



SETTING PRIORITY LIST FOR CONSTRUCTION WORKS OF BICYCLE PATH SEGMENTS BASED ON ECKENRODE RATING AND ARAS-F DECISION SUPPORT METHOD INTEGRATED IN GIS

Jurgis ZAGORSKAS^{1*}, Zenonas TURSKIS²

¹Dept of Engineering Graphics, Vilnius Gediminas Technical University, Lithuania

²Dept of Construction Management and Real Estate, Vilnius Gediminas Technical University, Lithuania

Received 3 May 2019; revised 27 June 2019, 12 August 2019; accepted 7 October 2019

Abstract. Bicycling and walking are essential elements of sustainable transportation. These transportation modes effectively reduce the negative environmental impacts of transport and improve the quality of life. It is not only recognized by governments but also naturally become more prevalent in modern society. Nowadays research on bicycling and interest in related topics is dramatically increasing, but while researchers focus on modern technologies and collecting data from portable devices, there are quite a few studies on the effectiveness of investments in bicycle infrastructure, and even less discussed is a question how to set the priorities for construction works of the bicycle path network. To fill this gap this paper presents the universal method of ranking the priorities for development and renewal of bicycle pathway segments. The process is realized by hybrid Multi-Criteria Decision-Making (MCDM) Additive Ratio Assessment with Fuzzy (ARAS-F) model, based on Eckenrode rating. Given criteria and their weights apply only to the specifics of this case study, and it need adaptation if used for other territories. Presented case study gives insight into the task of upgrading bicycle networks – how to overcome the inequalities, fragmentation and build missing links. Developed hybrid MCDM model integrated into Geographic Information System (GIS) allows quickly find rationally balanced solutions and develop bicycle network in efficient way.

Keywords: sustainable transportation, cycling, bicycle route, multi-criteria decision-making (MCDM), Eckenrode rating, additive ratio assessment with fuzzy (ARAS-F), criteria, value.

Notations

AHP – Analytic Hierarchy Process;	MCDM – Multi-Criteria Decision-Making;
ARAS – Additive RAtio Assessment;	MOORA – Multi-Objective Optimization on the basis of Ratio Analysis;
ARAS-F – ARAS with Fuzzy;	MULTIMOORA – MOORA plus full multiplicative form;
ARAS-G – ARAS with Grey relations;	SAW – Simple Additive Weighting;
CODAS – Combinative Distance-based Assessment;	SWARA – Step-wise Weight Assessment Ratio Analysis;
ELECTRE – ELimination Et Choice Translating REality (in French: <i>ELimination Et Choix Traduisant la REalité</i>);	TODIM – Interactive and Multi-criteria Decision Making (in Portuguese: <i>TOmada de Decisão Interativa Multicritério</i>);
FUCOM – FULL Consistency Method;	TOPSIS – Technique for Order of Preference by Similarity to Ideal Solution;
GIS – Geographic Information System;	VIKOR – Multi-Criteria Optimization and compromise Solution (in Serbian: <i>VIšeKriterijumska Optimizacija i kompromisno Rešenje</i>).
MABAC – Multi-Attributive Border Approximation area Comparison;	
MAIRCA – Multi-Attributive Ideal-Real Comparative Analysis;	
MADM – Multiple-Attribute Decision-Making;	

*Corresponding author. E-mail: jurgis.zagorskas@vgtu.lt

Introduction

Transportation, behind electricity, is the second major contributor of ever-increasing CO₂ and greenhouse gas emissions (27% of emissions). Near half of the transportation greenhouse gas emissions are from cars and trucks. Great volumes of motorized traffic reduce air quality and create noise in sensible urban environment. Besides that, car uses up to 10 times more street area than a bicycle and creates the problem of congestion in usually already limited urban spaces. In a dense urban environment, cars are regarded as an unsustainable mode of transportation, and alternative options, such as bicycles, are being put at a higher priority. Bikes contribute zero greenhouse gas emissions, therefore governments of many cities are now focusing on bicycle network enhancement, route safety and adequate infrastructure. As the climate change issue rises, bicycle planning becomes more prevalent in urban planning and transportation planning. While the number of vehicles is rapidly growing, the urban planners and transportation planners are attempting to change people's travel mode selection to less energy-intensive modes, particularly, cycling.

Bicycle network is the part of the town transportation system, and in significant part, it shares the same infrastructure with cars, pedestrian sidewalks, have the same travel origins and destinations and so forth.

This underlying issue motivated our study and raised the main research questions:

- how to determine the missing links in the bicycle network?
- how to define the most critical sectors of bicycle path network?
- how to manage the construction works and priorities with a limited budget?

Cyclists choose their route differently to drivers of automobiles. They usually have multiple objectives when choosing their route: the travel time and the suitability of a route. Relevance can be evaluated by non-subjective factors including safety, traffic volumes, traffic speeds, presence of bicycle lanes, whether the terrain is flat or hilly, and so forth. These objectives can be combined into a single value with the help of MCDM.

The bicycle path construction works usually are executed by contracting several road construction companies for specified segments. The segments to be developed are usually taken from city transportation plan, city sustainable mobility plan, from a transportation part of a general city plan or other planning document. Existing planning documents have imperfections – the planners often rely only on engineering intuition and their expertise, without consideration of objective goals. In addition, the valid plans are quite often outdated due to the extended approval procedures and do not reflect the recent changes in travel origin-destination, developed and reconstructed segments and other dynamic changes. The municipality department responsible for transportation system quite often lacks the arguments why construction works were

started in one part and not the other. Lack of the arguments creates the doubt in effectiveness of investments and at the same time the chance to misuse the funding. As a common practice, the priorities are considered and priority list is created directly by experts or responsible municipality workers. The MCDM were never used for setting the priority line for construction works of this kind previously. MCDM approach can help to make solid base for setting the schedule and priorities in construction works of bicycle pathways and solve the above mentioned problems.

This study was focused on finding the essential criteria to compare existing and proposed bicycle path segments by multiple criteria with the goal of organizing the construction process more effectively by setting the priority list for construction of bicycle path network segments. Through a collaborative process of organized expert surveys, the system of criteria was developed and integrated in GIS to function as a tool for defining the most potential and important segments in bicycle network. This tool has potential to advance the development and manage investments effectively. The developed tool in work is demonstrated on Kaunas City (Lithuania) case study. Authors have contributed to creating the criteria system and organizing the expert surveys, mathematically describing the ranks of criteria and writing the script for GIS, also collecting and filling the data describing the bicycle network segments in case study area. This study concentrates on the interests of urban planners, policymakers, stakeholders, cyclists and citizens, and particularly, on setting the priority line for bicycle path construction works. The ARAS-F method was selected from a variety of methods because it does not have the rank reversal quality, i.e. when the alternatives are added or removed, the existing rank listing remains the same with inclusion or exclusion of other alternatives. Rank reversal can be harmful in the specifics of proposed application.

The paper is organized as follows – first section is introduction and introductory materials for setting up the scene. The next section presents literature review with focus on MCDM use in transport and research on other aspects of bicycle network. In the last section a brief description of the method and case study data with calculations are given, outlining the critical points for adaptation of this method to different possible situations. Conclusions and discussion section of this paper describe the novelty of proposed methodology, provide general recommendations for applying it in practice, discuss the limitations of common practice in bicycle path construction and renewal and shows the necessity to periodically rethink development strategy. Rebirth in planning and construction of bicycle pathways in Europe.

1. Promotion of cycling in European countries

The promotion of cycling in European cities is as an effective and efficient tool for reducing the negative environmental impacts of transport and improving quality

of life. Active transportation modes such as bicycling is a critical element of sustainable transportation (Luo *et al.* 2020). Reduced motorized transportation can also help to achieve other strategic targets - the cities can reduce greenhouse gas contribution, noise levels and improve air quality. Increasing cycling rates also have substantial health benefits, despite the increased exposure to air pollution and traffic.

In response to the interests of bicycling to the environment and public health, the municipalities work to establish new bicycle routes and to promote bicycle use not only as sports activities but also for commuting trips.

A holistic approach to the quality of cycling experience promotes cycling as an alternative vehicle. The holistic approach of these main factors: road safety, psychological and physical perception, ease of travel, easy access and a highly connected network.

The latest research topics show that separating bicycle lanes from main motorized traffic volumes for health reasons is essential and recognized strategy (Jack *et al.* 2018; Jereb *et al.* 2018; Luo *et al.* 2020; Minet *et al.* 2018). The importance of relocating urban bike lanes to the calmer streets, especially in the cities is stressed in many research papers (Gongora *et al.* 2018; Gössling *et al.* 2019; Otero *et al.* 2018; Zalakeviciute *et al.* 2019).

While recognizing the environmental and health benefits of cycling, cities around the world are promoting the use of bicycles, but their information about cyclists' preferences is usually limited. Only in a few cases is mentioned the efficiency of the investment in the bicycle infrastructure (Diez *et al.* 2018; Gu *et al.* 2017; Hood *et al.* 2011; Macmillan *et al.* 2014).

Another critical trend is exploring the safety of bicycle routes. Many researchers put efforts in establishing the methods to address bicycle safety by reflecting urban conditions explicitly, and have found that many factors influence the safety, starting from traffic volume, lane width, population density, highway classification, and presence of vertical grades, one-way streets, and truck routes. These urban conditions were taken into account to predict the severity of an injury that would result from a motor vehicle crash that occurred at a specific location in many recent studies (Allen-Munley *et al.* 2004; Aziz *et al.* 2018; Kang, Fricker 2018; Rossetti *et al.* 2018).

Recently with growing concern about public health and safety issues, the revival of separating bicycle paths from motorized traffic is observed. The bicycle networks are planned to be separated and moved away from heavy traffic to safer and healthier environments like unused riversides, parks and natural territories.

In all European countries striving for sustainable development, most contemporary urban policies include the sustainable mobility policy, which is currently in the developing stage. The sustainable mobility concept is the shift from a focus on transportation modes and traffic flows (traditional transportation managing) to focus on people in order to take account of citizens' varied needs

and activities in everyday life, involve citizens, and move from the top-down expert forms to transparent and participatory forms of planning. However, the mobility-based approaches de facto still dominate in transportation planning in most countries.

In sustainable mobility, the main focus lies on making cities mixed-use, compact, better connected and accessible by non-motorized travel modes. The vision of the urban future is often described in terms of “a closer city”, “near metropolitan region” with the strategies to promote slower transport modes, public transport, and local living, while other cities have started to evaluate accessibility improvement in terms of geographical distances between people and everyday activities. Besides, many medium-sized cities, in their comprehensive planning, define “the near city”, “the compact city center”, and “mixed land use” as leading goals for future development, stressing the importance of nearness in everyday life for all citizens (Gil Solá, Vilhelmson 2018).

When such shifts in planning and practice occur, the importance of the bicycle network naturally increases. The overall connectivity and proximity of the bicycle network and pedestrian pathway network become a critical issue.

When the question comes to the implementation of sustainable mobility plans very often, we found a knowledge and practice gap for making investments successful and leading to the actual improvement of overall bicycle path network performance.

2. Literature review

In recent decades, scientists have devoted much attention to researching transport issues. MCDM are used in transportation planning and research usually at the initial stage of strategic planning, when there is a need to consider between different alternatives (Hood *et al.* 2011; Kabak *et al.* 2018; Hashemi *et al.* 2018; Petraška *et al.* 2017, 2018; Hashemkhani Zolfani *et al.* 2013; Olariaga, Moreno 2019; Tsami *et al.* 2018). These methods are used by researchers to find the best location for transportation terminals, to decide between several alternative connecting roads or railway lines when planning the network development and other similar objects of transportation system (Wang, Yeo 2018; Vasilienė-Vasiliauskienė *et al.* 2019; Nouredine, Ristic 2019; Efimenko *et al.* 2018; Dahooie *et al.* 2018; Zavadskas *et al.* 2015; Palevičius *et al.* 2018; Stojić *et al.* 2018; Sharma *et al.* 2018; Wagale, Singh 2019). MCDM also are widely used for logistics (Zanjirani *et al.* 2019; Gogas *et al.* 2014; Turuskis, Zavadskas 2010a; Stević *et al.* 2017; Prentkovskis *et al.* 2018; Wang, Yeo 2018; Tsami *et al.* 2018; Zavadskas *et al.* 2018a, 2018b; Tanackov *et al.* 2019). In most study cases fuzzy criteria weights are used (Zavadskas *et al.* 2009; Zagorskis *et al.* 2014; Turuskis *et al.* 2015; Medineckienė *et al.* 2015). The fuzzy evaluation method is particularly suitable for expressing experts' thinking and preferences characterized by uncertainty, ambiguity, non-observability, and scarcity.

In the study to select intermodal routing from Korea to Central Asia used the fuzzy Delphi method was applied to obtain the factor structure to evaluate intermodal routing from Korea to Central Asia by clustering opinions from experts, and Fuzzy ELECTRE I was used to evaluate the route selection process (Wang, Yeo 2018). Other case study demonstrates application of fuzzy SAW method to define the priorities for reconstruction of sections of damaged road in Pringsewu, Lampung, Indonesia. The method is used to consider between 5 alternative road sections and set the priority line (Muslihudin *et al.* 2018). Some aspects of bicycle infrastructure were studied in similar approach by other authors. Recently many studies to find best locations for bicycle sharing stations were conducted. Some of them use MCDM and GIS combination. The study of bicycle sharing station locations in Karsiyaka, Izmir demonstrates the application of AHP, MOORA and GIS data to solve the problem (Kabak *et al.* 2018). In the same manner the MCDM approach is used instead of purely statistical number of accident and social pressure prerogatives to define the necessity for level crossings of road and rail traffic. Authors use combined FUCOM-MAIRCA method (Pamučar *et al.* 2018). Other branch of using MCDM in transport planning is selection of best routes. As an example the study of 15 routes by which hazardous materials can be transported must be noted. The researchers use combined FUCOM-TOPSIS-MABAC model. This model was tested on the real example of the transport Eurodiesel in Serbia (Noureddine, Ristic 2019). The methods used in mentioned studies are suitable only for single time evaluation. In the case of setting, the priority line and then executing it, with the changes of initial matrix and adding or removing alternatives these methods can disclose rank-reversal feature. It may then compromise the decisions already made and bring a conflict in contracting process.

Bicycle path network as a part of transportation system has been studied by many scholars usually without application of MCDM. The focus of recent research lies mostly on finding the most used pathways and analysing the cyclist preferences for choosing the route, the aim of such studies is usually to predict the volumes of cyclists. During the past decades, researchers endorsed several methods for the selection of suitable bicycle routes including meta-heuristics, Q-learning algorithm and combined techniques (Chen *et al.* 2018; Lawrence, Oxley 2019; Osaba *et al.* 2018; Pritchard 2018). Many findings of cyclist preferences and behaviour were collected from smartphones (Bernardi *et al.* 2018; Ghanayim, Bekhor 2018; Park, Akar 2019; Wu *et al.* 2018) and big data sources (Zeng 2018; Zhang, Mi, 2018; Zhang *et al.* 2019) and show that the cyclists preferences are less predictive than it can appear. Many cyclists have several route options and they select these routes with individual preferences that bring uncertainty and difficulties in prediction. Collection of locational choices from smart phone and big data sources were focused mostly on bicyclist travel route preference in an existing network to predict the travel demand and highlight safety

problems, but some of these findings could be used to enhance solutions for developing the existing bicycle network – the studies show the importance of surroundings and psychological comfort of the cyclist, as well as preferences to drive in safer and calm traffic streets.

There are several studies done in exploring the priorities of choosing the route for cycling. The findings show that each cyclist may prioritize differently between travel time and suitability when they choose a route, and most cyclists travel on two to three routes within the same origin-destination pair and that safety and environment friendliness are the most important factors (Ehrgott *et al.* 2012; Majumdar, Mitra 2018; Pritchard 2018).

The bicycle pathway construction works are less discussed topic between researchers. The main reasons for this are the difficulty to define and compare the alternative segments and the domination of intuitive planning methods. There are instances when the scientific approach is not welcome due to local construction market division and similar monetary questions.

3. Materials and methods

3.1. ARAS method with fuzzy criteria values (ARAS-F)

In scientific literature authors present dozens of MCDM techniques to solve modern multifaceted problems. Zavadskas *et al.* (2013a, 2013b) presented three hybrid methods SWARA-TOPSIS, SWARA-ELECTRE III, SWARA-VIKOR were to assess different construction technologies. Bagočius *et al.* (2014) presented group decision-making approach based on the multi-criteria integrated additive-multiplicative utility function and the AHP method. Keshavarz Ghorabae *et al.* (2016) presented CODAS method to assess changes of microclimate in buildings. Ruzgys *et al.* (2014) applied integrated evaluation of construction alternatives using SWARA-TODIM MCDM method. Zavadskas *et al.* (2013a, 2013b) verified robustness of WASPAS and MULTIMOORA methods when assessing alternative solutions. Šaparauskas *et al.* (2011) used integrated additive-multiplicative function and entropy-based model to choose among available options.

The MCDM hybrid model, which includes the ARAS with fuzzy criteria values, was selected to solve the problem of finding the most critical sections of bicycle paths. Zavadskas and Turskis (2010) developed the ARAS method. Later, modifications of the ARAS method: ARAS-G (with grey relations) and ARAS-F were published (Turskis, Zavadskas 2010a, 2010b). There are many applications of ARAS method (Turskis *et al.* 2012; Zavadskas *et al.* 2015; Turskis, Juodagalvienė 2016).

ARAS method (Zavadskas, Turskis 2010) is based on the argument that the phenomena of the complicated world could be understood by using simple relative comparisons. It is argued that the ratio of the sum of normalized and weighted criteria scores, which describe alternative under consideration, to the sum of the values

of normalized and weighted criteria, which represents the optimal alternative, is a degree of optimality, which is reached by choice under comparison.

According to the ARAS method (Zavadskas, Turskis 2010), a utility function value determining the complex relative efficiency of a reasonable alternative is directly proportional to the relative effect of values and weights of the main criteria considered in a project.

The most significant value is the best, and the last one is the worst. The optimality function \tilde{S}_i has a direct and proportional relationship with the values \tilde{x}_{ij} and weights \tilde{w}_j of the investigated criteria and their relative influence on the final result. Therefore, the higher the value of the optimality function \tilde{S}_i , the more effective the alternative. The priorities of other options determined according to the value \tilde{S}_i . Consequently, it is convenient to evaluate and rank decision alternatives using this method.

There are various approaches for assessing weights (Zavadskas *et al.* 2010), e.g., the eigenvector method, SWARA, expert method, entropy method, and so forth.

Fuzzy group weight is determined as follows:

After obtaining the criteria weights from fuzzy Eckenrode rating technique (Turskis *et al.* 2019a; 2019b), the synthesizing of ratio judgements is done.

Suppose $\tilde{W} = [\tilde{w}_1, \tilde{w}_2, \dots, \tilde{w}_n]$ is fuzzy group weight for n criteria and \tilde{w}_j is a fuzzy triangular number:

$$\tilde{w}_j = (w_{j\alpha}, w_{j\beta}, w_{j\gamma}),$$

where: $w_{j\alpha} = \min_k y_{jk}$, $j = \overline{1, n}$, $k = \overline{1, p}$ is the minimum possible value;

$$w_{j\beta} = \left(\prod_{k=1}^p y_{jk} \right)^{\frac{1}{p}}, \quad j = \overline{1, n}, \quad k = \overline{1, p} \text{ is the most probable value;}$$

$w_{j\gamma} = \max_k y_{jk}$, $j = \overline{1, n}$, $k = \overline{1, p}$ is the maximal potential value of j th criterion.

3.2. Proposed criteria for an estimation of the importance of bicycle network segments

The general aim of creating criteria system with criteria weights was to establish a priority line for existing and proposed bicycle path network segments. The priority line should be used to select a number of segments that can be renovated or constructed with the current budget. The system of criteria was created to cover all possible aspects of segment suitability and expediency. At the beginning the expert surveys were performed, selecting the experts from the field of professional town planners, traffic engineers and also the target group – bicycle users. At the same time the survey data from sustainable transportation plan of Kaunas City, where 2000 inhabitants were surveyed was used to improve the results. Criteria system was developed by an expert group consisting of seven experts (two town planners, two road engineers and road construction managers, three local cyclists). The criteria value

data was filled according to the opinion of local cyclists and field observations. Some values were obtained from other sources described in Table 1.

Experts defined main four criteria groups, which can be shortly described as follows.

Usefulness (G1) – explaining the necessity of the bicycle path segment. The measure for this criterion derived from:

- defining the centrality of the sector in overall bicycle network;
- existing bicycle traffic volume or prognosis.

Safety (G2) – most experts agree that security is one of the most important factors limiting the use of the bicycle in modern towns. The value for this criterion derived by summing three components if the cyclists share the road with cars:

- car traffic intensity;
- speed of car traffic;
- presence of heavy transport, trucks.

If the cyclist path is separated, most of the safety problems disappear, and bicyclists become vulnerable only when crossing the streets.

Convenience (G3) – the cyclist, will not use the path (and in some cases choose another mode of transport) if it is not convenient and will rather drive on the street. Therefore, this criterion should also be matched, and it consists of:

- path quality;
- elevation gain; more than 40 m of elevation gain in the section of 200 m length makes cyclist sweat and is unbearable for less prepared cyclist; more than 10° steep climbs are also unacceptable for the general public;
- a number of crossings; if crossings where a cyclist has to stop appear more often than every 200 m, it makes cycling slow and not convenient.

Comfort (G4) – the physical and psychological factors of satisfaction are crucial to invite people to cycle. These consist of:

- presence of natural or artificial sun shades, windshields (trees, buildings etc.);
- spectacularity of the surroundings of the path segment;
- the positive impact of exposure to nature or adverse effects of exposure to urban wasteland, industrial, abandoned territories, vast open spaces.

It resulted in 11 GIS data attributes. Experts ranked the importance criteria group and then the importance of each separate criterion inside the criteria group. The ranking basis is the Likert-type scale with fuzzy criteria weights. Table 1 presents the normalized expert ranking results.

For each bicycle network segment (each entity in GIS) the attribute values must be filled using collected data or expert (usually local users) estimations. The criteria describing the pathway have fuzzy characteristics and were described in min, max and average value. To defuzzify values center of area approach was used.

Table 1. Expert rankings of importance for criteria groups and criterions inside each group

Criteria group	Criteria group importance in overall decision-making			Criteria number	Description of separate criteria and comments on the assigned values*	Separate criterion importance in the group		
	α	β	γ			α	β	γ
G1 – usefulness	0.19	0.37	0.25	c_{11}	Existing or predicted bicycle traffic volume. The volume was taken from STRAVA heat-map (https://www.strava.com/heatmap) and corrected with some field study results available	0.28	0.83	0.55
				c_{12}	The centrality of the segment in the whole bicycle network. The centrality value was taken from space syntax theory, calculated by <i>DepthMapNetworkX</i> software	0.14	0.69	0.51
G2 – safety	0.19	0.37	0.26	c_{21}	Car traffic intensity. Was evaluated in 10 point system where 6 and less means street segments with calm traffic	0.31	0.46	0.39
				c_{22}	Average observed speed of motorized traffic flow. The higher the speed – the less safe is cycling and the more significant the need to separate the bicycle lane from motorized part of traffic	0.15	0.38	0.28
				c_{23}	Presence of heavy transport – trucks etc. When this type of transport is present, it dramatically decreases the safety of cycling. Therefore there is a need to separate bicycle lanes	0.23	0.46	0.33
G3 – convenience	0.12	0.37	0.26	c_{31}	Path quality. The path segments of poor quality have the priority for reconstruction works because they can strongly influence the decision of the city population to cycle	0.31	0.46	0.37
				c_{32}	Elevation gain. The critical elevation gain in a short segment was considered 40 m. Critical incline, which can compromise the use of bicycle proposed by the cyclists was 7°	0.15	0.46	0.30
				c_{33}	A number of crossings. If the crossings with congested streets are present in smaller than 200 m distance, it creates some inconvenience for both cyclists and other traffic users	0.23	0.38	0.33
G4 – comfort	0.12	0.31	0.19	c_{41}	Presence of natural and artificial sunshade, windshields. In many narrow streets or densely built-up streets, these elements are present	0.10	0.62	0.37
				c_{42}	Spectacularity. The things that attract cyclist attention and are relevant to them were considered – beautiful views, charming facades and exciting layouts of the streets, presence of street activity, shops	0.10	0.52	0.36
				c_{43}	Exposure to nature elements. Mostly this added value to the separated bicycle path segments going through parks and green areas. These should be promoted if possible	0.10	0.52	0.30

Note: *all criteria values were estimated in points except safety group “average observed speed of motorized traffic flow”, which was estimated by [km/h].

4. Specifics of case study and other cities that need to be noted

Every town has its own positive and negative factors that influence the use of the bicycle. All these must be carefully studied and considered – there is a need to involve local cyclists and local specialists to do not miss these most important formants of the bicycle network. In every city, limitations are occurring from natural and anthropogenic barriers of the environment. It can be rivers, highways, railroad lines, significant climbs or uneven surface that prevents the cyclists from using the bicycle or limits the connectivity. The measures to cope with these barriers

must be considered separately from the construction of bicycle lanes. The technical measures can be costly (i.e. building a new bridge or adding funicular), or in contrary – policy measures can cost nothing (i.e. the allowance to transport a bicycle in public transport for free), but the implementation of such actions can change the whole situation and connectivity in the city. After the application of serious measures each time the priorities of bicycle network development must be reconsidered to avoid inefficient investment.

The cities and the conditions for bicycling in the cities differ in every aspect – the natural environment, the climate, the economics, social-demographic conditions, life-

style and habits of inhabitants, compactness and rational dislocation of the city, land use and mixture or separation of uses, use and development level of other transportation modes, existing infrastructure for bicycling, etc. Only local users can know the sum of these conditions resulting in the decision to cycle or not. Therefore it is necessary to involve local cyclists in the bicycle network development plan making.

The developed method was tested on Kaunas City (population 289380, area 157 km²). This example illustrates essential key elements of research – defining the specifics of planned territory, evaluating the criteria and calculating the results. Figure 1 shows natural and other occurring limitations in the city. Kaunas City territory can be divided into the upper and lower terrace. Lower terrace represents the deep river valleys, where downtown and most of the historic districts are situated. The upper terrace is divided by these valleys into three parts by 40...60 m valley hills with extreme natural slopes of 10...20°, which are levelled down in some places by human activities. The altitude difference between these two terraces prevents the general mass of people from cycling between them, only the cyclist in better than the typical physical form can climb such heights without challenge. However this impediment is gradually becoming less significant with the increased use of e-bicycles and e-scooters. Other occurring divisions are created by highway belt around the city – the highways should not be crossed by foot or bicycle, although in some places it can be observed. Railway lines are the third obstacle and dividing element. As Kaunas City case study shows, in similar way every city has the natural and artificial obstacles that influence the bicycling network and overall use of a bicycle.

There are further key points necessary to overlook for full analysis. One of the main limitations in such type of study is that to be able to derive accurate results the studied territory must be homogeneous. Urban territories have different morphological structure (i.e. living areas with single-family housing or multifamily blocks, town center and downtown, industry areas). The criteria system must be adopted to describe the specifics of territory. If the urban area has significant differences in morphological structure, there can be difficulties with establishing criteria weights properly. It leads to the problem of comparing alternatives objectively, and it can result in mistakes and illogical priorities. The best way to deal with the issue of homogeneity is to divide town territory and analyse it in separate segments.

Bicycle pathways serve two different types of journeys – recreational and commuting. In the presented case study, the stress was put on making people use bicycle not for recreation (recreational cycling takes more than half of bicycle rides in Kaunas City today) but for transportation and daily communication home–work–shopping/leisure chains. The bicycle is meant to replace other modes of transport and only in some part as a sporting activity in the strategic vision of town municipality.

This goal has made clear criteria for initially selecting the territories that are proper for cycling and can benefit most from this mode of transport. Those are the parts of the city without barriers and with a biggest concentration of living, working places and places of public attraction. In Kaunas City, the main historical city center and the downtown area is on the lower terrace and, although, has quite big numbers of working and public places to visit, is separated from modern development and new center.

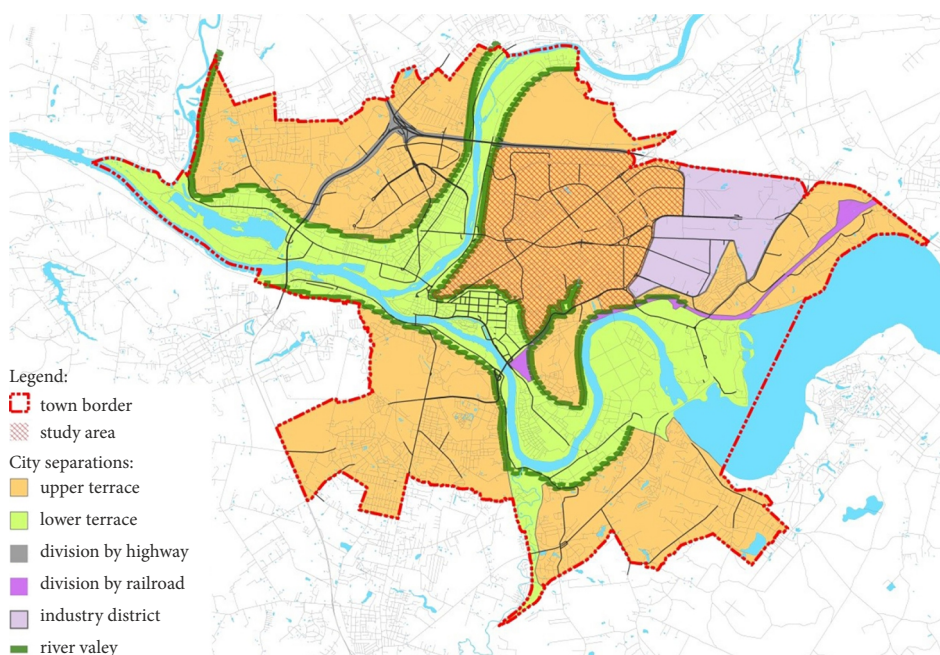


Figure 1. Definition of barriers and divisions of the city significant for the cyclists

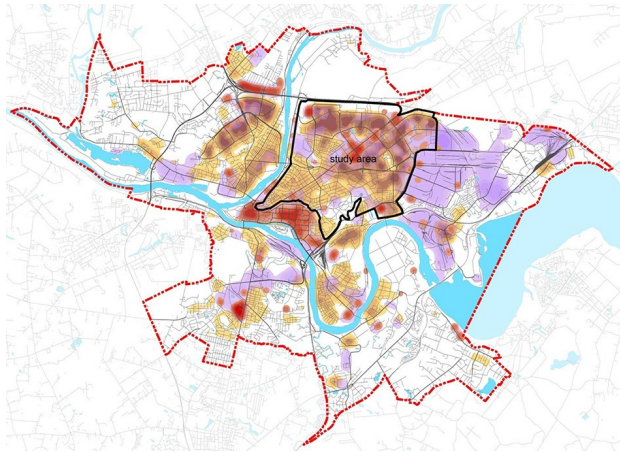


Figure 2. Case study description – concentration of living, working places, and objects that attract the public daily. The density of living places is shown in brown, working areas – in purple, public attraction places in red colours

The downtown area was excluded from the study because it has completely different specifics: most of the streets are pedestrian or calm traffic streets, the cyclist shares the same space with cars and pedestrians. In addition, downtown and center area in Kaunas City need specific measures to connect them with the upper terrace to make a journey to the center and back comfortable for the cyclist with lower physical form. Figure 2 presents the selected area where newly built bicycle paths would have the highest effect.

The selected area is most important of all upper terrace territories; it is homogeneous and catches a significant part of Kaunas City travel destinations. It catches 40.5% of living places in the city, 19% of working places and is close to another 17% of working places in industry district, 31% of public places.

5. Case study calculations and results

Existing systems of bicycle pathways in post-Soviet countries have deficiencies left from periods of economic instability and uncertainties in management. There were periods while municipalities were not collecting enough funds, or it was unclear who is responsible for renewal of existing bicycle pathway constructions. As the cities were going through severe reorganization processes and changes of development trends (e.g. people moving from multi-family blocks to individual housing suburbs), the planning of development of bicycle network was quite often left without attention. During the period from 1990 until 2010 in Lithuania, there were considerable mismatches between planning and implementation of bicycle infrastructure development.

The problem of building a bicycle network consistently in Lithuanian towns exists even today – there is a considerable discrepancy between the plans and capabilities to construct. Usually, the gaps in the network to be filled are quite significant, there is a substantial portion of poorly maintained bicycle pathways, and there are no clear pri-

orities. In this situation construction works are becoming fragmental and very often they cannot be accomplished on time. It has become a widely discussed topic of concern amongst municipalities. To meet the requirements of European Union municipalities of Baltic States also started to conduct sustainable transportation plans, putting much effort on promoting bicycle network and other measures to encourage cycling. However often the development marked in these plans is not proper and reasonable – too many new segments are proposed without considering local financial and constructional capabilities, there is no prioritization of construction works, and it results in a delay in the improvement of network functioning.

Due to the lack of arguments and missing holistic approach the planners sometimes fail even to identify the main problems and challenges to the development of the bicycle network. Such is the case with Kaunas City where the proposed pathway segments show the links that are impossible to climb due to height altitude; some of them are of relatively low importance and can be left for next decades; too many segments are proposed to be built at once.

As world practice shows, people start to use the newly built bicycle pathways only in five years. In a dynamically changing urban environment, five years matter a lot – there can be shifts in travel destinations, population densities, and travel modes. In five-year period bicycle paths wear a lot in natural conditions of the Baltic region. It is not always predictable how fast the existing pathways will wear-off, what important attraction objects and in what places will emerge in the city creating and changing the travel demand.

The development of small sectors that are essential in connecting the whole network is much more valuable than big scale construction because it can be adapted to changes of the situation and easily modified if necessary. The whole bicycle pathway network must be re-examined periodically, every year before making further steps.

In this case study, the analysed bicycle network consisted of 179 segments of bicycle paths. Some of these segments were newly built, some were only planned to establish where the cyclist shares the space with automobiles at the present moment. The data was collected for every path segment mostly by direct observation and recorded in 11 GIS attributes. Table 2 shows the resultant normalized calculation matrix.

Decision-makers consider all criteria of the MADM task as independent from each other, and the people making decisions (experts), are essential in the determination of a set of criteria, values of qualitative measures and definition of the importance of specific goals of the stakeholders. Development of composite indicators for integrated performance in societies typically relies on a priori assumptions rather than model-free, data-driven evidence (Servadio, Convertino 2018). Traditional variable selection processes tend not to consider relatedness and redundancy among variables, instead of thinking only individual correlations. The analysis of sensitivity and uncertainty is one of the complex problems of application of the MADM models (Convertino *et al.* 2014). The majority of discrete optimiza-

Table 2. The normalized calculation matrix (presented partially due to the huge amount of data) for ARAS-F method with calculated utility function value S and utility degree of alternative K

	c_{11}				c_{43}			S	K
	α	γ	β		α	γ	β		
Utopia	0.00035	0.00093	0.00210	...	0.00021	0.00094	0.00263	0.0136	1.000
1	0.00035	0.00093	0.00210		0.00002	0.00009	0.00026	0.0054	0.394
2	0.00021	0.00056	0.00126		0.00002	0.00009	0.00026	0.0049	0.361
3	0.00021	0.00056	0.00126		0.00002	0.00009	0.00026	0.0044	0.324
4	0.00024	0.00065	0.00147		0.00002	0.00009	0.00026	0.0049	0.362
5	0.00024	0.00065	0.00147		0.00002	0.00009	0.00026	0.0048	0.354
				⋮					
175	0.00028	0.00075	0.00168	...	0.00002	0.00009	0.00026	0.0052	0.380
176	0.00028	0.00075	0.00168		0.00013	0.00057	0.00158	0.0062	0.454
177	0.00028	0.00075	0.00168		0.00013	0.00057	0.00158	0.0061	0.448
178	0.00028	0.00075	0.00168		0.00013	0.00057	0.00158	0.0061	0.445

tion (MADM), parameters of optimization of a cumulative distribution function are unknown, and in most cases, the decision maker cannot define it. With the advent of advanced estimation techniques, mutual information has become a viable means of characterizing input-output interactions in complex problems. Lüttke *et al.* (2008) recommend Entropy-based sensitivity analysis. The sensitivity analysis in this paper lays the theoretical foundations for an information-theoretic sensitivity analysis that assigns credit or influence to input variables in terms of their overall contribution to a system’s output entropy. It is based on the review of the difference between a change of input data and results of the multi-attribute utility function (Saltelli *et al.* 2008). The entropy-based sensitivity analysis shows that criterion c_{43} (exposure to nature elements) has the most significant impact on the final solution in this particular matrix (about 31%). Criterion c_{21} (car traffic intensity) and is considered to be in the second place to influence the final decision (about 23%). The difference between the most important criterion c_{43} and the least essential criterion c_{32} (elevation gain) is about 26%. The elevation gain is not important here because the selected area is flat, in other cases this criteria has great significance.

ARAS-F method was integrated into GIS by the means of PYTHON scripting tool (<https://www.python.org>), which is widely supported by GIS programs. The attributes were taken into the calculation, and derived values were added as data attributes to represent the utility degree of alternative. The priority line can be made by merely arranging GIS table elements according to this calculated value. The ARAS-F method calculations can be embedded in simple PYTHON script and with the call of the function recalculated whenever there are changes in path consistency (i.e. new segments are added), attribute values, criteria system, weights of criteria. The developed method is very flexible and can function as a tool for decision support. The system can be improved with involving more experts, adding new criteria or removing unnecessary.

Figure 3 presents case study results for Kaunas City.

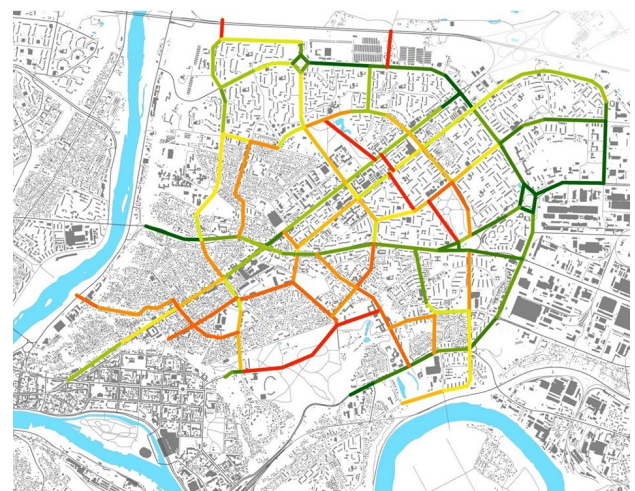


Figure 3. Case study results – priorities are shown in graduated colours where red means the highest priority and green – the lowest priority for construction or renovation of the bicycle path segment (the preferences, as expert group concluded, are given to the segments, which are not yet developed, run through calm and bicycle friendly surroundings, are safe and convenient for cyclist)

6. Discussion

The cities and the conditions for bicycling in the cities differ in every aspect – the natural environment, the climate, the economics, social-demographic conditions, lifestyle and habits of inhabitants, compactness and of the city, land use and mixture or separation of uses, use and development level of other transportation modes, existing infrastructure for bicycling, etc. In every city, there are limitations occurring from natural and anthropogenic barriers of the environment. It can be rivers, highways, railroad lines, significant climbs or uneven surface that prevents the cyclists from using the bicycle or limits the connectivity. Bicycle network is a part of the transportation system and belongs to dynamical and quickly changing urban environment. Development of a bicycle path

network is a gradual process, which must go together with changes in travel preferences and lifestyle of the general population.

The problem of building a bicycle network consistently exists in many cities – there is a considerable discrepancy between the plans and capabilities to construct. Usually, the gaps in the network to be filled are quite significant, there is a substantial portion of poorly maintained bicycle pathways, and there are no clear priorities. In this situation construction works are becoming fragmental and often they cannot be accomplished on time. Due to the lack of arguments and missing holistic approach, the planners sometimes fail to identify the problems and challenges for the development of the bicycle network. The decisions in common practice are based on engineering intuition of experts, and as such, they cannot be based strong arguments when setting the priority line.

Construction and renewal works cannot be done at once; it requires specific resources, time, and have limited financing therefore; it can only be implemented step by step. To decide, which actions must be taken in a certain period the priorities must be set. After finding the most critical links and sectors in the bicycle network and making improvements, there is a need to re-evaluate the performance and sum up the changes. Bicycle pathway network situation must be re-examined periodically, every year before making further steps.

To set the priorities, the criteria system must be developed, from the beginning of this process having in mind what are the main goals of development. The criteria system must be designed to describe the essential characteristics on which the decision will be based. If the strategic goals change, the criteria system must be adjusted accordingly. All criteria and criteria weight system must also be periodically reconsidered.

Proposed mathematical model would help to make solid decisions and manage investments in bicycle infrastructure more effectively. The method implies also measures of monitoring the environment, which in practice are quite often forgotten. The attribute values usually cannot be de-

rived from readily available data, and much of field observation must take place to give sound and mistake-prone results. With renewing of attribute information for bicycle network segments many other insights would appear.

The ARAS-F method calculations can be embedded in GIS by PYTHON scripting and recalculated whenever there are changes in path consistency (i.e. new segments are added, there are changes in transportation plans), attribute values, criteria system, weights of criteria. The developed method is very flexible and can function as a tool for decision support for many years. The system can be improved with involving more experts, adding new criterions or removing unnecessary.

The flowchart presented in Figure 4 shows the main steps of implementation of proposed method. Setting the strategic goals and setting criteria, criteria weights is done at the initial stage. Bicycle pathway segments are taken from existing situation and development plans. Big part of the attribute information can only be filled by field observation and needs to be periodically updated – the quality of pavement, traffic volumes, etc. (Sivilevičius *et al.* 2008; Gössling *et al.* 2019; Zalakeviciute *et al.* 2019; Minet *et al.* 2018; Luo *et al.* 2020; Wagale, Singh 2019). When the initial stage is finished the systems enters repeating loop of creating reports, updates and recalculations. ARAS-F method ensures that added planned segments will not reverse the priority line after recalculations. GIS functionality can be efficiently used to visualize the priorities and to embed MCDM as well as recalculate the priorities with every update of the information.

Conclusions

The cities and the conditions for bicycling in the cities differ from region to region and must be considered before planning the development and setting the criteria. Bicycle network is a part of the transportation system and belongs to dynamical and quickly changing urban environment therefore development plans must be periodically revised and reconsidered.

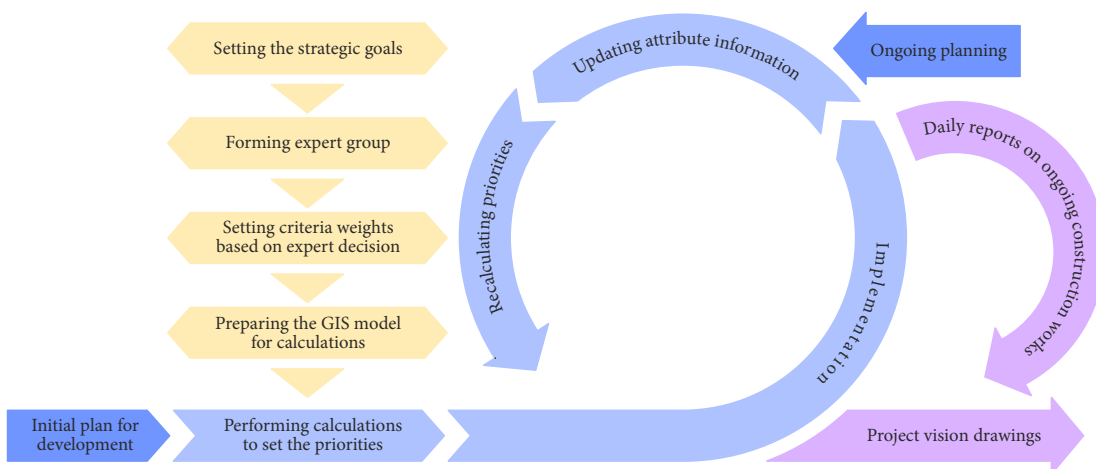


Figure 4. Steps to install proposed method and run it in consistent loop at responsible for bicycle network development institutions

Construction and renewal works cannot be done at once; it requires specific resources, time, and have limited financing therefore, it can only be implemented step by step. To decide which actions must be taken in a certain period the priorities must be set. After finding the most critical links and sectors in the bicycle network and making improvements, there is a need to re-evaluate the performance and sum up the changes. Bicycle pathway network situation must be re-examined periodically, every year before making further steps.

The problem of building a bicycle network consistently exists in many cities – there is a considerable discrepancy between the plans and capabilities to construct. Usually, the gaps in the network to be filled are quite significant, there is a substantial portion of poorly maintained bicycle pathways, and there are no clear priorities. In this situation, construction works are becoming fragmental and often they cannot be accomplished on time. Due to the lack of arguments and missing holistic approach, the planners sometimes fail to identify the problems and challenges for the development of the bicycle network. The decisions in common practice are based on engineering intuition of experts, and as such, they cannot be based strong arguments when setting the priority line.

Proposed method for setting priorities in development and maintenance of bicycle pathway can help to respond to dynamic changes of urban environment and overcome uncertainties in decision-making when considering the sequence and order in which construction works must take place. Proposed mathematical model would help to make solid decisions and manage investments in bicycle infrastructure more effectively. The method implies also measures of monitoring the environment, which in practice are quite often forgotten. The attribute values usually cannot be derived from readily available data, and much of field observation must take place to give sound and mistake-prone results.

In case study example, the evaluation system consisted of four groups of criteria – usefulness, safety, convenience and comfort. Each group had several sub-criteria. The entropy-based sensitivity analysis shows that criterion c_{43} (exposure to nature elements) has the most significant impact on the final solution in particular matrix (about 31%). Criterion c_{21} (car traffic intensity) is considered to be in the second place to influence the final decision (about 23%). It shows that in Kaunas City case study the biggest concern was comfort and safety. The difference between the most important criterion c_{43} and the least essential criterion c_{32} (elevation gain) is about 26%, which is normal range and there is no need to remove unimportant criteria. System of criteria can be modified and changed with the changes in strategic goals or new insights. Proposed system with slight modifications can be adapted to other cities with a wide range of urban circumstances.

Author contributions

Jurgis Zagorskas conceived the study and was responsible for the design and data collection, analysis and interpretation, expert survey, scripting.

Zenonas Turskis conceived MCDM part and was responsible for the application of MCDM, criteria weight estimations and comparison of alternatives.

Disclosure statement

Authors of this paper do not have any competing financial, professional, or personal interests from other parties for presenting this material.

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