorporated into the structure, and
- upported design with the sleepers laid onto the structure.

Ballasted track is marked as alternative 1, and can usually be used on routes where the light rail is separated from road traffic (suburban areas).

Discrete supported rails with sleepers of compact design (alternatives 2 to 4) include all Rheda design types for LRT tracks (Rheda City - Figure 2, Rheda NBS, Rheda City Berlin) [20], where it is common that the twin-block concrete sleepers are inserted through concrete bearing layers.

Discrete supported rails with sleepers of supported design (alternatives 5 and 6) include ATD tracks with bi-block sleepers on asphalt layers, the Stedef system with "booted" concrete blocks, and similar systems.

Discrete supported rails without sleepers (alternatives 7 to 9) are usually applied in systems with prefabricated elements like the BÖGL slab track system, WSG track system with precast concrete longitudinal frames, and the INPLACE track system with longitudinal girders, and so on [20].

Continuously supported rails (alternatives 10 and 11) are represented by systems such as the STRAILastic track frame system, INFUNDO slab track with grooves, ORTEC track system, PHOENIX track system, CDM Cocon track, and by similar systems.

Special solutions for LRT track superstructures may vary to a great extent, depending on the isolation and comfort demands. Some of them are the so-called "mass-spring" systems that can be divided into three different types: full surface elastic layer, linear elastic support, and discrete elastic bearings [21, 22].

4. Assessment criteria / attributes

All previously mentioned track superstructure systems for LRT must fulfil various assessment criteria/attributes, and meet a variety of requirements. The twenty-eight criteria applied in order to compare the solutions are classified into (Table 1):

- technical/design criteria;
- operation and maintenance based criteria;
- environmental impact criteria;
- safety criteria.

All criteria are for guidance only and should be omitted or changed as appropriate. They may be specific to, and need to be evaluated for, particular circumstances. The criteria items are weighted on the basis of the degree of their significance to the decision on the final track choice, and can vary depending on the stakeholder's preferences. In this study, the investor, contractor and passenger preferences are taken into account in the optimization process (Table 2). The importance weighting grades range from 1 (not important),...to 4 (less important),...to 7 (important),... and to 10 (highly important).

Construction cost of a specific track type will depend on local conditions, and the length of track section [23]. According to current knowledge, all types of slab track have an installation cost level from around 1.2 (sleeperless design) to about 2.6 times that of the ballasted track (500 euros per 1m of track length) with great dissipation [3]. The ballasted track option with under-ballast mats raises the price by about 40 %. The deviation of the cost factor can be attributed to several factors [23]:

- The distinction made between different cases of supporting structure (earth works / bridges / tunnels);
- The specification of each project with labour and supply costs that vary according to individual cities and logistical conditions of each working site;
- The options chosen by the infrastructure owner, especially for replaceable components, adjustable fastenings, and equipment for protection against noise and vibration.

Slab track is worth more than it costs, as it improves the quality and availability of LRT lines.

If profitability factors like importance are taken into account, the costs over the entire lifetime (life-cycle costs, LCCs) need to be examined in each particular case. In many instances, the selection of the lowest installation cost will result in continued heavy maintenance, with the corresponding high costs.

The higher production investment costs for slab track are compensated for by cost savings in the maintenance, and by additional revenue due to greater availability of the route. Slab track systems require hardly any maintenance. The ballastless track is more economic than the ballast track because its long-term annual costs are lower [23].

Certainly, construction costs can be reduced by standardization of track design and track works, as well as by prefabrication or semi-prefabrication.

Construction time is expressed in terms of track superstructure length in meters per one working shift. It is a function of the mechanized construction method used. Thanks to long construction experience, the traditional ballasted track structure is more advantageous when this criterion is considered. The construction time also depends on whether the structure is new or a replacement track is made. In the first case it should include a formation or other preparatory work. In the latter case it should include the length of time the track will be unavailable. This criterion is linked with other design criteria as described below.

Building materials delivery is related to the ease with which materials can be delivered. It depends on the availability of local sources, and the supply chain of construction materials. Also, a small quantity of readily available materials constitutes an advantage, as this reduces the storage required for maintenance.

Access conditions for mechanical plant will be site-specific and will depend on traffic conditions, as well as on the building method. Working in an urban environment is not the same as working in a fenced-in building site, or a rural area. Barricades can prevent exposure to dangerous activities and materials. Space restrictions in inner-city track networks often prevent mechanical construction, and hence prolong the construction time.

Susceptibility to substructure quality level calls for settlement free foundation in the slab track design. For that reason, the layout in a tunnel or bridge/viaduct is more favourable with regard to the choice of slab track. Problem locations discovered during soil investigations must be remedied by suitable geotechnical ground improvement methods, in accordance with appropriate requirements. The presence of long term settlements can make the choice of ballastless track difficult and expensive. The ballast track itself exhibits adaptability to the uncontrolled and differential settlement of the support, and to modification of the track alignment and level.

Simplicity of the system (number of components) is met during the expected performance and is followed by the fitness for purpose. For the lines at street level that are subject to heavy load from the rail and road traffic, this criterion assumes a prominent role due to the difficulty of reaching structural components during maintenance, and the need to bring traffic disruptions to minimum levels.

Superstructure weight per meter is an important criterion for tracks on bridges and viaducts and those with a poor foundation. A lower track structure weight is economically justified for bridge structures. Additional measures are needed for the ballast track superstructure on bridges (e.g. under ballast mats or mass-spring systems), and the use of a slab track would be more favourable.

Superstructure height is an especially important criterion in tunnels. In longer tunnels (over 500 m) the slab track has been accepted as standard superstructure, because the maintenance work on ballasted track would be difficult and unsafe. The shallower slab track construction (thickness is reduced by about 30 cm) means a smaller tunnel cross-section and therefore reduced extent of excavation work. As a result, the installation costs for the track and tunnel combined are no higher for solid based track than for ballast track [3].

The concreting method (slipform, in-situ, precast) can shorten construction time, because the construction work in an urban environment causes traffic disruptions. To improve manufacturing tolerances, the semi-precast and fully precast unit solutions for slab track design are opted for, especially when building new LRT track sections [23].

Compatibility with switches and crossings, expansion joints, insulated joints etc. does not cause particular problems compared to plain track. Of course, track system components (such as fastenings) have to be adapted.

Adaptability to the transition structure design can be attained by a wide range of stiffness levels of the track structure, which includes the influence of structural elements (elastic layers, fastening elements, etc.).

Geometrical restraint means the ability of the structure to handle low radius curves and the absence of superelevation in curves, which makes a system attractive to passengers (high commercial speed and high level of comfort).

Availability of domestic materials and contractors is an economic criterion that brings down construction costs.

The possibility of regulating track geometry during installation means the flexibility of alignment and level changes and the ability to vary the gauge, rail inclination, individual rail height etc. The best way to do this is by using adequate elements (pads, nets with eccentric holes, etc.).

Integration in the street infrastructure is an important criterion when light rail lines are built on public roads. A conventional ballast superstructure remains the preferred solution for all tracks on independent formations. On the other hand, when tracks run along the streets a preference is given to slab tracks.

The frequency and level of inspection favour systems that need less inspection. Systems that can be inspected by CCD from service trains are preferred, as this reduces the need for qualified track inspectors to walk the track.

Frequency of rail grinding means that priority is given to systems that cause less grinding such as the systems with continuously supported rails. With ballastless track, a better control of the track support stiffness is achieved, which can reduce rail corrugation and some problems associated with corrugation.

Track quality retention could be a design or safety criterion; it is related to the system's capability to preserve the design track geometry. Maintenance work on track geometry is typical for the ballasted track. Slab track technologies promise a departure from the conventional "fit and repair" routine, and introduction of the "fit and forget" concept. The long-lasting good track quality, and durable and stable slab track position have so far been been proven [22].

The lifetime of the components/system needs to be long, as it is an advantage to avoid inspections, interventions, additional use of material, safety concerns, etc. This criterion is important in operational terms, because of disruptions that are often caused by maintenance and renovation works on inner-city track networks. The track lifetime for slab tracks is estimated at about 60 years but, so far, there has not been enough experience with it in inner-city areas [23].

Noise and vibration emission levels are highly site specific, and are dependent upon local regulations and the level of sensitivity and activity of local population. Such emissions will be affected by the choice of rail, pads, fastening clips, slab/sleepers, anti-noise/vibration devices, etc. Quality oriented devices (sound-absorbing components, "mass-spring" systems, and acoustic barriers) bring up investments costs.

Visual route integration in urban environment means better integration of the route with the urban environment. It shows all types of slab track design, and especially the so-called "green track" design, which greatly contribute to the acceptance of new lines.

Space occupancy of inner city areas means the extent to which the track system occupies a cross section, and how it can permanently enhance the available space.

Water contamination and soil degradation is the ability of the track system to withstand the effects vehicles and passengers have on the city environment. All types of slab track covered designs have this as a priority.

The possibility of evacuation and access by maintenance crews covers the area of safety and ease of access in case of accidents, especially in tunnels, when the track structure must be accessible to rescue vehicles; here the slab track structures are more favourable.

System safety is related to the susceptibility of the track system to all kinds of system damage, like broken rails, loss of pads etc. With ballastless track, better track geometry brings down the dynamic effort between tracks and vehicles, with no plastic distortions that might lead to some unacceptable disorders and defects.

Derailment protection is linked to passenger safety, and it also protects track slabs, sleepers, fastening clips, etc. against damage.

Track stability at high temperatures is linked with the track system and operating safety. The stability level is much higher in case of slab track structures. Priority is given to all types of covered slab track systems and embedded rail systems. Some additional measures are needed for ballasted tracks.

Ease of renewal in case of accidents depends on the construction method used to build the structure, on the number of system components, and on the ease of removal and replacement. The renewal of slab track structure is very complicated and expensive, but no precise renewal costs are available since no major repairs have been required so far. In general, the more solid the design, the higher the costs of renovation compared with the ballasted track alone. Among the solutions, priority should be given to those with precast components.

5. Ranking / assessment process

The procedure for ranking/assessment of the LRT track superstructure contains several steps for developing the optimum track structure from the current options/alternatives, and using the predefined criteria/attributes. The process of ranking alternatives using majority of MCA (multicriteria analysis) methods consists of the following four steps:

- Definiranje opcija/mogućnosti koje treba međusobno rangirati,
- Izbor i definiranje kriterija/atributa,
- Procjena svake opcije/mogućnosti prema svakom od kriterija,
- Postupak optimizacije/rangiranja upotrebom MaVT.

5.1. Defining options/alternatives to be ranked against each other

Twelve available and most frequently used options/alternatives are chosen for ranking. The intention during the identification of slab track options is that they should come from all types of structures, as in Section 3 of this paper.

5.2. Selection and definition of criteria/attributes

It is necessary to determine all issues relating to the decision for selecting the LRT track structure. The determination will consider perceptions of all stakeholders. The stakeholders will include: passengers, local residents, LRT operators, infrastructure managers, contractors, investors, approval authorities, etc. They each have different understanding and preferences regarding the assessment criteria/attributes [24]. The total number of criteria/attributes extended from [16], and grouped in the way as mentioned in Section 4, is listed in Table 1. Also, the importance weightings for every single criterion, with the investor, contractor, and passenger preferences, are included separately in the analyses, and are given in Table 2.

5.3. Evaluation of each option/alternative with respect to each criterion

The options that have monetary value are expressed in monetary terms. Some of the values are taken from [23] and others from relevant sources, or from experience of the authors. All other options are qualitatively evaluated against each criterion in the following manner (see Table 1):
1. recommended value
2. satisfactory value
3. improvement needed
4. inapplicable for the system.

5.4. Optimization/ranking procedure using MaVT

The first three steps are identical in the majority of MCA (Multi-Criteria Analysis) methods. The final step depends on the method selected for the multi-criteria decision making process. Decision making at the level of the society or business is mainly of a multi-criteria type, that is, more factors or interest groups are interested in the final choice, when the decision is based on several alternatives. It is often very difficult to compare technical-technological, environmental, or other parameters [26]. The objective of decision-making is, in this case, to select the most favourable solution (alternative) for the construction of the light rail track superstructure by analysing 28 parameters (criteria). The character of the chosen criteria directly affects establishment of the importance of relationships between the criteria. In one case, the cost criterion is considered extremely important and significantly favoured over other parameters. In another case, the quality control staff wants to pay a special attention to meeting deadlines, thus reducing the time spent carrying out the works and hence the quality and durability, i.e. the service life of the structure.
The MaVT (Multi Attribute Value Theory) is suitable for solving problems in which there is a finite and discrete set of alternatives that are evaluated on the basis of different (often conflicting) objectives. The aim of the MaVT is to provide support to the decision maker in the process of making the choice between various alternatives. In other words, the MaVT techniques help the decision maker to articulate his preferences in a complex decision making environment. The advantages of using the MaVT can be seen in:
- The possibility of structuring the problem, because the classification of alternatives and criteria in terms of adaptation and comparison of different types of information is a prerequisite for the successful resolution of the problem;
- Securing resources for the communication and negotiation in order to preserve advantages and disadvantages of particular alternatives;
- The existence of advanced software solutions in which the MaVT method is integrated with weight coefficients, which enables a relatively simple analysis of large amounts of data, and a sensitivity analysis of the obtained solutions.

The value of an attribute is almost always expressed by means of different measurement scales (Figure 2). The MaVT is a multi-criteria analysis technique which allows good performance of some criteria in order to compensate for weaker performance of others, for weight coefficients given in Table 2. The total value of the alternatives is formed based on the performance of all criteria.

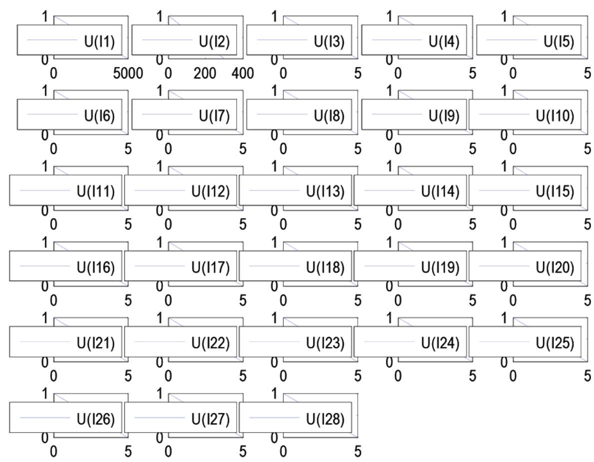

Figure 2. Environmental impact matrix m x n

The purpose of applying the MaVT technique is to give each alternative a real number on the basis of which they are ranked, thus helping the decision maker. It is assumed that a **U** function, defined by a set of real values, can be assigned to each decision-making problem. The **U** function is used to transform values of all attributes of one alternative into a single value.
The MaVT is based on the assumption that there is a real function **U** that represents wishes expressed by the decision maker. This function is used to join each alternative a_j (j=1,2,...n) with the criteria C_i (i=1,2,...n) that are considered in the given

Table 1. Criteria and attributes

Mark	Criteria / attributes	Options / alternatives											
		Ballasted track	Ballastless / slab track										
			Discrete supports with sleepers					Discrete supports without sleepers			Continuous supports		Special construcions
			Compact design			Supported design							
		1	2	3	4	5	6	7	8	9	10	11	12
Design criteria													
A	Superstructure construction costs [€/m1]	500	1200	1300	1200	1200	950	3000	3500	1300	2100	940	3500
B	Superstructure construction time [m1/shift]	300	280	250	280	200	200	200	200	280	200	200	200
C	Building materials delivery conditions	3	2	2	2	2	2	2	2	2	1	1	2
D	Site access conditions for mechanisation	3	2	2	2	2	2	1	2	2	1	1	1
E	Susceptibility to substructure quality	1	2	2	2	2	2	2	2	2	2	2	2
F	Simplicity of system (number of components)	3	2	2	2	2	2	2	2	2	1	1	2
G	Superstructure weight (bridges)	3	2	2	2	2	2	1	2	2	2	1	1
H	Superstructure height (tunnels)	3	1	1	2	2	1	2	2	1	1	2	1
I	Concreting method	4	3	3	3	3	1	1	1	3	3	2	1
J	Compatibility with switches & crossings	1	2	2	2	2	2	3	3	2	2	3	3
K	Adaptability to the transition structures	1	2	2	2	2	2	2	2	2	3	3	1
L	Geometrical restraints	2	1	1	1	1	1	2	2	1	3	3	2
M	Engagement of domestic materials / contractors	1	4	4	4	4	4	4	4	4	1	4	4
N	Possibility for track geometry regulation	1	1	1	1	2	2	1	2	2	3	3	2
O	Integration in the streets	4	2	2	2	2	2	2	2	2	1	1	2
Maintenance													
P	Frequency and level of inspection	3	2	2	2	2	2	2	2	2	1	1	2
Q	Frequency of rail grinding	3	2	2	2	2	2	2	2	2	1	1	2
R	Track quality retention	3	1	1	1	1	1	1	1	1	1	1	1
S	Lifetime of components / system	3	2	2	2	2	2	2	2	2	2	2	2
Environmental impacts													
T	Emission of noise and vibration	1	2	2	2	2	2	2	2	2	1	1	1
U	Visual integration of route in urban environment	4	1	1	1	1	1	1	1	1	1	1	1
V	Space occupancy in inner city areas	4	1	1	1	1	1	1	1	1	1	1	1
W	Water contamination and soil degradation	3	2	2	2	2	2	2	2	2	2	1	1
Safety													
X	Ease of evacuation and access for maintenance	3	2	2	3	3	3	2	3	3	1	1	1
Y	System safety (broken rail, loss of pads, etc.)	3	2	2	2	2	2	2	2	2	1	1	2
Z	Derailment protection	3	2	2	2	2	2	2	2	2	2	2	2
LJ	Track stability at high temperatures	3	2	2	2	2	2	2	2	2	1	1	2
NJ	Ease of renewal in case of accidents	1	3	3	3	1	1	1	1	2	3	3	2

Table 2. Preference weights

Mark	Criteria / attributes	Important weighting		
		Investor preference	Contractor preference	Passengers preferences
A	Superstructure construction costs [€/m']	10	8	4
B	Superstructure construction time [m'/shift]	10	8	8
C	Building materials delivery conditions	6	10	5
D	Site access conditions for mechanical plant	5	10	4
E	Susceptibility to substructure quality	4	8	2
F	Simplicity of system (number of components)	6	10	6
G	Superstructure weight (bridges)	7	5	1
H	Superstructure height (tunnels)	9	5	1
I	Concreting method	1	6	1
J	Compatibility with switches & crossings	5	5	2
K	Adaptability to transition structures	5	5	2
L	Geometrical restraints	5	2	3
M	Engagement of domestic materials / contractors	10	9	6
N	Possibility for track geometry regulation	3	9	4
O	Integration in streets	7	1	9
P	Frequency and level of inspection	5	3	8
Q	Frequency of rail grinding	2	4	8
R	Track quality retention	8	6	7
S	Lifetime of components/system	9	3	9
T	Emission of noise and vibration	8	5	10
U	Visual route integration in urban environment	7	1	9
V	Space occupancy of inner city areas	7	1	9
W	Water contamination and soil degradation	7	4	9
X	Ease of evacuation and access for maintenance	7	7	10
Y	System safety (broken rail, loss of pads, etc.)	7	4	10
Z	Derailment protection	8	4	10
LJ	Track stability at high temperatures	8	3	8
NJ	Ease of accident renewal	8	8	9

ranking problem. Using the general form of the function **U**, the problems can be defined as:
The best alternative is the alternative for which

$$U (C_1(a), C_2(a),... C_n(a)) = \max U (C_1(a_j), C_2(a_j),... C_n(a_j)), j=1,2,...m \quad (1)$$

In MaVT with n criteria $C_1, \ldots, C_n$ (n = A - NJ), each alternative a is represented by a vector a $(a_1, \ldots, a_n)$, where a_j (for j = 1, 2, . . . ,m = 12) is a raw measure or description of the tangible or intangible impact of a in the criterion C_j (e.g. Superstructure construction costs, Superstructure construction time).
Let $S = \{a^1, \ldots, a^n\}$ denote the set of all alternatives under evaluation. It can be assumed that the preference of the alternatives $a_1, \ldots, a_m$ with respect to a single criterion C_j is completely known and explicitly measured in an interval scale or ratio scale in which more is preferred to less. To obtain the best alternative, one must define the function **U**, which is quite a difficult and time-consuming process. One of the MaVT's decision-making rules is the rule of complete compensation according to which the totally bad criteria can be balanced out by good criteria.
The MAVT method is used for making various decisions in the public and private sectors. In the majority of cases, the additive form of MAVT is used in order to allow a more simple and transparent decision support, which can be implemented by a wide circle of users for many diverse problems.
It is important to bear in mind that this approach enables, e.g. when taking into consideration economic factors and the impact on environment, a complete change in environmental funding.
The simplest form of the **U** function can be represented as:

$$U=\sum_{i=1}^{n} V_i(x_i)w_i, \quad (2)$$

Where:
V_i - value of option x_i,
w_i - weight coefficient.

U is the overall value of the alternative x, $V_i(x_i)$ is the single attribute value function reflecting the alternative x's performance on attribute i, and w_i is the weight assigned to reflect importance of the attribute i. We applied the direct-rating method for the assessment of the single attribute value functions $V_i(x_i)$. In this method, the respondent is asked to estimate the strengths of preferences for different levels of an attribute on a numerical scale. First, the most and least preferred levels are identified and valued with 10 and 0, respectively.
The remaining levels are then rated between the two endpoints. The relative spacing between the levels of the attribute reflects the strength of preference of one level compared to another.
Different techniques for calculating the **U** function can be found in [27, 28].

6. Results and sensitivity analysis of ranking process

The main result of the analysis made in this paper is the proposed procedure for finding the optimal solution for the track superstructure for LRT railway lines in cities. It can be implemented for any type of railway using other alternatives and criteria.
For all three preferences (investor, contractor and passenger), proposed alternatives are ranked according to the MaVT technique as follows:
- For the investor preferences: [10, 11, 12, 6, 5, 7, 3, 2, 9, 4, 8, 1];
- For the contractor preferences: [10, 11, 12, 7, 6, 5, 3, 2, 8, 9, 4, 1];
- For the passenger preferences: [10, 11, 12, 7, 6, 5, 3, 2, 9, 8, 4, 1].

This means that the ballastless track superstructure with continuous rail supporting, and the constructions with special noise and vibration attenuation demands, have the priority as the LRT track superstructure under the proposed preferences. The next ranked group is the group of ballastless track superstructures with discrete rail support on sleepers, which lean onto a rigid base, i.e. they are not incorporated in the base. The remaining track type alternatives change their place on the ranking list depending on individual preferences.
The ballasted track is the last on the ranking list for all preferences although it should be noted that it is still the first preference for suburban areas where light rail is separated from road traffic.
The importance weighting is multiplied by several times In order to investigate the sensitivity of the ranking to the change of importance weighting for the investor, contractor and passenger preferences regarding the construction cost, construction time, and emission of noise and vibration, respectively. When multiplied by the multiplier values of 2, 4, and 8, these variations in importance weighting give the alternative ranking as shown in Table 3.
This sensitivity analysis shows that the ranking list does not change significantly even when the importance weighting of construction cost, as the investor's first criteria preference, is multiplied by several times. The ranking still gives priority to the ballastless track superstructures with continuous rail support and with discrete rail support on sleepers, which are not incorporated in the base. Only these two kinds of track superstructure change places on the ranking lists. However, the special ballastless superstructure, and the expensive options

Table 3. Ranking lists for different multipliers of investor, contractor and passenger preferences

Investor preferences (construction cost)	**Ranking lists**											
Without multiplier	10	11	12	6	5	7	3	2	9	4	8	1
With multiplier = 2	10	11	6	5	12	3	2	9	7	4	8	1
With multiplier = 4	11	10	6	5	3	2	9	4	12	7	1	8
With multiplier = 8	11	6	10	5	2	3	9	4	1	7	12	8
Contractor preferences (construction time)	**Ranking lists**											
Without multiplier	10	11	12	7	6	5	3	2	8	9	4	1
With multiplier = 2	10	11	12	7	2	6	4	3	8	9	5	1
With multiplier = 4	10	11	12	7	2	6	8	4	3	9	5	1
With multiplier = 8	10	11	12	7	2	6	8	4	3	9	5	1
Passengers preferences (emission of noise and vibration)	**Ranking lists**											
Without multiplier	10	11	12	7	6	5	3	2	9	8	4	1
With multiplier = 2	11	12	10	7	2	4	6	3	8	9	5	1
With multiplier = 4	11	12	10	7	4	3	2	6	8	9	5	1
With multiplier = 8	11	12	10	7	4	3	2	6	8	9	5	1

of ballastless superstructure with discrete rail support without sleepers, get a lower ranking on the ranking list. It follows that the ballasted track is not always the last on the ranking list.
When the importance weighting of construction time, as the contractor's first criteria preference, is multiplied by several times, the ranking list exhibits minor changes only. The ranking also gives priority to the ballastless track superstructures with continuous rail support, but next in ranking become the track without sleepers (alternative 7) and with discrete rail support of compact design (alternative 2). The ballastless superstructure option with discrete rail support, and with sleepers of supported design, drop on the ranking list (one option is even next to the last one). The ballasted track is always the last on the ranking list.
By multiplying by several times the importance weighting of emission of noise and vibration as the passengers' first criteria preference, after the ballastless track superstructures with continuous rail support, next in ranking become the track without sleepers (alternative 7) and with discrete rail support of compact design (all alternatives). The options of ballastless superstructure with discrete rail support, and with sleepers of supported design, drop once again on the ranking list. The ballasted track is always the last on the ranking list.

7. Conclusions

This paper deals with a specific area of urban railways and with selection of its superstructure by means of multicriteria optimization. It differs from other papers presented in available literature in that it introduces a large number of track superstructure alternatives and many influence factors (criteria) into the track superstructure optimization, and provides solution to the problem with the help of the multi-value attribute theory. The proposed procedure is not restricted to LRT tracks only, and can adequately be applied for all kinds of railways tracks.
The ranking procedure shows that the sensitivity to any particular criteria or weighting can be checked, but that it is not often critical to the final track superstructure type selection. The changes in importance weighting rarely affect the outcome of optimization, but this weigthing can be managed by the interested stakeholders. However, it should be noted that the result of the ranking process will be as good as the competence and experience of the team representing needs of all stakeholders. In fact, they should be highly familiar with available solutions, technology, and circumstances of a particular location.
This paper intends to identify requirements of urban track systems, by assessing the options available, and optimizing the choice of the best track superstructure under particular local circumstances. It is the only way of arriving at a technically and economically balanced result when selecting the design for a given track section from the proposed alternatives and based on the adopted criteria list.
Future research should concentrate on the use of some other multi-criteria techniques, to be backed by comparison of research results.

Acknowledgment

This work constitutes a part of the TR 36017 project, and its realisation was enabled thanks to financial support granted by the Ministry of Education, Science and Technological Development, Republic of Serbia.

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