The dynamic index of urban environment quality as a tool for sustainable urban development

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Abstract. Based on the analysis of domestic and foreign experience, the authors of the article have developed and tested the methodology for constructing a dynamic index of urban environment quality (DIUEQ) of a single municipal entity in Russia. The main methodological principle of building DIUEQ is a hierarchical approach, the main method is the method of summary indicators, and the main features of the calculation methodology of the index are its simplicity, clarity and transparency. Each of the four aggregated groups of indicators includes three sub-groups of the same name−indicators of provision, indicators of sociological measurements and economic indicators. The dynamics of DIUEQ and the dynamics of its structural components reflect the nature of changes in the city indicators both in retrospect and in forecasting. The authors give an example of calculating the index according to the proposed method for the city of Kirov for 2016. Moreover, the authors show how promising it is to assess by DIUEQ the dynamics of the quality of the urban environment in general, of certain groups and subgroups of indicators for the temporal dynamics of the corresponding indices included in the DIUEQ, as well as forecasting and setting the tasks of sustainable urban development by both municipalities and public groups.

1. Introduction. Domestic and foreign experience in measuring the quality of the urban environment

The quality of urban (city) environment can be defined as "...the ability of the urban environment to meet the objective needs and demands of the city's residents in accordance with generally accepted norms and standards of living" [1]. Integral quality assessment by virtually all domestic researchers is proposed in the form of a dimensionless index that takes into account all the factors presented in each specific methodology (usually environmental, economic, socio-demographic, infrastructural) [2–5]. At the same time, groups of factors and indicators taken into account in each group, methods of calculation, methods of translating the initial values of the indicators into the index form, including methods for rating the indicators, differ significantly in different methods.

The objectives of calculating the quality index of the urban environment include, as a rule, the definition of the current state of the urban environment, the development of activities for its improvement, and monitoring processes in the sphere of urban development [6]. But one of the purposes in many methodologies is to compare the quality of the urban environment or the quality of

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life in different municipalities or regions, which implies the construction of an appropriate rating by the magnitude of the index [5, 7 and 8].

Ratings of cities or regions on the quality of the urban environment, quality of life and other aspects developed by different state structures or expert communities plays an important role in Russia and abroad. In Russia, such indices are calculated and published in Internet resources, for example, by the rating agency Expert RA [8], consulting company Strelka KB [9], etc. The declared goals when constructing the quality index of the urban environment are not always realized. This is most typical for the indices used in the construction of ratings according to the ministerial methods of the Ministry of Regional Development of the Russian Federation [10] and the Ministry of Construction of the Russian Federation [6]. The current official methodology of the Ministry of Construction [6] is based on the consulting company Strelka KB [9]. It has developed the city's quality index, which makes it possible to evaluate each city in comparison with other cities. It is clear from the text of the document [6] that calculations of most indicators require obtaining and processing of large amounts of inaccessible information from cartographic services, geoinformation systems, special Internet services, and it is practically impossible to reproduce these calculations for verification or forecasting at the level of the leadership of a municipality or research group. The city index is determined by methods [6, 9] only in comparison with other cities for each year, that is, every year it is determined on a new basis for comparison.

The influence of the urban environment on the quality of life of people and on the sustainability of urban development is also revealed by various international comparisons. The UN Research Group has developed the City Prosperity Index (CPI) [11], one of the closest to the quality index of the urban environment. The most valuable for this work is the methodical approach of constructing the CPI index [12] based on four principles. The first principle is having three levels of nesting indices: dimension, sub-dimension, and indicator. The second is when an integral index, and all indices of groups, subgroups and indicators have the same limits of change – from zero (0) to hundred (100) when 0 is the worst value of the index and 100 is the best. The third one is when all the indices of the groups for the integral index, the indices of the subgroups for the group indices, and the indices of the dimensions for the index of the subgroup are in equilibrium, that is, all higher order indices are determined as the arithmetic mean of the indices of the preceding nesting level. The fourth is when all indices of indicators are subjected to the procedure of linear normalization.

The second important method is the Urban Sustainability Index (USI), used for the cities of the PRC. It was developed by the McKinsey Global Institute (MGI), and the Urban China Initiative (UCI) research center. The latest report on this index was published using a methodology modified in 2016 [13]. This report presented a rating for 185 cities of China of different sizes and at different stages of their development in terms of their sustainability in the period from 2006 to 2014 according to 23 indicators broken down into four groups covering the areas of the economy, social sphere, resources, and environment. A special feature of the report [14] is a deep analysis of the dynamics of the index change calculated by this method over the period under consideration for different groups of cities in the PRC, including consideration of index ratios between groups, between subgroups and within groups of indicators. Calculation of USI and CPI indices is carried out on the basis of a single standardization for several years in retrospect, which makes it possible to track the dynamics of changes in the state of the city for each indicator and for each group of indicators by the magnitude of the change in the corresponding index.

The third method, widely used in the world, was developed by Mercer Human Resource Consulting. Its experts use the world's quality of life index, which takes into account 39 factors grouped into 10 categories [15]. In 2017, this index was calculated for more than 450 cities around the world and based on its results a rating of 231 cities was compiled [16]. The peculiarity of this methodology is the presence of only subjective assessments based on relative differences for each factor between any two cities that respondents estimate in pairs.

The fourth method, which has a fairly wide popularity, is the Sustainable Cities Index (SCI) from ARCADIS [14]. The SCI index in 2016 includes 100 global cities estimated by experts. The city

receives an estimate for each of the three sustainability indicators, and the overall index score is equal to their average value.

In all considered and the overwhelming majority of other foreign methods (for example, [17, 18]), all indices are calculated on the basis of a methodical approach based on the use of the second and fourth principles from the CPI index technique (see above).

2. Methodological foundations for constructing a dynamic quality index of the urban environment

Based on the analysis of domestic and foreign experience, the purpose of this studies to develop and test the methodology for constructing the quality index of the urban environment of a single municipal entity in Russia, the temporal dynamics of which (and the dynamics of its structural components) would accurately reflect the nature of the changes in the indicators of this city both in retrospect and in forecasting, which would allow municipalities and public groups to set and solve the tasks of the sustainable city development. To distinguish it from alternative construction options, the newly developed index of urban environment quality is called dynamic (DIUEQ).

Methodological principles of this work are based on the use of the hierarchical approach, described in the monograph [19] and used in [3], and the method of summary indicators described and applied to form the index of the integral estimation of the life quality of the population in two Russian megacities in [4]. The composite indicator method is used as the basis of the methodology for constructing international indices CPI, USI, SCI; the methodology based on it is presented in detail in the document [12]. Also, the base for the development included the principles formulated in [5, 20]: the relative simplicity of the methodical apparatus; use of statistical [21] and other data from public sources; reliability, balance and comparability of the results of estimates; the ability to reproduce and verify the results of other researchers.

The work of Perm researchers [3], which describes the approach to the formation of the index of urban environment quality (IUEQ), served as the basis for the formation of DIUEQ in this study. Despite the necessary complexity of the assessment according to the methodology [3], expressed in the fact that it identifies nine structural elements of the urban space (groups of indicators), it has, in our opinion, excessive subjectivity in arbitrarily set scales of indicators and groups of indicators. In addition, the methodology [3] poorly presents economic aspects of the functioning of the urban environment, including indicators of budgetary provision.

When constructing DIUEQ, it is proposed to use a significant number of indicators used in [3]. These indicators, having dimensional or relative (specific) values, determined directly or by simple calculations based on objective data obtained from public sources (statistical reporting, reports of municipalities, the Ministry of Internal Affairs, the State Traffic Safety Inspectorate, other organizations) are called further indicators of provision. While forming DIUEQ, they form a subgroup of indicators of provision in each group of indicators. In addition, each group of indicators has two more subgroups, namely, objective economic indicators and subjective indicators of sociological measurements. The selection of the last subgroup is not mandatory and is carried out with the availability of data from measurements, obtained and processed according to a certain open methodology.

The selection in the methodology of the DIUEQ formation from three similar subgroups of indicators in each group allows expanding analytical and prognostic possibilities of the methodology by comparing the indices of subgroups within each group and the indices of the same subgroups of different groups of indicators. It is especially valuable when considering the time dynamics of all indicators.

3. Methods of forming a dynamic index of urban environment quality and an example of its implementation

With reference to the purpose of this work and in accordance with the stated methodological principles and positive international experience, the number of groups of indicators is minimized in such a way

as to ensure their a priori equilibrium on the one hand and cover in aggregate all aspects of the urban environment relevant to the analysis and sustainable development, on the other hand. Therefore, the groups of indicators for which DIUEQ is formed in this study are enlarged, in comparison with the methods closest in content [3, 6].

This methodology uses four groups of urban environment quality indicators: "Safety and Ecology", "Architectural and Landscape Environment", "Social and Leisure Environment", "Engineering and Transport Infrastructure". The methodology was first applied to the formation of the DIUEQ of the municipal entity "The city of Kirov", which is the regional center of the Kirov region, the subject of the Russian Federation.

The temporal discreteness of the determination of all indicators is established in one calendar year. The calculation example gives the values of the indicators determined for 2016, but the methodology assumes that the dynamics of the indicators change both to a depth of 3-5 years in retrospect, and to continue calculations based on the results of 2017 and subsequent years.

The dynamic index of urban environment quality has four levels: a) integral DIUEQ, denoted as I_k, reflects all the low-level indicators without exception and is calculated on their basis; b) group indices of urban environment quality, calculated on the basis of the indices of the subgroups entering into each group; c) subgroup quality indices of the urban environment, calculated on the basis of the indices of all the indicators included in each subgroup; d) indices of all indicators included in the subgroup, calculated on the basis of the values of the corresponding indicators (private indices). Each indicator can be used to calculate only one particular index and be counted only in one subgroup.

The values of all the partial indices, subgroup indices, group indices and DIUEQ have the same possible limits of quantitative change, namely: the lower limit is zero (0.0), the upper limit is 1.0. The lower limit of the index corresponds to the worst value of the indicator, the upper limit to the best. These limits for private indices are established by their normalization (setting the limits of the indicator for which the numerical value of the index cannot be below zero and its limits for which the numerical value of the index cannot be higher than unity, and also the mathematical formulas for calculating the value of the index of the indicator in range of its values corresponding to the value of the index between zero and one). Such a valuation is carried out by linear mathematical transformations of the first type [4, 12] for parameters for which the value of the index equal to 1 corresponds to the highest value of the index under normalization, or by transformations of the second type [4, 12] for parameters for which the index value, equal to 1, corresponds to the lowest value of the indicator at normalization.

DIUEQ of municipal formation I_k is calculated on the basis of indices of all n groups of indicators I_i, taking into account their weight coefficients B_i, the sum of which is equal to unity, according to the formula (1):

$$I_k = \sum_{i=1}^{n}(I_i \cdot B_i) \quad (1)$$

In determining subgroup indices and group indices, the formula (2) is used, where z is the number of indicators included in a given subgroup (from 4 to 12) or in a given group (z = 3, if there are all three subgroups, or z = 2, if there is no subgroup of sociological indicators):

$$I_k = \sum_{i,j,k=1}^{z} I_{ijk} / z \quad (2)$$

When applying formula (1), the weights of the individual groups of indicators should be justified. When calculating DIUEQ, formula (1) is used with equal values of the weights of all groups. In this case, the index I_k is defined as the arithmetic average of the group indices by formula (3), analogous to formula (2):

$$I_k = \sum_{i=1}^{n} I_i / z \quad (3)$$

The method of rationing of each particular index is of particular importance. Normalization of each indicator of provision and the economic indicator is carried out once. Rationing, if possible, is performed on the basis of the natural limits of the minimum and maximum values of the indicator.

If this is not possible, either legislative norms or local government regulations are used for it. In the absence of such standards, rationing is carried out with a single use of the values of the corresponding indicators for a representative group of large and largest cities of the Russian Federation (with a population of more than 250 thousand people). Rationing of each indicator on the upper and lower limit of the index is carried out strictly individually and once; for this purpose, the absolute values of the corresponding indicators are used, and not the places of the cities of the representative group in the ranking by the indicator.

The standardization of quantitatively determined indicators of sociological measurements is also carried out by linear mathematical transformations of the first or second type [4, 12]. Respondents chose the answers mostly on a five-point or a ten-point scale. To convert the first type to the minimum value on the response scale (1 point), the index value equal to 0.0, the maximum equal to 5 or 10, the index value equal to 1.0 was put in correspondence. Intermediate scores for the index calculation were normalized by linear transformation in the range from minimum to maximum. The resulting value of the index of indicators of sociological measurements was formed as the arithmetic mean of the respondents' indices; the total number of questionnaires of a representative sample of residents of the city of Kirov was more than a thousand.

Further, Tables 1 to 4 are given as an example of methodology, the numerical values for the security indicators for Kirov in 2016 (in total 36 indicators in four groups).

Table 1. Indicators of the quality of the urban environment of Kirov in 2016 for the group "Safety and Ecology"

Number, formulation of the indicator and units of measure	Indicator value	Indicator index
1.1.1. The quantity of pollutants from all stationary sources per capita, kg/person	292.017	0.5133
1.1.2. The density of air emissions of pollutants from stationary sources, t/sq. km	49.637	0.7518
1.1.3. The density of emissions of pollutants into the atmosphere from road transport, t/sq. km	27.351	0.5442
1.1.4. The quantity of solid household waste exported per capita, m^3/person.	2.796	0.6990
1.1.5. Crime rate per 10 000 people	186.8	0.3160
1.1.6. Number of injured in an accident for 100 000 people	163.9	0.4537
1.1.7. Number of people killed in an accident for 100 000 people	6.064	0.3936
1.1.8. Number of accidents per 100 000 people	135.7	0.4572
1.1.9. Number of participants in the voluntary formations of the population for the protection of public order for 10 000 people	16.18	0.5393

Indicators of subgroups of sociological measurements are similarly defined (32 indicators, with the majority of indicators being aggregated, that is, they were determined by the results of respondents' answers to several questions), and for subgroups of economic indicators (24 indicators in total, formed mainly in size, in rubles per person, or share, as a percentage of the expenditure part of the budget of the municipality, budgetary security).

The components of DIUEQ for Kirov in groups and subgroups of indicators are given in Table 5 and in Figures 1 and 2.

DIUEQ for the city of Kirov in 2016, calculated according to formula (3) with equal weights of subgroups and groups of indicators, is $I_k = 0.4985$, as shown in Table 5; DIUEQ, calculated without regard to sociological indicators, is 0.5164. According to the indicators of provision and sociological

indicators, the group "Social and leisure environment" has the highest value of subgroup indices, where these two subgroups of indicators are sufficiently balanced among themselves. The indicators of these two subgroups are even more balanced for the second and fourth groups, Table 5. The indicators of provision reflect mainly the quantitative characteristics of the urban environment, and the sociological indicators are predominantly qualitative, and therefore they complement each other well.

Table 2. Indicators of the quality of the urban environment in Kirov in 2016 for the group "Architectural and landscape environment"

Number, formulation of the indicator and units of measure	Indicator value	Indicator index
2.1.1. Provision of the population with housing stock, sq. m/person	22.9	0.2900
2.1.2. The share of old and dilapidated housing stock in the total housing stock, %	0.89	0.7527
2.1.3. Number of construction permits issued per 1000 inhabitants	0.12	0.0800
2.1.4. The share of green space in the total area of urban land, %	22.93	0.5733
2.1.5. Commissioning of the total area of housing, sq. m. per 1000 people	942.8	0.5893
2.1.6. Level of the city illumination, %	81.98	0.8198
2.1.7. Diversity of residential development, %	8.96	0.2987

Table 3. Indicators of the quality of urban environment in Kirov in 2016 for the group "Social and leisure environment"

Number, formulation of the indicator and units of measure	Indicator value	Indicator index
3.1.1. Coefficient of migration growth by 10 000 people	65.8	0.2700
3.1.2. Provision of the population with doctors for 10 000 people	29.3	0.7146
3.1.3. Proportion of children aged 1–6 years who receive pre-school educational services and (or) service for their maintenance in municipal organizations, %	76.5	0.8703
3.1.4. Proportion of children aged 5–18 years who receive supplementary education services, %	78.2	0.8026
3.1.5. Proportion of students in municipal general education institutions who study in the second (third) shift, %	33.1	0.6827
3.1.6. Level of actual provision of clubs from the regulatory requirements, %.	94.5	0.9450
3.1.7. Level of actual provision in cultural institutions of the club type in terms of the number of spectator seats from the normative requirements for 2016, %	16.91	0.1691
3.1.8. Retail area of retail trade facilities for 10 000 people, sq. m.	34250	0.8346
3.1.9. Number of places in public catering facilities for 10 000 people	666.6	0.4943

This trend of mutual complementarity was manifested to an even greater extent for the indicators of the group "Security and ecology". For this group, the overall group index is the lowest, which indicates that there are more significant problems in this area than in others. As for the indices of

subgroups of economic indicators, on the whole they correspond to the indices of the other two subgroups.

Table 4. Indicators of the quality of urban environment in Kirov in 2016 for the group "Engineering and Transport Infrastructure"

Number, formulation of the indicator and units of measure	Indicator value	Indicator index
4.1.1. The share of vehicles with equipment for low-mobility citizens, %	11	0.3055
4.1.2. The share of the length of public roads of local importance that do not meet regulatory requirements, %	77.6	0.1378
4.1.3. Passenger turnover of public transport per capita, passenger-km / person	1037	0.6481
4.1.4. Average distance between public transport stops, m	305.6	0.9813
4.1.5. The share of heat networks need to be replaced, %	57.69	0.4231
4.1.6. The share of replaced heat networks, %	1.9662	0.2458
4.1.7. The share of a street water supply network need to be replaced, %	60.28	0.3972
4.1.8. The share of replaced street water supply network, %	0.8685	0.1086
4.1.9. The share of a street sewer network needs to be replaced, %	54.65	0.4535
4.1.10. The share of replaced sewerage network, %	1.2021	0.3005
4.1.11. State of the street gas network	0.0000	1.0000

Table 5. Components of DIUEQ of the city of Kirov in 2016

Number and name of the indicator group	Designation and value of the index of the group	Number and index of the subgroup of indicators of provision	Number and index of the subgroup of sociological indicators	Number and index of the subgroup of economic indicators
1. Safety and ecology	$I_1 = 0.4186$	$I_{11} = 0.5186$	$I_{12} = 0.4089$	$I_{13} = 0.3283$
2. Architectural and landscape environment	$I_2 = 0.5131$	$I_{21} = 0.4863$	$I_{22} = 0.4658$	$I_{23} = 0.5873$
3. Social and leisure environment	$I_3 = 0.5565$	$I_{31} = 0.6426$	$I_{32} = 0.5338$	$I_{33} = 0.4932$
4. Engineering and transport infrastructure	$I_4 = 0.5058$	$I_{41} = 0.4547$	$I_{42} = 0.4432$	$I_{43} = 0.6195$
Total	$I_k = 0.4985$	$I_{sc} = 0.5256$	$I_{sl} = 0.4629$	$I_{ec} = 0.5071$

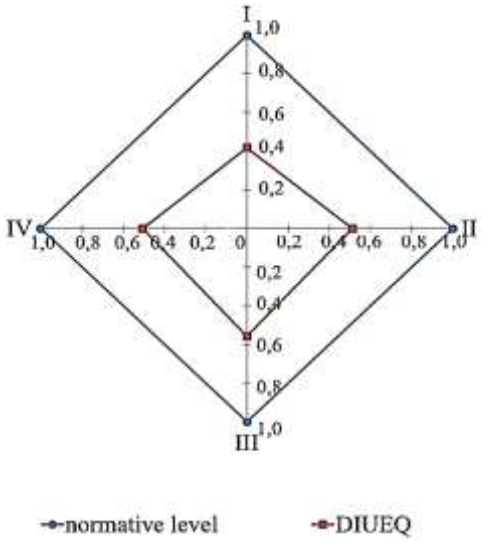


Figure 1. The square of the quality of the urban environment of the city of Kirov for 2016 by DIUEQ and by group indices

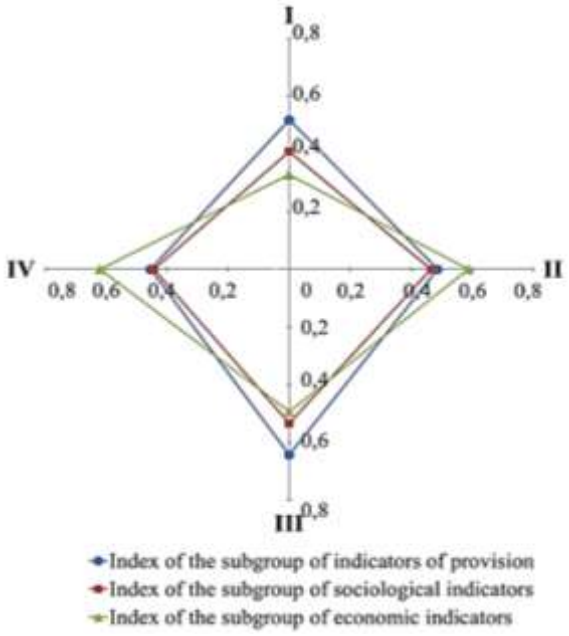


Figure 2. The square of the quality of the urban environment of the city of Kirov for 2016 by indices of subgroups of indicators

In Figures 1, 2: I – Safety and ecology; II – Architectural and landscape environment; III – Social and leisure environment; IV – Engineering and transport infrastructure

4. Conclusion

The authors have solved the following tasks according to the goal of the research.

1. The most simple, clear and transparent method for calculating DIUEQ, suitable for any city or municipal entity, is proposed. At the same time, there was used positive domestic and international experience of methods of constructing indices of urban environment quality, quality of life and sustainable development. One of the main elements of this methodology is the identification of four groups of indicators; each group includes three sub-groups of the same name – indicators of provision, indicators of sociological measurements and economic indicators.

2. The calculation of the index excludes indicators that are determined by inaccessible sources or by complex methods.

3. Comparability of all private, group indices and DIUEQ as a whole: the possibility of correction or replacement of indicators for a particular city is ensured.

4. Methodically, it is possible by means of DIUEQ to assess the dynamics of the quality of the urban environment in general and of certain groups of indicators on the temporal dynamics of the corresponding indices, including the assessment and prediction of sustainable development of cities. The effectiveness of the application of this technique for this purpose is confirmed by the use in China of the USI index.

5. When calculating and recalculating (with time variation) all the partial indices, there is no need to directly compare them with the indices of other cities due to a single normalization of all the partial indices in the initial construction of each of them.

The management of municipalities can use the proposed methodology for assessing the effectiveness of management actions for changing certain parameters of urban environment quality, both for the past time period and for planning. According to the authors, the sustainability of urban development can be achieved by ensuring the growth on a temporary basis of at least 5 years of both

DIUEQ itself and its group indices, if there is a significant reduction in the value of the index for no subgroup of indicators in each group. At the same time, economic indicators, expressed in absolute units per capita, are subject to recalculation taking into account the average annual inflation (GDP deflator).

The experience of applying the proposed methodology for calculating the DIUEQ for Kirov in 2016 showed its effectiveness and expediency of performing calculations using this method for Kirov both for the previous period (in particular, for 2012–2015) and for the accounting data in 2017. It is also planned to test this technique in 2018 in relation to other cities of the Kirov region.

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