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Multi-Criteria Decision Making Process in Metropolitan Transport Means Selection Based on the Sharing Mobility Idea

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Abstract: The article presents the idea of modeling the decision-making process in the field of the metropolitan areas transport system. Due to the increasing process of metropolization and urbanization, which is predicted to be 68.4% worldwide and 83.7% in Europe in 2050, the issue will be even more sophisticated. The problem of depletion of transport network capacity as well as the implementation of modern technology solutions forces metropolitan committees to apply tools for metropolitan passenger transport system optimization. Significantly, the policy and regulations on sustainable urban mobility management are based on the mobility demand predictions and understanding of the travel decision-making process of citizens. The scientific purpose of this article is to build a mathematical model, as a tool supporting the multi-criteria decision-making process regarding the choice of means of transport in a developing metropolis. The issue raised in this article considers the most important research areas of the metropolitan transport means selection, which includes transport safety, qualitative, financial, and ecological aspects. The model was implemented in Silesian Metropolis in Poland with a particular emphasis on sharing mobility transport means users. As a result, a ranking of sharing transport means was developed, which is a piece of significant information for planners and future investors in the development of the metropolitan transport system.

Keywords: metropolitan transport system; the model of metropolitan transport means selection; multi-criteria decision making; sharing mobility; sustainable mobility; sustainable transport

1. Introduction

In the world and Europe, socio-economic and technological development affecting the lifestyle change of inhabitants have been observed since the post-war period. Cities and agglomerations have become increasingly important in providing more and more of society's needs. This resulted in attracting people to these areas, causing their expansion, and thus the need to ensure access to areas inhabited by people translating into the need to develop the transport network.

An efficient and effective metropolitan passenger transport system is a big challenge enabling the improvement of the quality of life. It is threatened by the increase of metropolization and urbanization. In 2018 the percentage of population residing in urban areas was about 55.3% worldwide and in Europe 75.4%, while in 2050 it is predicted to be, accordingly: 68.4% and 83.7% [1].

A special case concerns those newly created or in the initial phase of metropolis transformation where the transport systems of many neighboring cities are unified. On one hand, this creates problems associated with the need for multifaceted integration into a uniform passenger communication system [2–4], which most often concerns a joint fare and ticket plan. On the other hand, however, the possibility of development and transformation creates the opportunity to use an integrated communication system that would combine all means of communication into one coherent cooperating whole, respecting economic and ecological aspects and responding to the needs of residents and modern trends.

The Sustainable Urban Mobility Plan (SUMP) is the answer to the challenges related to the need to design efficient and ecological public transport systems. In the study [5], authors indicated decision-making problems related to the development of transport systems in the face of planning challenges of sustainable urban mobility.

The issue raised in this article is relevant and important for several reasons. First of all, it concerns the significant problem of depletion of transport network capacity resulting from the fact that the pace of development of the transport network with the continuous increase in population does not ensure that all needs are met. Despite this situation, society is not discouraged from inhabiting areas with high population density, which causes their continuous expansion creating metropolitan areas, which from a transport point of view are characterized by:

- the presence of a large number of traffic generators and thus a large number of optional or mandatory needs,
- transport behavior of a highly mobile society,
- a wide range of travel options using various means of transport.

Secondly, the article refers to the real problem of the excessive increase in the number of cars used by residents of large cities. This creates problems associated with the development of streets, parking spaces, and reorganization of traffic in cities due to undesirable phenomena of congestion. For this reason, conditions should be created for the transport system to develop sustainably, most often limiting the use of individual transport in favor of public transport and new, flexible forms of travel. Currently, means of transport, including those based on the idea of transport sharing, must flexibly meet the transport needs of residents through:

- ensuring the possibility of starting and ending a travel when a transport need arises (without waiting and thus wasting time), with a high level of so-called "temporary availability,"
- ensuring the possibility of starting and ending the travel at the place where the transport need arose and where it ends, with a high level of so-called "spatial accessibility,"
- the need to ensure the highest level of flexibility, even in the context of sharing this mode of transport with other users, and also in the context that the transport means of must provide the possibility of traveling in a multimodal way.

Thirdly, the conducted research concerns the means of transport selection, which constitute a significant part of the transport system of cities and regions. Before traveling, many large residents face the dilemma of which mode of transport to choose. The decision-making process is the more difficult the more developed the offer of transport service operators. Thus, it is a challenge to determine the demand for transport means. Due to the diversity of passenger preferences, the formulation of selection criteria can be a big mistake.

The scientific purpose of this article is to build a mathematical model, which is a tool supporting the multi-criteria decision-making process regarding the choice of transport means in a developing metropolitan areas from the perspective of transport systems planners and sustainable urban mobility plan engineers as a support for decision makers (politicians). This article considers the most important research areas of the metropolis transport means selection, which includes transport safety, qualitative, financial, and ecological aspects. Therefore, a measurable result of the research presented in the article is a multidimensional decision support model when choosing the transport means in the implementation of travel in metropolitan areas, which can be used as a tool for shaping sustainable transport development in emerging metropolises.

The research area is Upper Silesia, Poland, where a cluster of cities called the Upper Silesian-Zaglebie Metropolis (in short Silesian Metropolis) is located. This area, as an example of a European developing metropolis, is a conurbation with several central centers (including Katowice), which are surrounded by smaller satellite cities. Creating a single sustainable and modern system of passenger transport for more than two million numerous inhabitants is one of the priority activities of the joint venture cities and municipalities.

The paper is organized as follows. Section 2 includes a review of the literature on the aspects raised in the article. The problem is discussed with particular emphasis on metropolitan transport integration and the growing share of pro-ecological concepts in mobility management, including the share of sharing mobility ideas in the space of transport systems. Section 3 describes the research approach and indicates the applied methods. It also presents a diagram illustrating the course of research divided into individual four stages. Section 4 includes an essential part of the article related to building the model of metropolitan transport means selection. Section 5 is devoted to model verification among the research area in Silesian Metropolis. The analysis covered multi-criteria decision on metropolitan transport means selection, which allowed to present a ranking list of available variants. The results were presented in the form of charts, and additionally, detailed data were presented in tables. Finally, Section 6 is devoted to the discussion of the results and conclusions.

The overall objective of the paper is to present the possibilities of using the model to rationalize decisions in the field of mobility management for the implementation of sustainable solutions in urban transport. Identifying and implementing them can contribute to improving the quality of life in the city by reducing the negative impact of transport on the environment and human health.

2. Literature Review

Metropolitan transportation is perceived as the lifeblood of cities because it provides the essential link of the constantly moving population in this area. It should provide livable urban environments, as well as modes of transport, that functionally complement each other [6,7]. In that way, transportation is a link between five variables of livability: local inhabitants, community life, service level, local economy, and physical place [8]. The livability of cities is an important issue as it shapes public perception and infrastructure investments in cities, as well as competition among cities for the attention of the public, investment communities, and potentially fickle and mobile human capital [9]. The infrastructural investments affect not only spatial distribution of travels (where and from people are traveling) but also the distribution of transport tasks (what kind of mean of transport is used) [10]. The comfort of city life can be so satisfying that the concept of the lovable city was created [11].

However, in many cities today, sustainable transport policy is applied, consisting of the development of the transport system while maintaining a high quality of life in the city and fulfilling Sustainable Development Goals (SDGs) [12,13]. To promote sustainable and livable urban cities, private, public, and non-motorized transport [14,15], so important in many geographical areas, must functionally complement each other by forming balanced integrated systems. Several levels of metropolis transportation systems are outlined: operational (composed of layout, schedule, and information, fare, and ticket integration), physical, and organizational [16–18]. Especially the operational integration refers to the coordination and planning of the transport system with minimum interruption in space and time to promote smooth, continuous, and seamless services, without interchanges [19].

Changing lifestyles around the world have created a growing demand for personal transport. Mobility and transport patterns are linked in complex ways with significant social trends, such as the adoption of suburban lifestyles or the aging of populations [18–20]. The dominance of the private vehicle in urban transport makes automobile mobility essential everywhere, with the possible exception of the centers of the largest cities [21,22]. Therefore, it is crucial to policy to avoid further increase of individual automobile transport in towns and causes of a decrease in travel speed, irregularity of public transport operation, and impact on passengers in public transport. The increase of individual automobile transport causes other problems such as decreasing road safety, increasing air pollution, traffic noise, and global warming [23].

This is the reason why so many different ideas of decreasing the number of individual vehicles in the cities have been developed in the literature [24]. Some of them are incentives to attract passengers to transit: collective taxis [25–27], mobility management (MM) [28–32], carpooling [33–36], car-sharing [37–39], or clean transit fleets [40]. The other works present tools for disincentives to the use of private cars, for example, time access restrictions [41,42], optimization of the access control system [43], pedestrian zones [44], permits for central areas only for clean vehicles [45], pricing policies [46,47], goods delivery distribution systems [48], infrastructure investments [49–51] and others.

Previous studies have attempted to show that modern solutions in the field of transport systems and its elements, including innovative solutions among means of transport as a substitute for private vehicles, are implicated. Many publications prove that semi-autonomous vehicles [52], highly autonomous vehicles (HAVs) [53], or fully autonomous vehicles (FAVs) [54,55], can be an option instead of conventionally driven vehicles (CDV) for urban traffic. Some of the transport means allow improving the sustainability of both aerial and ground-based transportation modes, like vertical takeoff and landing aircraft (VTOLs) [56] commonly known as flying cars [57,58]. It is proven in [59,60] that flying vehicles, such as Personal Aerial Vehicles (PAV), and Passengers Unmanned Aerial Vehicles (PUAV) are becoming operational in several countries.

Besides the inventions in different transport modes, the communities are very often seeking to improve the sustainability of their transportation systems [61] by shifting routine automobile travel to walking and bicycling basing on the Theory of Routine Mode Choice Decisions. According to [62,63], the modal shift could be promoted through each of the five steps: awareness and availability (e.g., offer individual marketing programs), basic safety and security (e.g., make pedestrian and bicycle facility improvements and increase education and enforcement efforts), convenience and cost (e.g., institute higher-density, mixed land uses, and limited, more expensive automobile parking), enjoyment (e.g., plant street trees and increase awareness of non-motorized transportation benefits), and habit (e.g., target information about sustainable transportation options to people making key life changes) [64].

The possibility of using so many different organizational and technological options becomes a decision problem for passengers in terms of its choice, as well as for urban mobility organizers in terms of policy and investment plans. According to [65], a decision problem is a complex task or issue that needs to be solved and arises when the subject making the decision (the decision-maker) is looking for the most desired action among the many acceptable ones. Therefore, the decision problem is understood as the problem of selecting the appropriate variant of assessing individual variants from various criteria [66–68]. Often, the most appropriate way of mapping a decision situation and its solution is to build a mathematical model that enables the search, using mathematical methods, to find the best solution for a given problem due to the selected criterion, taking into account certain limitations [69]. The limitations and criteria can be grouped into relevant research areas reflecting the environmental surrounding of the problem: e.g., social, technological, technical, economic, ecological, political, legal, ethical, and demographic issues.

The criteria which are considered by citizen are difficult to predict and is strictly connected with the theory of travel decision-making. Generally, an attitude is defined as a psychological construct, composed of affective, cognitive, and behavioral components, which may be used to describe human evaluative responses [70,71]. The theory of travel decision making is widely described in the literature is related to issues of:

- human activity, meaning, that the travel demand is derived from a demand for activities [71,72], connected with the hierarchy of walking needs [73] and the theory of routine mode choice decisions [62].
- the hierarchy of travel needs [74], which defines characteristics of those needs, motivations, or intentions and attributes of alternatives that are of importance during travel decision-making, usually divided into five groups: feasibility [75,76], accessibility [77], safety and security [78], cost [79], and pleasure [80].
- sociodemographic, socioeconomics [81], influencing the process due to poverty, elder citizens
- weather [82], social media trends [83], availability of travel planning applications [84,85] based on ITS (Intelligent Transportation System) [86] and other.

Due to the number of influencing variables on the travel decision-making, the choice of a method of traveling in cities is a multi-criteria decision problem. According to [87,88], a multi-criteria decision problem may involve:

- the problem of choice (optimization): the decision-maker determines a subset of decisions (action, options) considered the best ones in terms of the considered family of criteria,
- the problem of classification (sorting): the decision-maker splits a set of decisions (activities, and action variants) into subsets (classes, categories), under the accepted standards,
- the problem of ranking: the decision-maker aims to put the variants in order from the best to the worst one.

Often the multi-criteria decision process is very time-consuming. The final choice, however, is an individual matter and depends on the needs and previous experiences of passengers. Besides this, identifying these needs when building a model may, in turn, allow decision-makers managing transport systems to adjust the collective transport offer or to allow organizers of short-term rental of means of transport in the sharing system.

The issue of choosing a means of transport for travel has been the subject of many studies and scientific articles for many years. These can include monograph [89] or articles mentioned above. However, research work has so far focused on identifying factors influencing the choice of means of transport [70–86] or modeling choice of means of transport [87,88]. They mainly concerned individual transport vehicles and public transport vehicles. The vast minority of the work applies to vehicles of category “sharing mobility,” and the issue of multi-criteria decision support when choosing the means of transport sharing mobility in a systemic perspective, taking into account four groups of factors: environmental, financial, safety and quality, constitutes a research gap.

Proper activities of shaping transport systems in the emerging metropolitan areas based on verified models are of significant importance for the life of the inhabitants.

3. Materials and Methods

The research was conducted in four stages.

Stage I was the initial stage focused on the literature and documents (legal acts, strategies, and program reviews). As a result, the assumptions and objectives of sharing mobility in metropolitan transport systems were developed. Also, the basis of multi-criteria decision-making methods and the main research aspects for the characteristics and criteria of the model were defined.

Stage II was focused on the decision model of metropolitan transport means selection building. In this stage, the necessary decision variables of metropolitan transport means were defined. Then, data (parameters) determined by research areas were defined in sets of criteria, weight rates, and characteristics. Finally, limiting conditions and the functions, as well as criterion function, was defined.

Stage III of the research was concentrated on model verification. The model was implemented in Silesian Metropolis in Poland and the survey was made among residents with particular emphasis on sharing mobility transport means users.

Finally, stage IV covered the estimation of survey results mainly connected with the ranking of metropolitan-transport-means-based sharing mobility obtained. Further conclusions related to usability and universality of the metropolitan transport means selection model was made.

The diagram showing the implementation of particular stages of the research is illustrated in Figure 1.

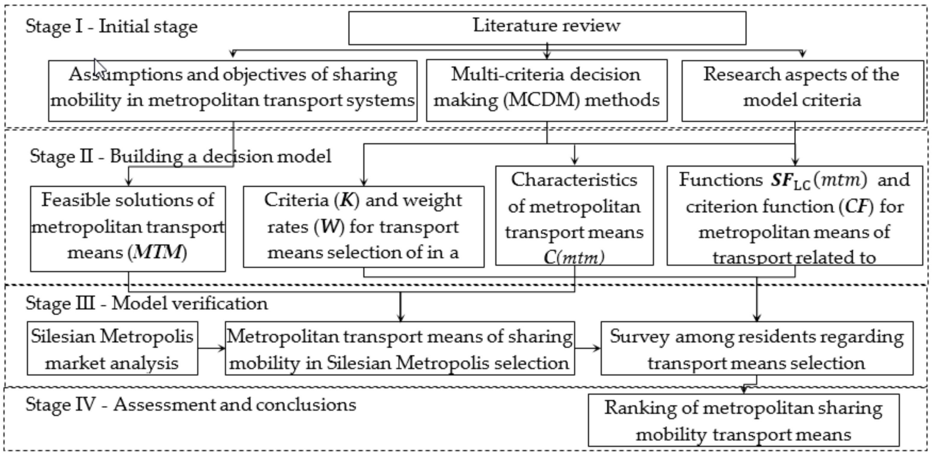


Figure 1. Research stages.

Model verification was made among residents of Silesian Metropolis and special attention was paid to these transport means, which are based on the idea of shared transport and include services such as car-sharing, bike-sharing, and scooter-sharing. The research was carried out over 5 weeks. Over 3000 people took part in the study, mainly from Katowice city (with 294,510 residents at the end of 2018 [90]), the biggest city of Silesian Agglomeration, where sharing mobility is most common.

The following criteria were adopted to support decision-making in shaping sharing mobility in metropolitan areas: transport safety, qualitative, financial, and ecological. The main factor influencing the inclusion of these aspects was their overall importance in any decision-making process. Costs are a criterion that determines the possibility of implementing a specific solution. In turn, security is very important for many stakeholder groups. Designers cannot develop solutions that contribute to the deterioration of the level of safety, because they are responsible for them. Policymakers, on the other hand, treat safety as a goal to improve the quality of life (especially in metropolitan areas), similarly to a society for which the level of security is a direct determinant of the choice of a given means of transport in the implementation of travel in specific relationships. The quality is also of similar importance, which according to numerous studies is an important transport demand [12,13,91]. On the other hand, environmental conditions are, in turn, essential in almost every aspect of human life.

The choice of a multi-criteria analysis method is important and may constitute a separate research problem. However, this is not the main goal of the article, so the authors used the multi-criteria decision-making method called MAJA recommended in the paper [92] as the basis for the development of the model due to the possibility of taking into account a holistic approach to the design of transport systems. The MAJA method assumes the use of detailed assessments of project task variants, taking into account the coefficients of relative importance of the assessment. Moreover, an important argument in favor of choosing this method for the research goal is the possibility of developing a ranking list, showing the preferred order of target solutions, taking into account the hierarchy of goals.

4. Model of Metropolitan Transport Means Selection

The mathematical model as a tool supporting the decision-making process should take into account such elements as data (parameters), decision variables, determined by systems of limitations and the value of the objective function, limiting conditions (a set of acceptable solutions), and the objective function.

Considering the elements defined above, it is possible to build a mathematical model for metropolitan transport means selection $\boldsymbol{MTSM}(mtm)$.

A set of available metropolitan transport means $\boldsymbol{MTM}$ can be defined as follows:

$$\boldsymbol{MTM} = \left\{1, \ldots,\ mtm,\ \ldots,\ \overline{MTM}\right\} \tag{1}$$

Due to the large differences between the means of transport, a set of characteristics $\boldsymbol{C}(mtm)$ for the available metropolitan transport means $mtm \in \boldsymbol{MTM}$ is also set, which can be defined as:

$$\boldsymbol{C}(mtm) = \left\{\mathbf{C}_{\mathrm{TS}}(mtm), \mathbf{C}_{\mathrm{Q}}(mtm), \mathbf{C}_{\mathrm{F}}(mtm), \mathbf{C}_{\mathrm{E}}(mtm)\right\},\ mtm \in \boldsymbol{MTM}, \tag{2}$$

where:

$\mathbf{C}_{\mathrm{TS}}(mtm)$ —a set of characteristics related to transport safety aspects describing features for available metropolitan transport modes $mtm \in \boldsymbol{MTM}$, defined as:

$$\mathbf{C}_{\mathrm{TS}}(mtm) = \left[c_{\mathrm{TS}}^{ka}(mtm): \quad ka = 1, \ldots, \overline{C_{\mathrm{TS}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{C}_{\mathrm{Q}}(mtm)$ —a set of characteristics related to quality aspects describing features for available metropolitan transport modes $mtm \in \boldsymbol{MTM}$, defined as:

$$\mathbf{C}_{\mathrm{Q}}(mtm) = \left[c_{\mathrm{Q}}^{kb}(mtm): \quad kb = 1, \ldots, \overline{C_{\mathrm{Q}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{C}_{\mathrm{F}}(mtm)$ —a set of characteristics related to financial aspects describing features for available metropolitan transport modes $mtm \in \boldsymbol{MTM}$, defined as:

$$\mathbf{C}_{\mathrm{F}}(mtm) = \left[c_{\mathrm{F}}^{kc}(mtm): \quad kc = 1, \ldots, \overline{C_{\mathrm{F}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{C}_{\mathrm{E}}(mtm)$ —a set of characteristics related to ecological aspects describing features for available metropolitan transport modes $mtm \in \boldsymbol{MTM}$, defined as:

$$\mathbf{C}_{\mathrm{E}}(mtm) = \left[c_{\mathrm{E}}^{kd}(mtm): \quad kd = 1, \ldots, \overline{C_{\mathrm{E}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM}.$$

A list of examples of characteristics describing the features of available metropolitan transport means divided into individual decision-making aspects is presented in Table 1.

Table 1. Characteristics describing the features of available metropolitan transport means.

Research Area	Characteristics
transport safety $\mathbf{C}_{\mathrm{TS}}(mtm)$	$c_{\mathrm{TS}}^{1}(mtm)$—number of road accidents involving means of transport $c_{\mathrm{TS}}^{2}(mtm)$—number of fatalities involving means of transport $c_{\mathrm{TS}}^{3}(mtm)$—number of people injured involving means of transport $c_{\mathrm{TS}}^{4}(mtm)$—number of damaged means of transport
quality $\mathbf{C}_{\mathrm{Q}}(mtm)$	$c_{\mathrm{Q}}^{1}(mtm)$—number of available means of transport $c_{\mathrm{Q}}^{2}(mtm)$—average waiting time for means of transport $c_{\mathrm{Q}}^{3}(mtm)$—comfort level of transport use
financial $\mathbf{C}_{\mathrm{F}}(mtm)$	$c_{\mathrm{F}}^{1}(mtm)$—value of the transport means operating costs $c_{\mathrm{F}}^{2}(mtm)$—value of the transport means infrastructure costs $c_{\mathrm{F}}^{3}(mtm)$—value of transport costs per 1 km
ecological $\mathbf{C}_{\mathrm{E}}(mtm)$	$c_{\mathrm{E}}^{1}(mtm)$—average travel speed of a given means of transport $c_{\mathrm{E}}^{2}(mtm)$—CO_2 emissions from means of transport $c_{\mathrm{E}}^{3}(mtm)$—ratio of alternative fuels supplying means of transport

Besides these, a set of criteria $\boldsymbol{K}$ for selecting means of transport in the metropolitan area is defined as follows:

$$\boldsymbol{K} = \left\{\mathbf{K}_{\mathrm{TS}},\ \mathbf{K}_{\mathrm{Q}},\ \mathbf{K}_{\mathrm{F}},\ \mathbf{K}_{\mathrm{E}}\right\}, \tag{3}$$

where:

$\mathbf{K}_{\mathrm{TS}}$ —criteria vector for metropolitan transport means selection, depending on transport safety aspects, in the following form: $\mathbf{K}_{\mathrm{TS}} = \left[k_{\mathrm{T}}^{ma}: \quad ma = 1, \ldots, \overline{K_{\mathrm{TS}}}\right]$,

$\mathbf{K}_{\mathrm{Q}}$ —criteria vector for metropolitan transport means selection, depending on quality aspects, in the following form: $\mathbf{K}_{\mathrm{Q}} = \left[k_{\mathrm{Q}}^{mb}: \quad mb = 1, \ldots, \overline{K_{\mathrm{Q}}}\right]$,

$\mathbf{K}_{\mathrm{F}}$ —criteria vector for metropolitan transport means selection, depending on financial aspects, in the following form: $\mathbf{K}_{\mathrm{F}} = \left[k_{\mathrm{F}}^{mc}: \quad mc = 1, \ldots, \overline{K_{\mathrm{F}}}\right]$,

$\mathbf{K}_{\mathrm{E}}$ —criteria vector for metropolitan transport means selection, depending on ecological aspects, in the following form: $\mathbf{K}_{\mathrm{E}} = \left[k_{\mathrm{E}}^{md}: \quad md = 1, \ldots, \overline{K_{\mathrm{E}}}\right]$.

A list of examples of criteria for selecting a transport means in the metropolis area, which should take into account the needs of all groups of stakeholders, divided into individual decision-making aspects, is presented in Table 2. It is worth emphasizing that the list should be freely modified to adapt it to a specific decision problem.

Table 2. Criteria of metropolitan transport mean selection.

Research Area	Characteristics
transport safety $\mathbf{K}_{\mathrm{TS}}$	k_{TS}^{1}—safety level of driving a given means of transport
quality $\mathbf{K}_{\mathrm{Q}}$	k_{Q}^{1}—level of quality of transport services k_{Q}^{2}—the comfort of using a given means of transport
financial $\mathbf{K}_{\mathrm{F}}$	k_{F}^{1}—costs of operating and maintaining transport infrastructure k_{F}^{2}—traveling costs
ecological $\mathbf{K}_{\mathrm{E}}$	k_{E}^{1}—environmental pollution resulting from the use of transport means k_{E}^{2}—utilization of alternative fuels to power transport means

Many criteria can be defined in individual research areas, and it is worth emphasizing that when determining their measurements later, their quantitative and qualitative nature should be taken into account.

For the above-mentioned set of criteria, the rating weight set $\boldsymbol{W}$, which allows differentiation of the importance of given criteria in the decision-making process, is described as follows:

$$\boldsymbol{W} = \left\{\mathbf{W}_{\mathrm{K,TS}}, \mathbf{W}_{\mathrm{K,Q}}, \mathbf{W}_{\mathrm{K,F}}, \mathbf{W}_{\mathrm{K,E}}\right\}, \tag{4}$$

where:

$\mathbf{W}_{\mathrm{K,TS}}$ —criteria rating weight vector for metropolitan transport means selection, depending on transport safety aspects, in the following form: $\mathbf{W}_{\mathrm{K,TS}} = \left[w_{\mathrm{K,TS}}\left(k_{\mathrm{TS}}^{ma}\right): \quad k_{\mathrm{TS}}^{ma} \in \boldsymbol{K}_{\mathrm{TS}}\right]$,

$\mathbf{W}_{\mathrm{K,Q}}$ —criteria rating weight vector for metropolitan transport means selection, depending on quality aspects, in the following form: $\mathbf{W}_{\mathrm{K,Q}} = \left[w_{\mathrm{K,Q}}\left(k_{\mathrm{Q}}^{mb}\right): \quad k_{\mathrm{Q}}^{mb} \in \boldsymbol{K}_{\mathrm{Q}}\right]$,

$\mathbf{W}_{\mathrm{K,F}}$ —criteria rating weight vector for metropolitan transport means selection, depending on financial aspects, in the following form: $\mathbf{W}_{\mathrm{K,F}} = \left[w_{\mathrm{K,F}}\left(k_{\mathrm{F}}^{mc}\right): \quad k_{\mathrm{F}}^{mc} \in \boldsymbol{K}_{\mathrm{F}}\right]$,

$\mathbf{W}_{\mathrm{K,E}}$ —criteria rating weight vector for metropolitan transport means selection, depending on ecological aspects, in the following form: $\mathbf{W}_{\mathrm{K,E}} = \left[w_{\mathrm{K,E}}\left(k_{\mathrm{E}}^{md}\right): \quad k_{\mathrm{E}}^{md} \in \boldsymbol{K}_{\mathrm{E}}\right]$.

Next, a set of functions $\boldsymbol{SF}_{\mathrm{LC}}(mtm)$ for the available metropolitan transport means $mtm \in \boldsymbol{MTM}$ related to limitations and conditions, affecting decisions, were defined as follows:

$$\boldsymbol{SF}_{\mathrm{LC}}(mtm) = \left\{\mathbf{F}_{\mathrm{LC,\,TS}}(mtm),\ \mathbf{F}_{\mathrm{LC,QJ}}(mtm), \mathbf{F}_{\mathrm{LC,\,F}}(mtm), \mathbf{F}_{\mathrm{LC,\,E}}(mtm)\right\}, \quad (5)$$

where:

$\mathbf{F}_{\mathrm{LC,\,TS}}(mtm)$ —a vector containing the values of the function reflecting the limitations and conditions relating to transport safety aspects of the available metropolitan transport means $mtm \in \boldsymbol{MTM}$, influencing decisions about travel behavior, defined as:

$$\mathbf{F}_{\mathrm{LC,\,TS}}(mtm) = \left[f^{la}_{\mathrm{LC,TS}}(mtm) : \quad la = 1, \ldots, \overline{F_{\mathrm{LC,TS}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{F}_{\mathrm{LC,Q}}(mtm)$—a vector containing the values of the function reflecting the limitations and conditions relating to quality aspects of the available metropolitan transport means $mtm \in \boldsymbol{MTM}$, influencing decisions about travel behavior, defined as:

$$\mathbf{F}_{\mathrm{LC,Q}}(mtm) = \left[f^{lb}_{\mathrm{LC,Q}}(mtm) : \quad lb = 1, \ldots, \overline{F_{\mathrm{LC,Q}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{F}_{\mathrm{LC,\,F}}(mtm)$—a vector containing the values of the function reflecting the limitations and conditions relating to financial aspects of the available metropolitan transport means $mtm \in \boldsymbol{MTM}$, influencing decisions about travel behavior, defined as:

$$\mathbf{F}_{\mathrm{LC,\,F}}(mtm) = \left[f^{lc}_{\mathrm{LC,F}}(mtm) : \quad lc = 1, \ldots, \overline{F_{\mathrm{LC,F}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM},$$

$\mathbf{F}_{\mathrm{LC,\,E}}(mtm)$—a vector containing the values of the function reflecting the limitations and conditions relating to ecological aspects of the available metropolitan transport means $mtm \in \boldsymbol{MTM}$, influencing decisions about travel behavior, defined as:

$$\mathbf{F}_{\mathrm{LC,\,E}}(mtm) = \left[f^{ld}_{\mathrm{LC,E}}(mtm) : \quad ld = 1, \ldots, \overline{F_{\mathrm{LC,E}}(mtm)}\right], \quad mtm \in \boldsymbol{MTM}.$$

A list of examples of functions reflecting the limitations and conditions for the selection of available metropolitan transport means by individual decision-making aspects is presented in Table 3.

Table 3. Functions reflecting the limitations and conditions of metropolitan transport means selection.

Research Area	Functions
transport safety $\mathbf{F}_{\mathrm{LC,\,TS}}(mtm)$	$f^1_{\mathrm{LC,TS}}(mtm)$—minimum level of transport safety
quality $\mathbf{F}_{\mathrm{LC,\,Q}}(mtm)$	$f^1_{\mathrm{LC,Q}}(mtm)$—maximum number of available means of transport $f^2_{\mathrm{LC,Q}}(mtm)$—maximum waiting time for the means of transport $f^3_{\mathrm{LC,Q}}(mtm)$—an adequate level of quality to price of means of transport
financial $\mathbf{F}_{\mathrm{LC,\,F}}(mtm)$	$f^1_{\mathrm{LC,F}}(mtm)$—maximum level of operating costs for means of transport $f^2_{\mathrm{LC,F}}(mtm)$—maximum level of maintaining the infrastructure costs of means of transport $f^3_{\mathrm{LC,F}}(mtm)$—maximum level of traveling costs
ecological $\mathbf{F}_{\mathrm{LC,\,E}}(mtm)$	$f^1_{\mathrm{LC,E}}(mtm)$—maximum CO_2 emissions from means of transport $f^2_{\mathrm{LC,E}}(mtm)$—minimal share of alternative fuels supplying means of transport

For the data described in this way, it is necessary to determine in the mathematical model for metropolitan transport means selection $\boldsymbol{MTSM}(mtm)$ the binary value of decision variable X, which is a potential optimal solution for the selection of the metropolitan means of transport under appropriate limiting conditions, taking the form:

$$X = [x(mtm) : \quad x(mtm) \in \{0,1\}], \quad mtm \in \boldsymbol{MTM}. \tag{6}$$

For transport safety decision-making aspects, examples of restrictive conditions are:

- number of road accidents involving means of transport is less than or equal to the minimum level of transport safety for the variable $x(mtm)$:

$$f^{1}_{\mathrm{LC,TS}}(mtm) \cdot x(mtm) \geq c^{1}_{\mathrm{TS}}(mtm), \quad mtm \in \boldsymbol{MTM}, \tag{7}$$

- number of damaged means of transport is less than or equal to the minimum level of transport safety for the variable $x(mtm)$:

$$f^{1}_{\mathrm{LC,TS}}(mtm) \cdot x(mtm) \geq c^{4}_{\mathrm{TS}}(mtm), \quad mtm \in \boldsymbol{MTM}. \tag{8}$$

For quality decision-making aspects, examples of restrictive conditions are:

- number of available means of transport is less than or equal to the maximum number of available means of transport for the variable $x(mtm)$:

$$f^{1}_{\mathrm{LC,Q}}(mtm) \cdot x(mtm) \geq c^{1}_{\mathrm{Q}}(mtm), \quad mtm \in \boldsymbol{MTM}, \tag{9}$$

- average waiting time for means of transport is less than or equal to the maximum waiting time for the means of transport for the variable $x(mtm)$:

$$f^{2}_{\mathrm{LC,Q}}(mtm) \cdot x(mtm) \geq c^{2}_{\mathrm{Q}}(mtm), \quad mtm \in \boldsymbol{MTM}, \tag{10}$$

- the comfort level of transport use is greater than or equal to the adequate level of quality to price of means of transport for the variable $x(mtm)$:

$$f^{3}_{\mathrm{LC,Q}}(mtm) \cdot x(mtm) \leq c^{3}_{\mathrm{Q}}(mtm), \quad mtm \in \boldsymbol{MTM}. \tag{11}$$

For financial decision-making aspects, examples of restrictive conditions are:

- value of the transport means operating costs is less than or equal to the maximum level of operating costs for means of transport for the variable $x(mtm)$:

$$f^{1}_{\mathrm{LC,F}}(mtm) \cdot x(mtm) \geq c^{1}_{\mathrm{F}}(mtm), \quad mtm \in \boldsymbol{MTM}, \tag{12}$$

- value of transport costs per 1 km is less than or equal to the maximum level of traveling costs for the variable $x(mtm)$:

$$f^{3}_{\mathrm{LC,F}}(mtm) \cdot x(mtm) \geq c^{3}_{\mathrm{F}}(mtm), \quad mtm \in \boldsymbol{MTM}. \tag{13}$$

For transport safety decision-making aspects, examples of restrictive conditions are:

- CO_2 emissions from means of transport are less than or equal to the maximum CO_2 emissions from means of transport for the variable $x(mtm)$:

$$f^{1}_{\mathrm{LC,E}}(mtm) \cdot x(mtm) \geq c^{2}_{\mathrm{E}}(mtm), \quad mtm \in \boldsymbol{MTM}, \tag{14}$$

- the ratio of alternative fuels supplying means of transport is greater than or equal to the minimal share of alternative fuels supplying means of transport for the variable $x(mtm)$:

$$f^2_{\mathrm{LC,E}}(mtm)\cdot x(mtm) \leq c^3_{\mathrm{E}}(mtm), \qquad mtm \in \boldsymbol{MTM}. \tag{15}$$

Also, the mathematical model for metropolitan transport means selection $\boldsymbol{MTSM}(mtm)$ should take into account the restrictive conditions imposed on the rating weights of the criterion:

$$\sum_{k^{ma}_{\mathrm{TS}} \in K_{\mathrm{TS}}} w_{\mathrm{K,TS}}\left(k^{ma}_{\mathrm{TS}}\right) + \sum_{k^{mb}_{\mathrm{Q}} \in K_{\mathrm{Q}}} w_{\mathrm{K,Q}}\left(k^{mb}_{\mathrm{Q}}\right) + \sum_{k^{mc}_{\mathrm{F}} \in K_{\mathrm{F}}} w_{\mathrm{K,F}}\left(k^{mc}_{\mathrm{F}}\right) + \sum_{k^{md}_{\mathrm{E}} \in K_{\mathrm{E}}} w_{\mathrm{K,E}}\left(k^{md}_{\mathrm{E}}\right) = 1 \tag{16}$$

For the above data, under the limiting conditions listed above, the value of decision variable X should be determined in a mathematical model for metropolitan transport means selection $\boldsymbol{MTSM}(mtm)$ in such a way that the values of the measures of the individual criteria function are optimal:

$$\boldsymbol{CF} = \langle \mathbf{M}_{\mathrm{TS}},\ \mathbf{M}_{\mathrm{Q}},\ \mathbf{M}_{\mathrm{F}},\ \mathbf{M}_{\mathrm{E}} \rangle \tag{17}$$

where:

$\mathbf{M}_{\mathrm{TS}}$ —the matrix containing the measurement values of the criteria for selecting metropolitan transport means, depending on transport safety aspects, defined as:

$$\mathbf{M}_{\mathrm{TS}} = \left[m^{na}_{\mathrm{TS}}\left(k^{ma}_{\mathrm{TS}}, mtm\right) : \quad na = 1, \ldots, \overline{M_{\mathrm{TS}}\left(k^{ma}_{\mathrm{TS}}\right),} \quad k^{ma}_{\mathrm{TS}} \in \boldsymbol{K}_{\mathrm{TS}},\ mtm \in \boldsymbol{MTM} \right],$$

$\mathbf{M}_{\mathrm{Q}}$ —the matrix containing the measurement values of the criteria for selecting metropolitan transport means, depending on quality aspects, defined as:

$$\mathbf{M}_{\mathrm{Q}} = \left[m^{nb}_{\mathrm{Q}}\left(k^{mb}_{\mathrm{Q}}, mtm\right) : \quad nb = 1, \ldots, \overline{M_{\mathrm{Q}}\left(k^{mb}_{\mathrm{Q}}\right), \quad k^{mb}_{\mathrm{Q}} \in \boldsymbol{K}_{\mathrm{Q}},\ mtm \in \boldsymbol{MTM}} \right]$$

$\mathbf{M}_{\mathrm{F}}$ —the matrix containing the measurement values of the criteria for selecting metropolitan transport means, depending on financial aspects, defined as:

$$\mathbf{M}_{\mathrm{F}} = \left[m^{nc}_{\mathrm{F}}\left(k^{mc}_{\mathrm{F}}, mtm\right) : \quad nc = 1, \ldots, \overline{M_{\mathrm{F}}\left(k^{mc}_{\mathrm{F}}\right), \quad k^{mc}_{\mathrm{F}} \in \boldsymbol{K}_{\mathrm{F}},\ mtm \in \boldsymbol{MTM}} \right]$$

$\mathbf{M}_{\mathrm{E}}$ —the matrix containing the measurement values of the criteria for selecting metropolitan transport means, depending on ecological aspects, defined as:

$$\mathbf{M}_{\mathrm{E}} = \left[m^{nd}_{\mathrm{E}}\left(k^{md}_{\mathrm{E}}, mtm\right) : \quad nd = 1, \ldots, \overline{M_{\mathrm{E}}\left(k^{md}_{\mathrm{E}}\right), \quad k^{md}_{\mathrm{E}} \in \boldsymbol{K}_{\mathrm{E}},\ mtm \in \boldsymbol{MTM}} \right].$$

The versatility of the presented model needs to be emphasized. It can be characterized by any features that reflect the conditions and restrictions, along with measures and the criteria and characteristics in such a way that it allows to reflect the specific nature of decisions in the transport field of the metropolitan area examined.

5. Transport Means Selection among Transport-Sharing Services in Silesian Metropolis

The model was verified on an example of Silesian Metropolis which is a region of Upper Silesia Agglomeration in Poland, inhabited by approximately 2.5 million people. About 69% of inhabitants live and concentrate their main economic activity and urban functions here. Analysis of shared transport services providers showed the widest activity in the largest city of Katowice. In Poland, transport services based on sharing mobility ideas are provided by a total of 21 companies, among which we can distinguish such companies as Nextbike, BikeU, Arcus Romet, Blinkee.city, Tauron, Hive, Lime, One Ślad, Trafficar, Greengoo, 4mobility, Vozilla, Bird, Hop.City, LOGO Sharing, Panek Carsharing, Omni, and others.

In a metropolis, shared journeys can be planned in many different ways. An integrated bicycle rental system operates at Silesian Metropolis. Bike-sharing is offered by City By Bike (Katowice), Kajteroz (Chorzow), and city bike systems in Gliwice, Tychy, Sosnowiec, Siemianowice Slaskie, and Zabrze cooperating. For now, about 900 bikes are available and a bike rented in one city can be easily returned to another. The metropolis is working on creating the Metropolitan Bicycle, which will be the largest electric bike rental shop in Europe. This system will create up to 10,000 electric two-wheelers. Larger distances can be covered on a scooter or kickscooter. Scooter-sharing is organized by Hop.City and blinkee.city; carsharing also operates in the cities of the metropolis. Various types of cars, both passenger (Traficar) and CityBee vans can be rented. In turn, Tauron and GreenGoo offer an electric car rental service. Short-term rental in the sharing system is convenient for the user. The settlement of the journey is instant, and above all clear to the user.

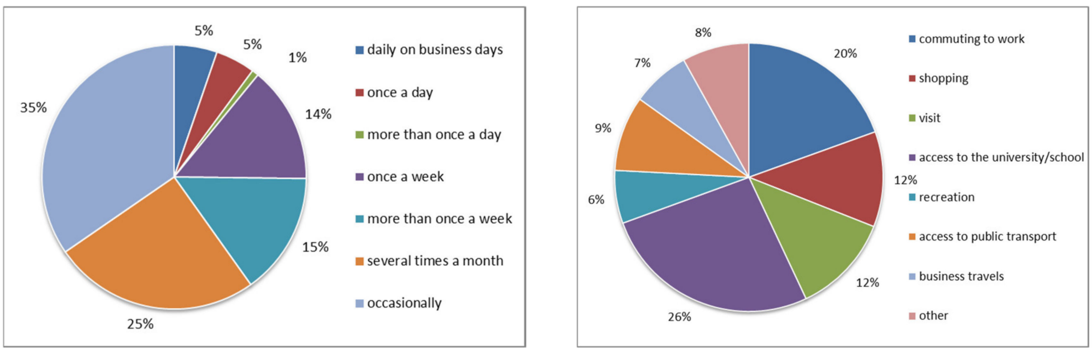
The questionnaire was provided to verify the impact of the sharing means of transport on the decisions of urban residents regarding their transport behavior [93]. The whole questionnaire consisted of six sections of questions related to the frequency of using individual means of transport, possession of means of transport, aspects, and factors of individual means of transport that could influence the decision to use a given one. Over 3000 people took part in the study. The respondents were dominated by people in the 15–25 age group (58%), mainly students and high school students, while the least interviewees were in the 46–55-year range (1%).

According to the model of metropolitan transport means selection, the input data for metropolitan transport means $mtm \in \boldsymbol{MTM}$ was determined and the needs related to the size and frequency and range of their use among the surveyed persons were verified (see Figures 2 and 3).

Among residents, up to 44% of people own a car, while 48% have a bicycle. The majority of respondents who own a bike (253) use the bike sporadically, e.g., for recreational purposes or in an emergency. Among the respondents, 89 people use the bike every day on business days, 82 people use the bike once a day, and only 14 people use the bike more than once a day. This may be due to leading a healthy lifestyle, and commuting to work, college, or school, during the week and on weekends.

The transport motivations of the respondents are usually connected with commuting to school or university. Other motivations were connected with shopping (12%), visits (12%), recreation (6%), travel to other means of transport (12%), or business travels (7%).

Usually, 791 people travel from 0 to 5 km in one day; this is due to the lack of a car, and the need to travel to work, school, or college. Similar transport trends were shown by people traveling from 5–10 km (645), 10–20 km (510), and 20–30 km (465). Only 600 people surveyed cover a distance greater than 30 km, which makes the possibility of using sharing-transport services even more attractive.



(**a**) (**b**)

Figure 2. Frequency (**a**) and reason (**b**) of using metropolitan transport means in Silesian Metropolis.

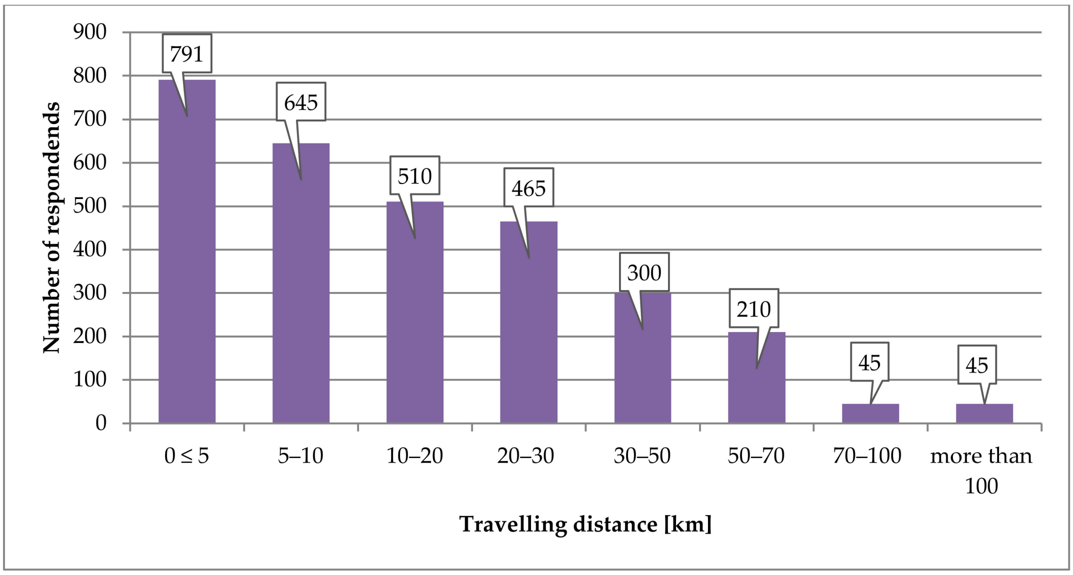


Figure 3. Trip distance in Silesian Metropolis.

On this basis, the values of functions for available metropolitan means of transport related to limitations and conditions in research aspects of transport safety, quality, financial, and ecological were defined: $\mathbf{F}_{\text{LC, TS}}(mtm)$, $\mathbf{F}_{\text{LC, Q}}(mtm)$, $\mathbf{F}_{\text{LC, F}}(mtm)$, $\mathbf{F}_{\text{LC, E}}(mtm)$ for $mtm \in \boldsymbol{MTM}$. Set of functions $SF_{\text{LC}}(mtm)$ for the available metropolitan transport means $mtm \in \boldsymbol{MTM}$ were compared with the values of elements in the set of characteristics $\boldsymbol{C}(mtm)$ for $mtm \in \boldsymbol{MTM}$, taking into account limitations and conditions: $\mathbf{C}_{\text{TS}}(mtm)$, $\mathbf{C}_{\text{Q}}(mtm)$, $\mathbf{C}_{\text{F}}(mtm)$, $\mathbf{C}_{\text{E}}(mtm)$. This allowed to determine the following set of acceptable solutions of metropolitan sharing transport means for $mtm \in \boldsymbol{MTM}$:

- $mtm = 1$—city bike,
- $mtm = 2$—electric kick scooter,
- $mtm = 3$—electric scooter,
- $mtm = 4$—electric car.

Basing on survey results, 1241 people did not use individual means of transport, but some of them expressed their willingness to use such. City bikes are the most popular, as surveyed people rented a bike at least once. Cars and electric scooters are the least popular, as only 535 people have rented a scooter at least once, and an electric car only 315. This may be due to higher costs. The largest number of people most often uses city bikes (889) compared to other alternative means of individual transport, and the smallest number, electric cars (181). This result may be due to greater availability and lower costs of use, relative to other means of transport. Renting a bike does not require a driving license and has a positive effect on the health or condition of users.

Basing on the survey results, the measures of the criteria that were relevant for the metropolitan population when deciding on the choice of means of transport were determined. Respondents could indicate no more than three factors that they consider when choosing a means of communication. The results are illustrated in Figure 4.

According to respondents, the most important factors affecting the choice of means of transport are travel time, cost of travel, and the availability of means of transport.

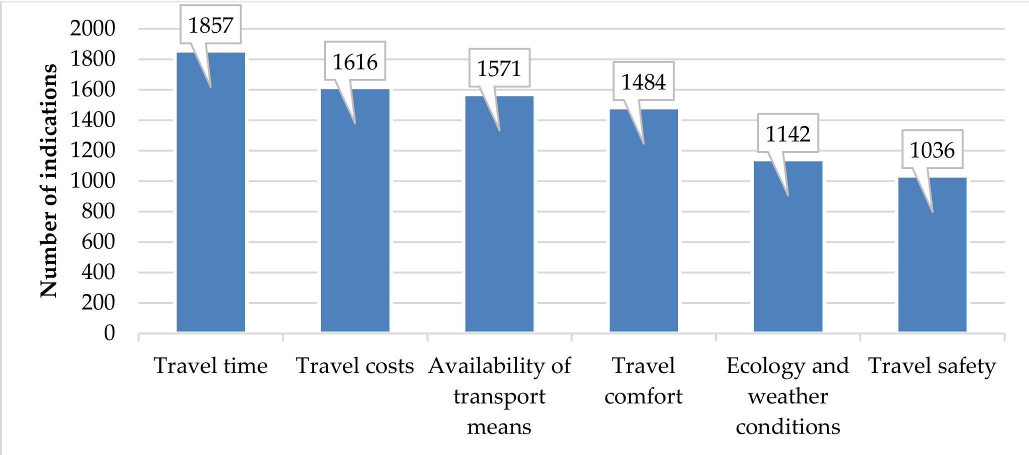


Figure 4. The number of indications for criteria for choosing particular metropolitan transport means.

The resident additionally pointed out modifications that would increase the popularity of given means of transport, and factors that could influence the decisions of choice. The following factors have been distinguished:

- lower prices of the service,
- promotions for regular customers and students,
- scooter availability in a larger area,
- a larger area of operating range for scooters and electric scooters,
- more electric cars offered,
- a lack of necessity to connect with a bank card to a user account.

These ideas may be taken into account when planning new business opportunities in the metropolis.

Subsequently, individual criteria were assigned to the research areas of the method, and criteria measures were subordinated. Then, based on the survey indications, the rating weights of individual criteria measures were determined, which reflect the importance of individual factors when choosing a means of movement for the residents of the metropolis.

Table 4 shows the weights according to the answers given in such a way that the total weight of four groups of aspects is equal to 1.

Table 4. Criteria measures and weight rates for Silesian Metropolis transport means selection.

Research Area	Criteria	Criteria Measures	Weight Rate
transport safety $\mathbf{K}_{TS}$	k^1_{TS}—travel safety	$m^1_{TS}\left(k^1_{TS}, mtm\right)$—number of road incidents with *mtm* per 100 thousand inhabitants per year	$w_{K,TS}\left(k^1_{TS}\right) = 0.12$
quality $\mathbf{K}_{Q}$	k^1_{Q}—travel time k^2_{Q}—availability of *mtm* k^3_{Q}—travel comfort	$m^1_{Q}\left(k^1_{Q}, mtm\right)$—*mtm* driving speed [km/h] $m^2_{Q}\left(k^2_{Q}, mtm\right)$—number of vehicles per km^2 [vehicle/km^2] $m^3_{Q}\left(k^3_{Q}, mtm\right)$—comfort level of using *mtm*	$w_{K,Q}\left(k^1_{Q}\right) = 0.21$ $w_{K,Q}\left(k^2_{Q}\right) = 0.18$ $w_{K,Q}\left(k^3_{Q}\right) = 0.17$
financial $\mathbf{K}_{F}$	k^1_{F}—travel costs	$m^1_{F}\left(k^1_{F}, mtm\right)$—*mtm* cost travel [PLN/min]	$w_{K,F}\left(k^1_{F}\right) = 0.19$
Ecological $\mathbf{K}_{E}$	k^1_{E}—ecology and weather conditions	$m^1_{E}\left(k^1_{E}, mtm\right)$—*mtm* weather resistance indicator	$w_{K,E}\left(k^1_{E}\right) = 0.13$

The final step of model verification was to select and approve the best alternative from the set of allowable variants. For this purpose, for the analyzed case study, the values of measurement criteria for each metropolitan transport mean were evaluated.

Quality criteria were estimated based on the offer of service providers of sharing transport services. In the case of the subjective factor, which is the comfort level, the values of measures were again based on the results of surveys taking into account the average because the actual values do not always reflect the feelings of residents. The assessment of this parameter is shown in Figure 5.

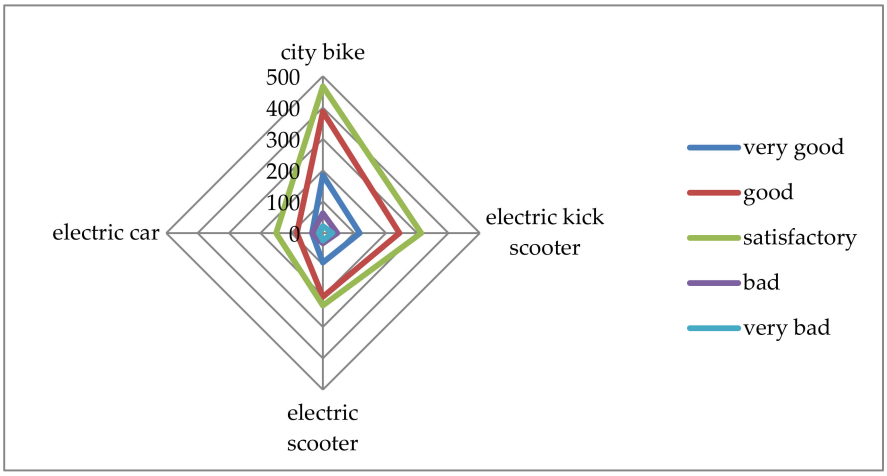


Figure 5. Evaluation of the comfort of using the analyzed means of transport based on the idea of sharing mobility by the residents of the Silesian Metropolis.

The financial factors were based on the estimation of the cost of transport by a given means of transport per minute of driving, although it should be outlined that the total costs from the user's point of view may also relate to the cost of renting and depend on the distance and time of use. In the last group of factors, it was known that all the means of transport considered were ecological, so the main measure for assessing this criterion was the weather resistance indicator developed for the needs of the model, where 100 means full protection of a given means of transport against the negative effects of bad weather and 0 indicates the impossibility of using it.

A summary of the values of criteria assessing measures for each metropolitan sharing transport means is presented in Table 5.

Table 5. Values of criteria assessing measures for Silesian Metropolis transport sharing means.

Research Area	Metropolitan Transport Means $mtm \in MTM$			
	$mtm = 1$	$mtm = 2$	$mtm = 3$	$mtm = 4$
$m^1_{TS}\left(k^1_{TS}, mtm\right)$	12.4	22.9	6.93	82.5
$m^1_{Q}\left(k^1_{Q}, mtm\right)$	15.00	25.00	35.00	50.00
$m^2_{Q}\left(k^2_{Q}, mtm\right)$	3.78	0.99	0.53	0.07
$m^3_{Q}\left(k^3_{Q}, mtm\right)$	3.58	3.50	3.53	3.29
$m^1_{F}\left(k^1_{F}, mtm\right)$	0.02	0.49	0.69	1.00
$m^1_{E}\left(k^1_{E}, mtm\right)$	20.00	40.00	40.00	100.00

Determining the most favorable transport mean, for the residents of Silesian Metropolis, is possible in the process of normalizing individual measures of criteria functions. According to [94–97], normalization involves normalizing evaluation of the options to take values in the range (0–1), wherein it is important to maintain the ratio between the values of the initial assessments (before normalization) and normalized. It is made for stimulant and destimulant. Assuming that the evaluation values after normalization are defined as $w_{d^n f_i}$, then the normalization for the d^n-th variant concerning the f_i-th function of the criterion by normalization is carried out based on the dependence of each type of diagnostic variable:

- stimulant (for the maximized f_i criterion)—the greater $x_{d^n f_i}$, the more favorable the result,

$$w_{d^n f_i} = \frac{x_{d^n f_i}}{\max\limits_{d^{n'} \in D}\left\{x_{d^{n'} f_i}\right\}} \quad (n = 1, 2 \ldots r; i = 1, 2 \ldots s)., \tag{18}$$

where: $x_{d^{n'} f_i}$ —the value of the ratings of the given considered variant d^n for each criterion f_i,

- destimulant (for the minimizes f_i criterion)—the smaller $x_{d^n f_i}$, the more favorable the result,

$$w_{d^n f_i} = \frac{\min\limits_{d^{n'} \in D}\left\{x_{d^{n'} f_i}\right\}}{x_{d^n f_i}} \quad (n = 1, 2 \ldots r; i = 1, 2 \ldots s), \tag{19}$$

where: $x_{d^{n'} f_i}$—the value of the ratings of the given considered variant d^n for each criterion f_i.

Depending on whether the given measure of criteria evaluation is to be minimized or maximized, Equation (18) or (19) was taken into account. In the further part of the analysis, the weighted evaluation values for all normalized criteria measures were determined, which is presented in Table 6.

Table 6. Normalized values of criteria assessing measures for Silesian Metropolis transport means.

Research Area	Metropolitan transport means mtm∈*MTM*			
	$mtm = 1$	$mtm = 2$	$mtm = 3$	$mtm = 4$
$m^1_{TS}\left(k^1_{TS}, mtm\right)$	0.067	0.036	0.120	0.010
$m^1_{Q}\left(k^1_{Q}, mtm\right)$	0.063	0.105	0.147	0.210
$m^2_{Q}\left(k^2_{Q}, mtm\right)$	0.180	0.047	0.025	0.003
$m^3_{Q}\left(k^3_{Q}, mtm\right)$	0.170	0.166	0.168	0.156
$m^1_{F}\left(k^1_{F}, mtm\right)$	0.190	0.008	0.006	0.004
$m^1_{E}\left(k^1_{E}, mtm\right)$	0.026	0.052	0.052	0.130
total	0.696	0.414	0.517	0.513

The sums of measures for assessing weighted criteria for each metropolitan transport means $mtm \in \boldsymbol{MTM}$ selected in the set of acceptable solutions and a graphic comparison is shown in Figure 6.

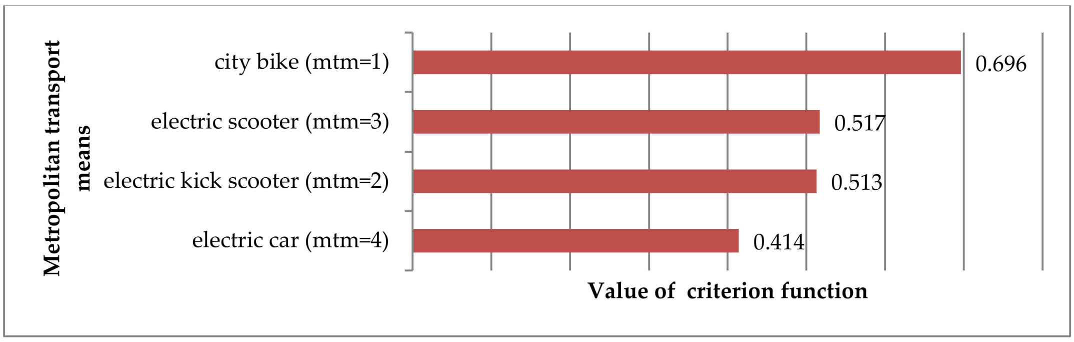


Figure 6. Ranking list of Silesian Metropolis means of transport based on the idea of sharing mobility.

The mathematical model for metropolitan transport means selection $\boldsymbol{MTSM}(mtm)$ was an appropriate tool to solve multi-criteria decision. The result is a ranking list, according to which residents of Silesian Metropolis most often choose city bike, and least often electric car because of the transport safety, quality, financial, and ecological issues.

The analysis of multi-variant decisions regarding the choice of metropolitan transport should be the basis for decisions on strategic plans. This may relate to the expansion of the publicly accessible charging infrastructure for cars, scooters, and bicycles. Over time, this can also be the creation of a network of battery pack exchange points (automats with batteries) plus the combination of all charging stations within one integrated tool.

In the short term, a subscription for transport will be created in the Metropolis to be able to take a bus, a bicycle, or rent a car based on one payment for mobility. The commuter pass should ultimately be not only a bus, tram, or train ticket, but every resident should be able to buy a subscription for all available means of transport, i.e., also for a city bike, car, or scooter used for minutes. Mobility should simply be a service that allows one to make payments for such a subscription and receive information on how to plan a daily journey through one application.

6. Conclusions

In developing metropolises, individual transport leads to serious problems related to congestion on roads and environmental pollution. Therefore, it is extremely important to strive to change people's travel behaviors towards the use of more sustainable means of transport: public transport, bicycle, walks, car, bicycle or scooter-sharing, carsharing, and carpooling. This can be achieved by sustainable urban mobility management based on the mobility demand predictions and understanding of the travel decision-making process of citizens.

The decision problem is understood as the problem of selecting the appropriate variant of assessing individual variants for various criteria. Building a mathematical model of mapping a decision situation enables finding the best solution for a given problem due to the selected criterion and certain limitations taken into account.

The research purpose of the work was achieved by building a mathematical model, as a tool supporting the multi-criteria decision-making process regarding the choice of means of transport in a developing metropolis. The main elements of the mathematical model for metropolitan transport mean selection $\boldsymbol{MTSM}(mtm)$ are:

- set of characteristics $C(mtm)$ for the available metropolitan transport means $mtm \in \boldsymbol{MTM}$,
- set of criteria $\boldsymbol{K}$ for selecting means of transport in the metropolis,
- rating weight set $\boldsymbol{W}$, which allows differentiation of the importance of given criteria in the decision-making process,
- set of functions $\boldsymbol{SF}_{\mathrm{LC}}(mtm)$ for the available metropolitan transport means $mtm \in \boldsymbol{MTM}$ related to limitations and conditions,
- criteria function $\boldsymbol{CF}$ with optimal measurement values of the criteria for selecting metropolitan transport means, depending on transport safety, quality, financial, and ecological aspects.

The model was implemented in Silesian Metropolis, Poland, with particular emphasis on sharing mobility transport means users. It allowed solving travel multi-criteria decision of the residents. City bikes are the most favorable means and electric car least according to transport safety, quality, financial, and ecological issues. The analysis of multi-variant decisions regarding the choice of metropolitan transport should be the basis for decisions on strategic plans over mobility and investments in the metropolis.

The method developed and presented in the article is used to support decision-making in the design of transport systems in metropolitan areas, the transport service of which can be carried out with the use of sharing mobility means. The tool of assigning different weights to individual criteria ensures the universality of the method. The main limitation of the method is a defined set of characteristics for individual criteria. The adoption of a larger number of these characteristics is a research field for further development of the method presented.

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