System Analysis Methodology for Determining the City Smartness

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Abstract

Such system analysis methodologies as Saaty's method, multi-criteria optimization according to the Pareto principle, Bayesian rule, and information system for comprehensive assessment of smart cities are considered in this paper. The results of the investigation are automated and reflected in the developed software operation. In order to compare the results of these methodologies, such cities of Western Ukraine such as Ternopil, Lviv, Rivne, Khmelnytskyi and Chernivtsi are selected.

Keywords

Smart city, methodology, method, characteristics, alternatives, indicators

1. Introduction

At present, the concept of smart city is gaining more and more attention. Smart cities have emerged in order to solve a number of problems, including rapid urbanization and urban agglomeration, transport problems, waste management, air quality, social pressure and inequality, economic speculation and ineffectiveness of emergency authorities [1]. Therefore, city planners all over the world are trying to develop models of 21st century city development that would meet the new requirements and expectations of the modern world and solve the problems of the future, taking into account all aspects of urbanization in the integrated way. One of the new concepts for solving modern city problems in the field of city planning is the development of smart cities, which has attracted much attention during the recent years [2].

In mid-November 2022, there are 8 billion people on the planet, more than half of whom live in cities. According to forecasts, this share will increase up to 68% by 2060 [3]. The problem of providing cities with modern IoT technologies and support from local authorities for the integrated interaction of citizens and intelligence elements is of great importance.

The first step for the construction and implementation of the smart city architecture and platform is to have clearly defined set of characteristics, criteria, and sub-criteria that make it possible to evaluate and compare the cities with each other. That is why it is necessary to apply system analysis (decision-making) methodologies, which can be defined as a set of actions resulting in the solution of decision-making problem that involves at least two significant alternatives, where the selected one offers the best result in relation to the set goal and the possibility of its implementation [4].

2. Related Works

In recent years the "smart cities" concept has attracted a lot of attention. "Smart cities" and "digital cities" are the most common terms in the literature which describe the transformation of urban areas. The European Commission defines the "smart city" as "a place where traditional networks and services

Proceedings ITTAP'2023: 3rd International Workshop on Information Technologies: Theoretical and Applied Problems, November 22–24, 2023, Ternopil, Ukraine, Opole, Poland
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are becoming more efficient due to the application of digital and communication technologies for the benefit of residents and businesses" [5]. Kuru et al. note [6] that there is neither agreed definition of the smart city, nor the “best way” to make every city smart.

The idea of the smart city creation involves development in key factors including energy, water supply, transportation, health and safety, and other key services [7].

Although there are many spheres to which “smart cities” belong and which are interconnected, there are common features that unite them among scientists and practitioners.

A number of attempts have been made to rank the cities according to various parameters, among which the most popular are “competitive cities”, “livable cities”, “sustainable cities”, “global cities”, “smart cities”, etc. These attempts are realized by means of such characteristics as “smart economy”, “smart mobility”, “smart environment”, “smart people”, “smart life”, and “smart governance” [8].

It is worth noting the “Global Power City Index” ranking concept from the Memorial Foundation. The foundation has published the ranking of the world’s largest cities based on their “magnetism, or comprehensive ability to attract human capital and businesses from around the world” every year since 2008 [9]. The multidimensional ranking system is based on functions such as economy, research and development, cultural interaction, livability, environment, and availability [9].

Lin et al. [10] conducted a reliability analysis to test the reliability of the current ranking system. A similar comparative study between three ranking models was carried out by Benamrou et al [11]. Wu [12] developed the “intelligent ranking” system for Chinese cities. Due to the complexity and diversity of living standards, research and development on”livable cities” has attracted much attention [13].

Akande et al. (2019) ranked 28 European capitals according to their smartness and sustainability using 32 indicators. Their methodology is based on hierarchical clustering and principal component analysis (PCA) [14]. Finally, Miloševic et al. (2019) included 35 key indicators to evaluate smart cities in Serbia. Their approach is based on hybrid fuzzy multi-criteria decision-making model [14].

The objective of this paper is to investigate different methodologies for determining the city smartness and compare their results, as well as to implement the information system for the evaluation of Ukrainian cities.

3. Determination of the smartest city in Western Ukraine by means of analytic hierarchy process

The analytic hierarchy process (AHP) is based on hierarchical representation of the elements of complex problem and uses ratings on the relations scale. The main option for problem presenting is the hierarchy with the same number and functional composition of alternatives under the criteria, i.e. a hierarchy where alternatives are evaluated according to all criteria of the penultimate level.

In AHP, priorities are used for pairwise comparison of criteria as well as for pairwise comparison of alternatives [4]. Professor Saaty established the following scale for priorities description:

- "1" - both compared elements (criteria/alternatives) equally contribute to the goal;
- "3" - thoughts and experience favor one element over the other;
- "5" - opinions and experience indicate a strong superiority of one element over the other;
- "7" - thoughts and experiences strongly favor one element over another;
- "9" - thoughts and experiences completely favor one element over the other.

You can also use “2”, “4”, “6” or “8” to express the intermediate level of preference [4].

Local priorities are obtained by calculating the set of principal eigenvectors for each of the inversely symmetric hierarchy matrices according to the formula:

$$A \cdot x = \lambda_{\max} \cdot x, \quad (1)$$

where $x = \{x_1, x_2, \dots, x_n\}$ – is the main eigenvector of the square matrix of pairwise comparisons $A = \{a_{ij}\}$;

$\lambda_{\max}$ – is the maximum eigenvalue of matrix A.

The quantitative characteristics of the inconsistency of the expert’s statements are the consistency index and the consistency ratio. The consistency index is defined in the following way:

$$I_y = \frac{\lambda_{\max} - n}{n-1}, \quad (2)$$

where I_y – consistency index;
$\lambda_{\max}$ – maximum eigenvalue ($\lambda_{\max} \approx n$);
n – matrix order.

The average values of the consistency index $M(I_y)$ for random matrices of different dimensions are shown in Table 1.

Table 1
Average values of the consistency index

Matrix dimension, n	1	2	3	4	5	6	7	8	9	10
Average value of consistency index, $M(I_y)$	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The consistency ratio I_0 is as follows:

$$I_0 = \frac{I_y}{M(I_y)} \quad (3)$$

The main task of AHP is to calculate the global priorities of alternatives, i.e. the priorities of alternatives relative to the entire hierarchy (the main goal). The local priorities are multiplied by the priority of the corresponding criterion at the highest level and then summed for each element. Hierarchical synthesis is used to weight the eigenvectors of the matrices of pairwise comparisons of alternatives by the weights of the criteria (elements) available in the hierarchy, as well as to calculate the overall priorities of the alternatives.

The most important criteria are 3 of the 6 characteristics of the European cities definition method: smart mobility, smart environment, and smart lifestyle.

The constructed hierarchy for solving the described problem is shown in Fig. 1.

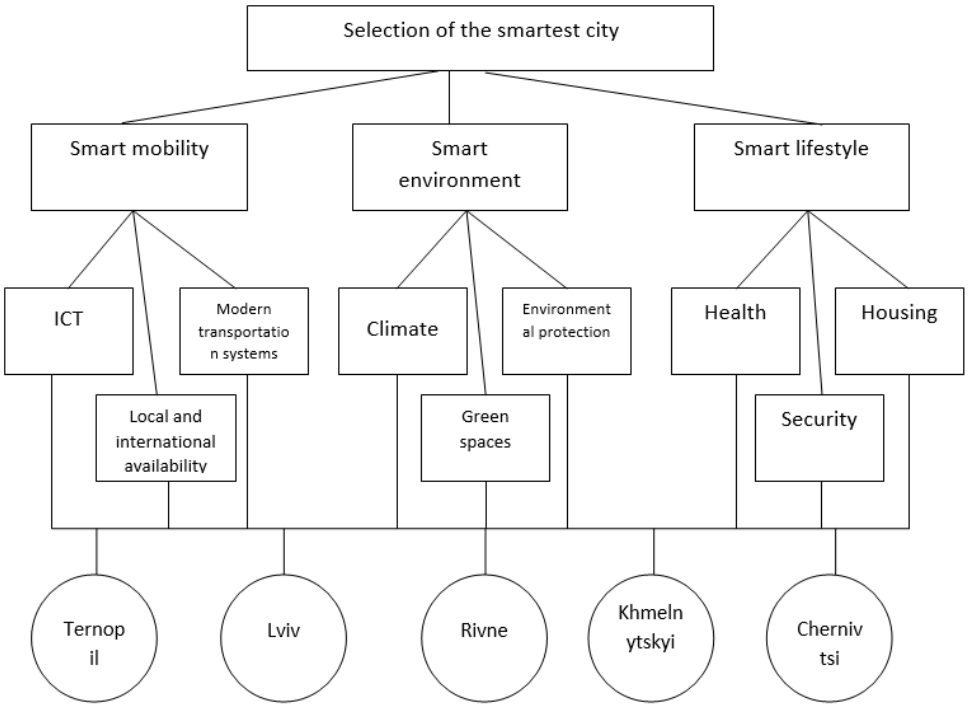

Figure 1: Hierarchy for solving the problem of determining the smartest city in Western Ukraine

Let us highlight the sub-criteria of the smart mobility criterion such as ICT, local and international accessibility, and modern transportation systems.

Let us point out the following sub-criteria of the smart environment criterion: climate, green areas, environmental protection.

And let us define such sub-criteria of the smart lifestyle criterion as health, safety, and accommodation.

In accordance with the selected criteria and sub-criteria, it is settled to select the smartest city among the following alternatives: Ternopil, Lviv, Rivne, Khmelnytskyi, and Chernivtsi. These cities are chosen because all of them are located in Western Ukraine.

In accordance with the above mentioned problem concerning the determination of the smartest city, we will solve this problem by means of the Analytic Hierarchy Process (AHP).

Figure 2 shows how to enter the problem name, criteria, sub-criteria, and alternatives into the program in order to make optimal decision.

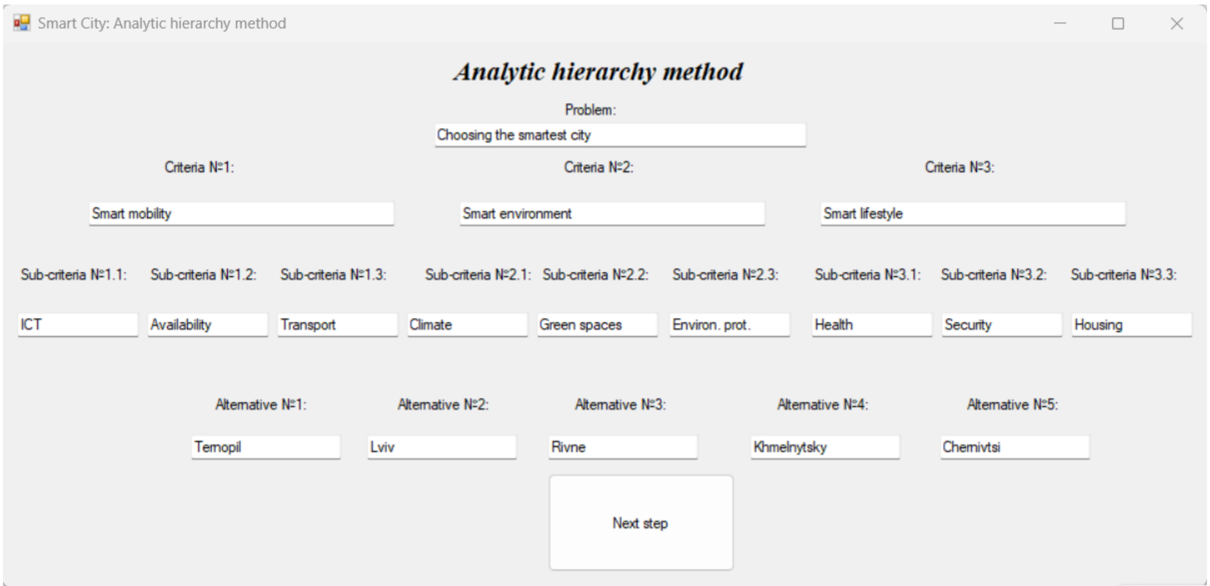

Figure 2: Entering data about the problem to be solved

We start the procedure of determining the local priorities of the descendant relative to the ancestor from the 2nd level of the hierarchy. The local priorities of the criteria relative to the problem are shown in Figure 3.

Figure 3: Local priorities of criteria in relation to the problem

It can be verified that PCM (pairwise comparison matrix) is correct, as the consistency ratio is < 0.1. The best local priority among the criteria in relation to the problem is the smart environment. This is determined by vector X, which is the eigenvector of this PCM according to the maximum value of the eigenvalues of the pairwise comparison matrix.

We continue the procedure of determining the local priorities of the descendant relative to the ancestor at the 3rd level of the hierarchy. The local priorities of the sub-criteria relative to the smart mobility criterion are shown in Figure 4.

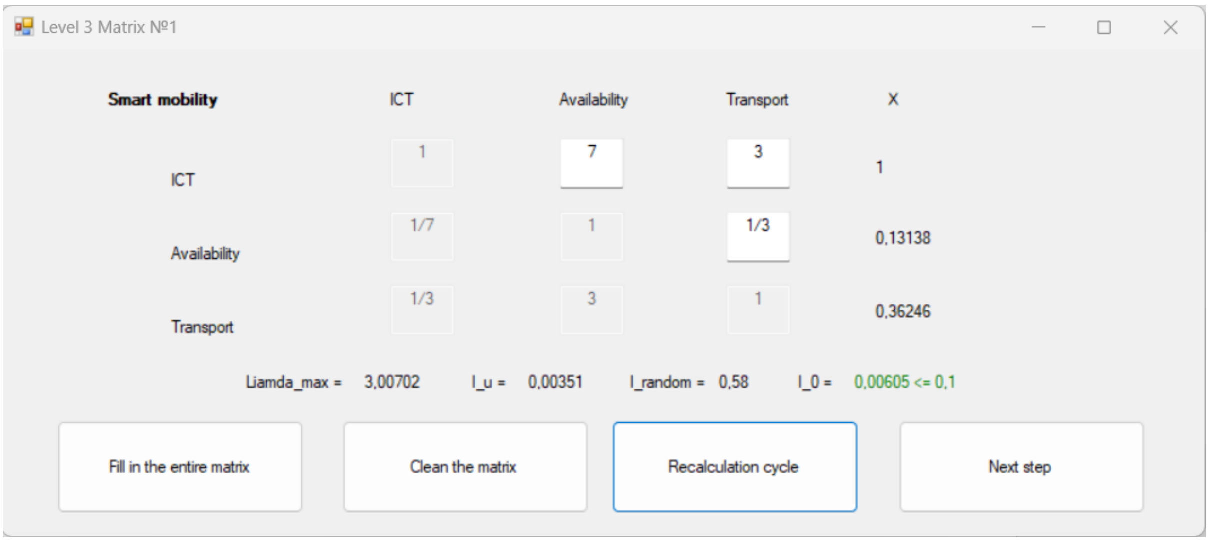

Figure 4: Local priorities of sub-criteria for smart mobility

PCM is valid, as the coherence ratio is < 0.1. The highest local priority among the sub-criteria in relation to smart mobility is ICT.

The local priorities of the sub-criteria in relation to the smart environment criterion are represented in Figure 5.

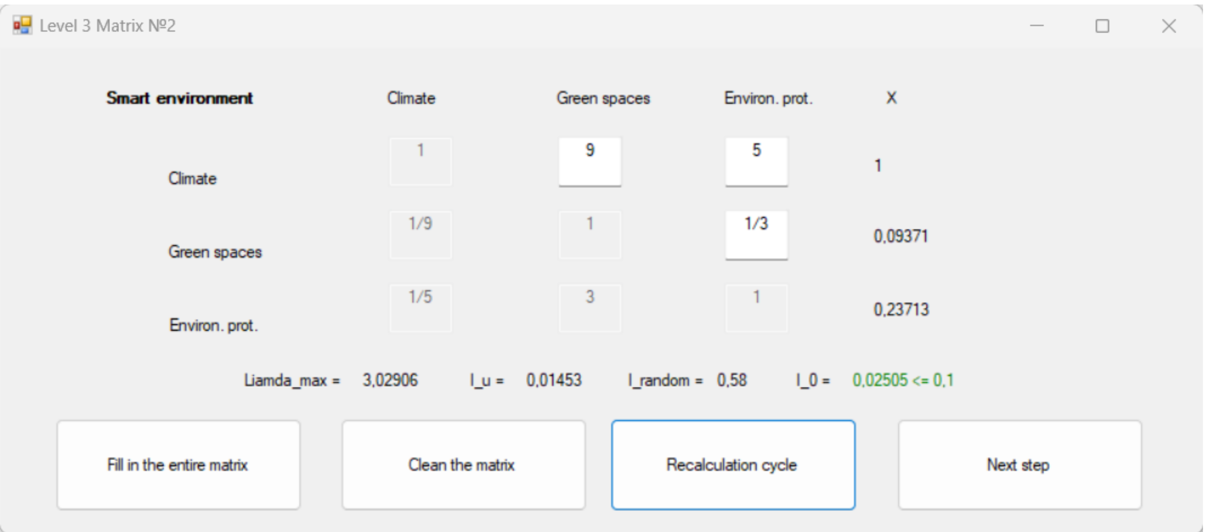

Figure 5: Local priorities of sub-criteria in relation to smart environment

The PCM is correct, as the coherence ratio is < 0.1. The highest local priority among the sub-criteria in relation to the smart environment is climate.

The local priorities of the sub-criteria in relation to the smart lifestyle criterion are shown in Figure 6.

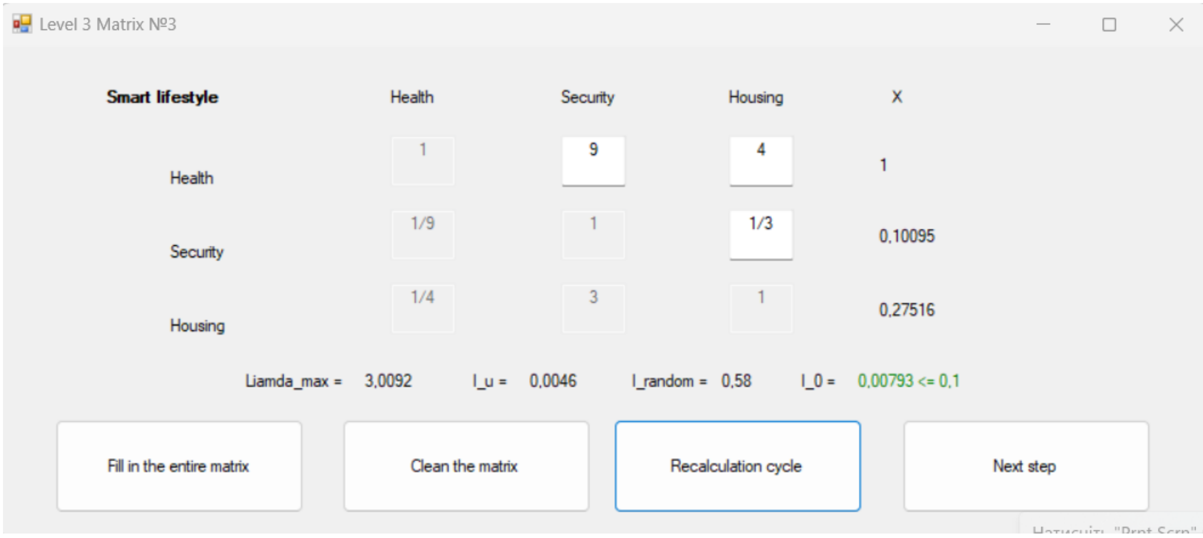

Figure 6: Local priorities of the sub-criteria in relation to healthy lifestyle

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the sub-criteria in relation to reasonable lifestyle is health.

We continue the procedure of determining the local priorities of the offspring relative to the ancestor at the 4th (last) level of the hierarchy. The local priorities of the alternatives relative to ICT sub-criterion are presented in Figure 7.

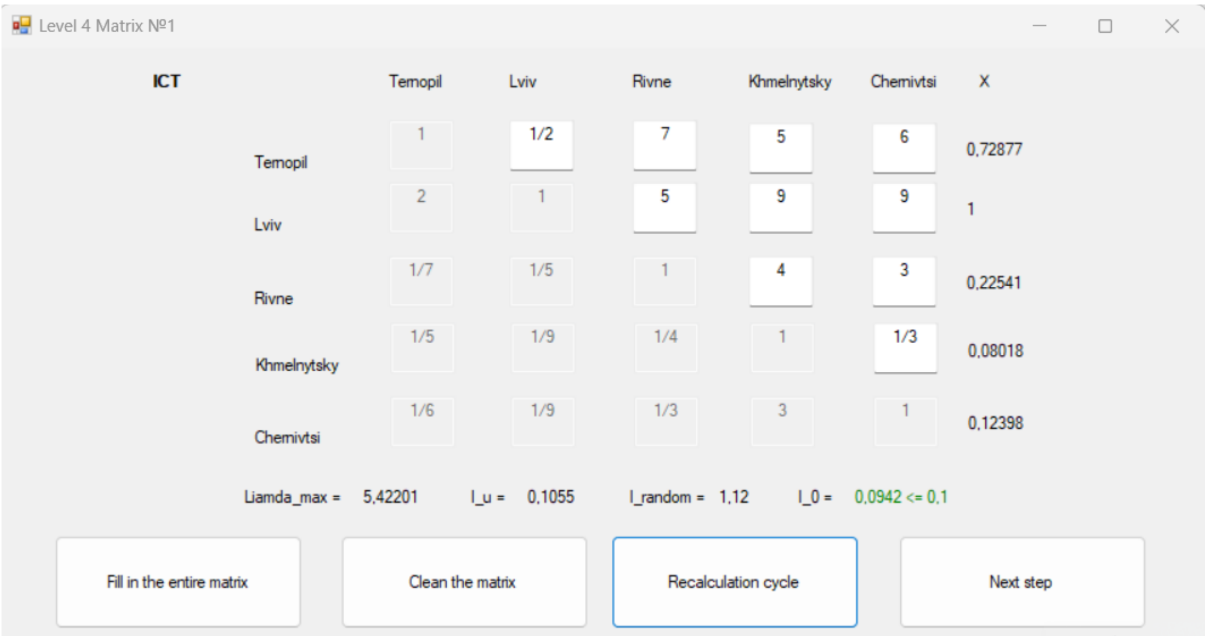

Figure 7: Local priorities of alternatives in relation to ICT sub-criterion

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the alternatives in terms of ICT is Lviv.

The local priorities of the alternatives in relation to the sub-criterion of local and international accessibility are shown in Figure 8.

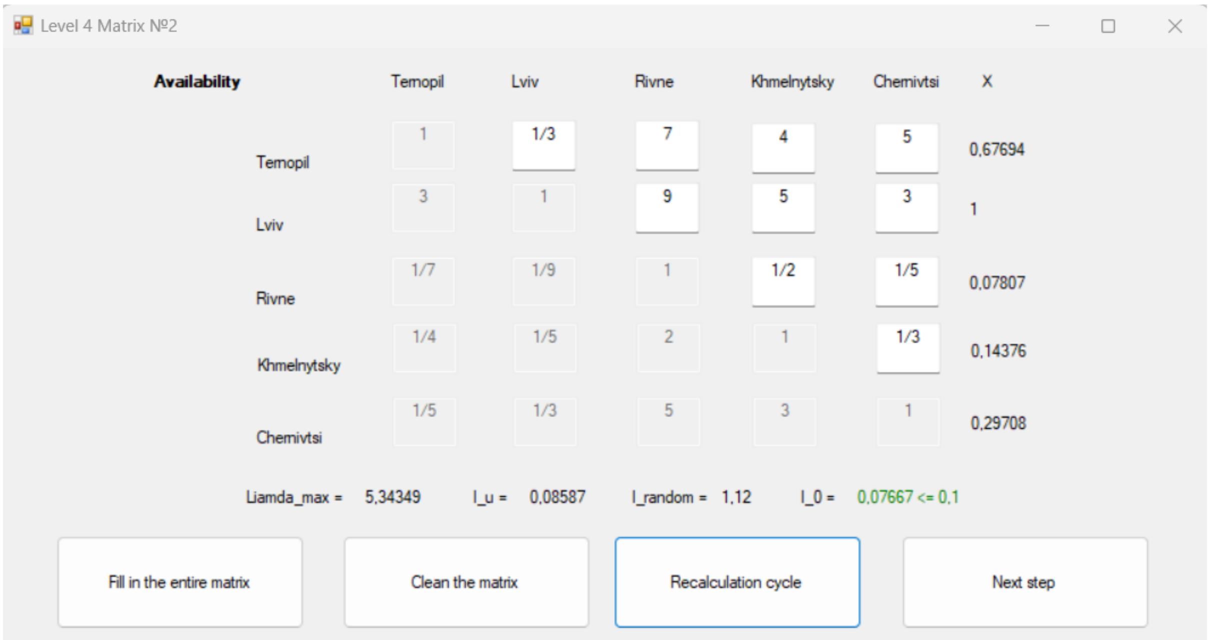

Figure 8: Local priorities of alternatives in relation to the sub-criterion of local and international accessibility

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the alternatives in terms of local and international accessibility is Lviv.

The local priorities of the alternatives in relation to the sub-criterion of modern transportation systems are represented in Figure 9.

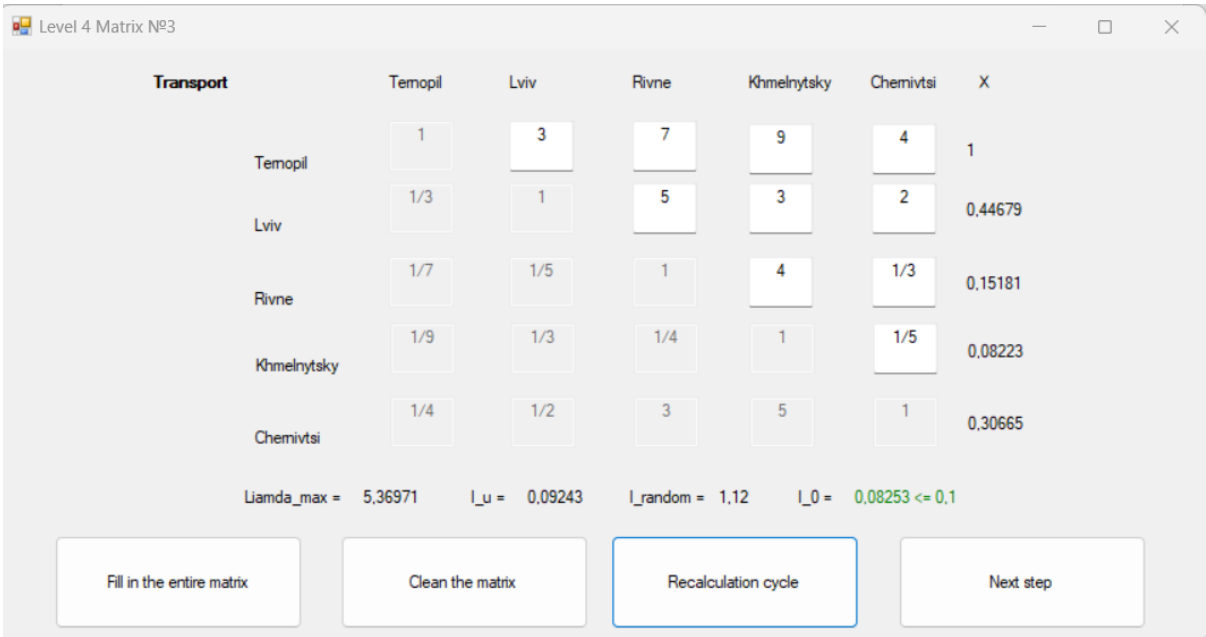

Figure 9: Local priorities of alternatives in relation to the sub-criterion of modern transportation systems

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the alternatives in relation to the current transportation systems is Ternopil.

The local priorities of the alternatives with respect to the climate sub-criterion are shown in Figure 10.

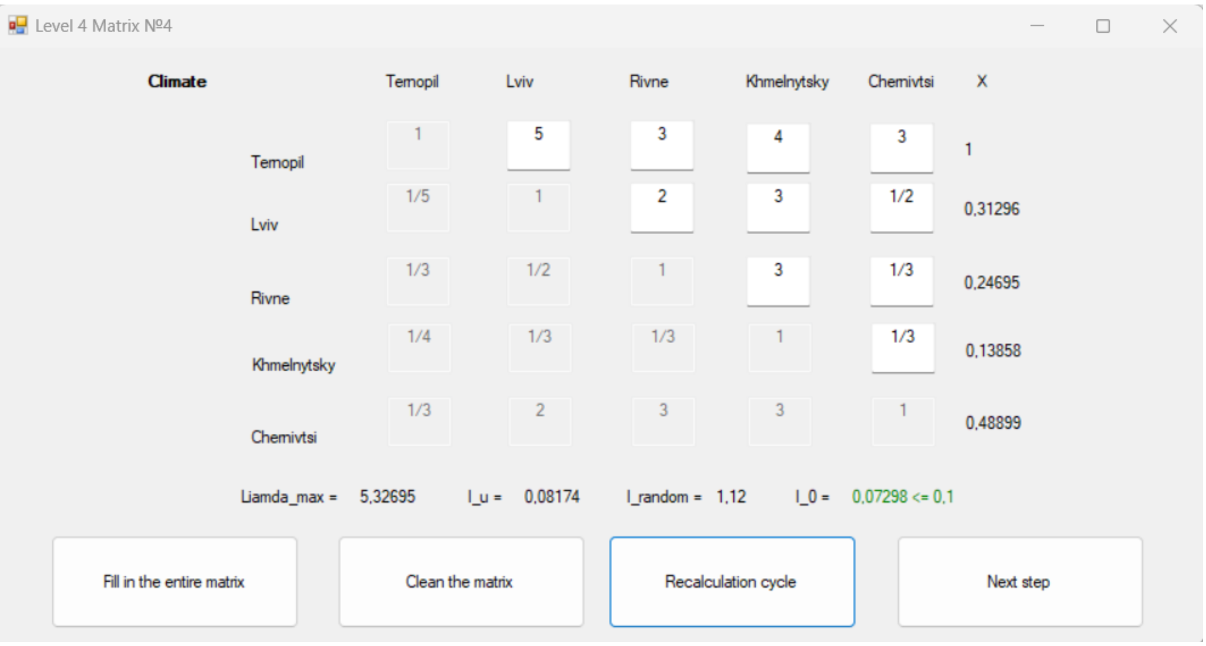

Figure 10: Local priorities of alternatives in relation to the climate sub-criterion

PCM is correct, as the consistency ratio is < 0.1. The best local priority among the alternatives in terms of climate is Ternopil.

The local priorities of the alternatives in relation to the green areas sub-criterion are shown in Figure 11.

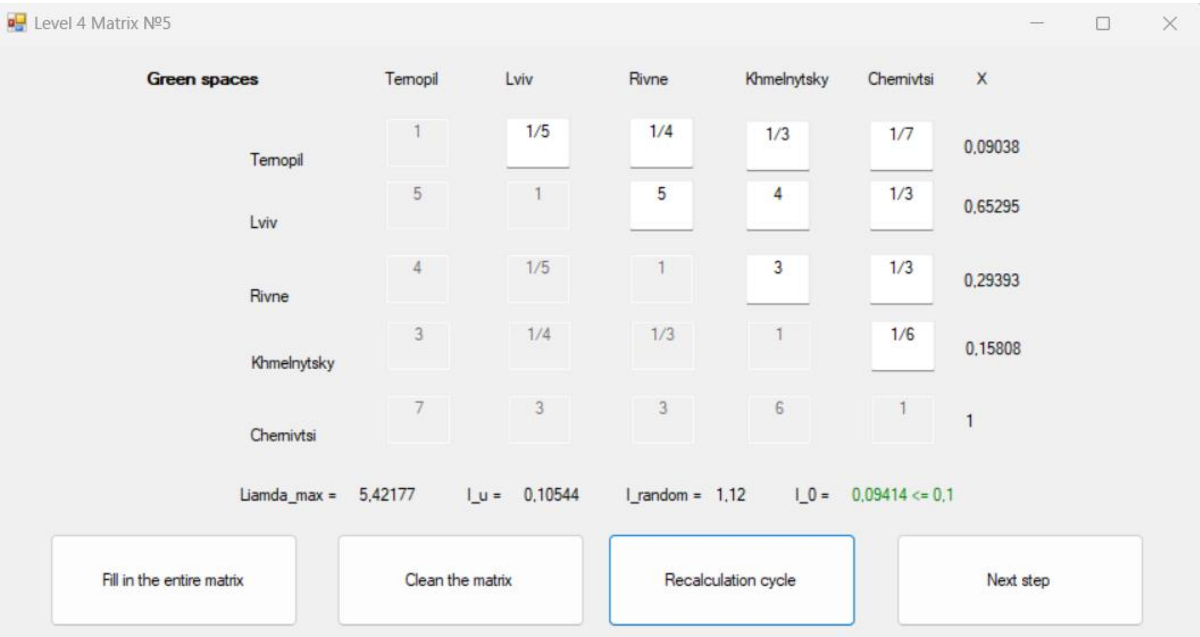

Figure 11: Local priorities of alternatives in relation to the green areas sub-criterion

PCM is valid, as the consistency ratio is < 0.1. The highest local priority among the alternatives in terms of green areas is Chernivtsi.

The local priorities of the alternatives in relation to the environmental protection sub-criterion are presented in Figure 12.

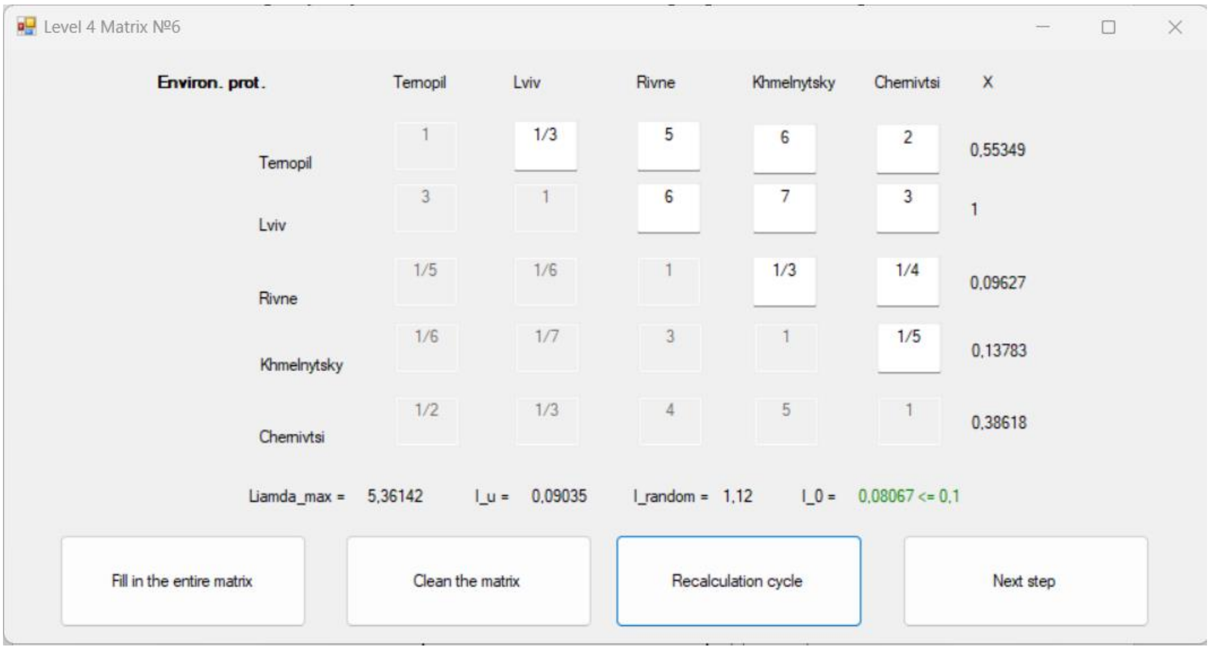

Figure 12: Local priorities of alternatives in relation to the environmental protection sub-criterion

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the alternatives with respect to environmental protection is Lviv.

The local priorities of the alternatives with respect to the health sub-criterion are depicted in Figure 13.

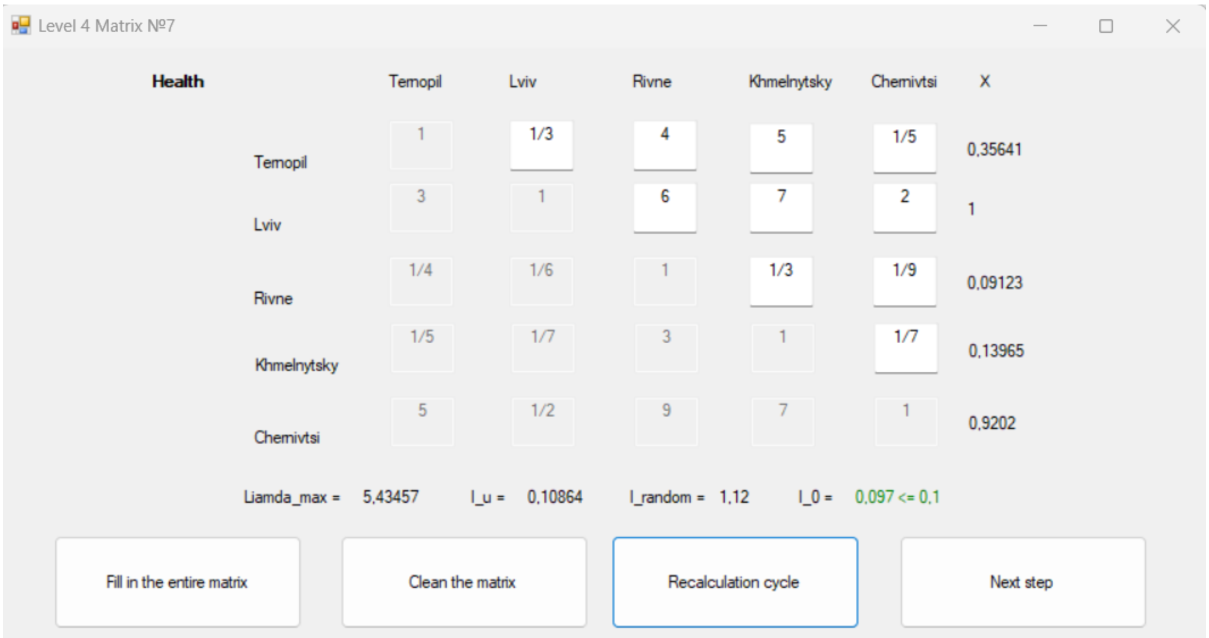

Figure 13: Local priorities of alternatives in relation to the health sub-criterion

PCM is correct, as the consistency ratio is < 0.1. The best local priority among the alternatives in terms of health is Lviv.

The local priorities of the alternatives with respect to the security sub-criterion are shown in Figure 14.

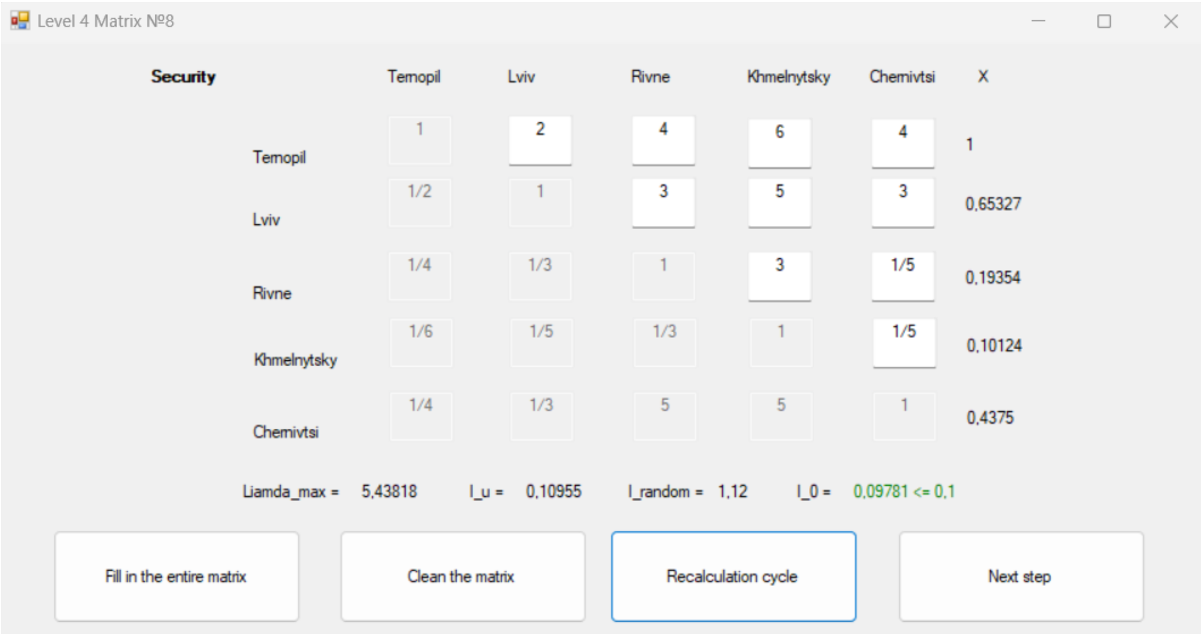

Figure 14: Local priorities of alternatives in relation to the security sub-criterion

PCM is right, as the consistency ratio is < 0.1. The highest local priority among the alternatives in terms of security is Ternopil.

The local priorities of the alternatives with respect to accommodation sub-criterion are represented in Figure 15.

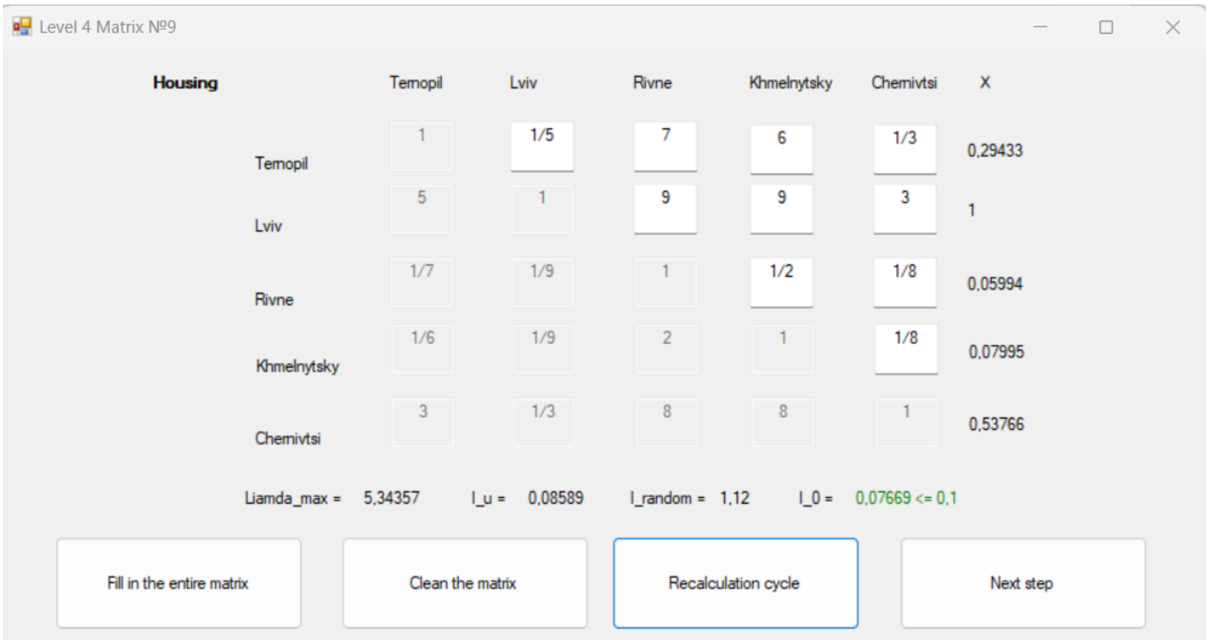

Figure 15: Local priorities of alternatives in relation to accommodation sub-criterion

PCM is valid, as the consistency ratio is < 0.1. The best local priority among the accommodation alternatives is Lviv.

Let's find the vectors of priorities of the alternatives relative to the factors (criteria).

Figure 16 shows the vector of priorities of the alternatives relative to the criterion of smart mobility, the vector of priorities of the alternatives with respect to the smart environment criterion and the vector of priorities of the alternatives with respect to the criterion of reasonable lifestyle.

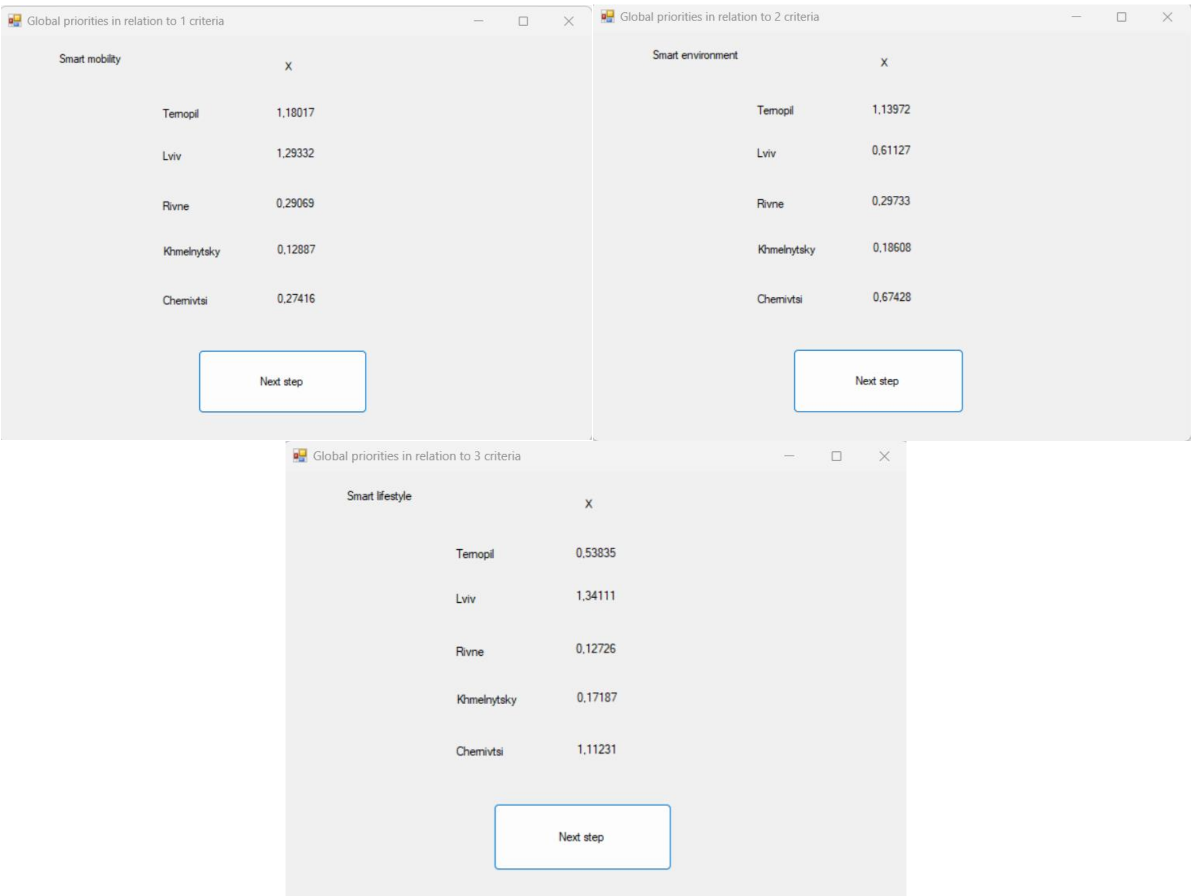

Figure 16: Priority vector of alternatives in relation to the smart mobility criterion, to the smart environment criterion and to the criterion of reasonable lifestyle

Thus, in terms of smart mobility, the best alternative is Lviv. Thus, in terms of smart environment, Ternopil alternative is the best one. So, in terms of reasonable lifestyle, the best alternative is Lviv.

In order to make the final decision, let's find the global priorities of the alternatives relative to the hierarchy focus (problem).

The global priorities of the alternatives relative to the problem of determining the smartest city in Western Ukraine are depicted in Figure 17.

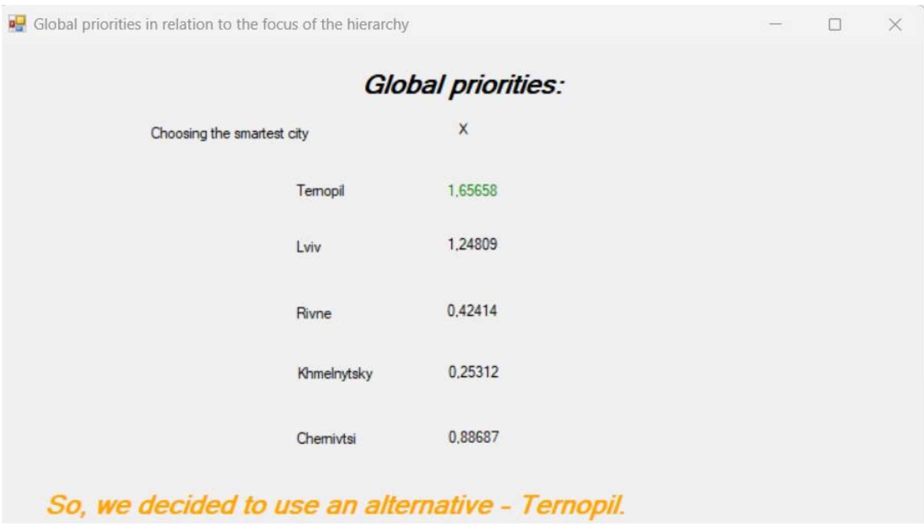

Figure 17: Global priorities of alternatives in relation to the problem

So, in terms of the problem, the best alternative is Ternopil.

4. Estimating the smartest city in Western Ukraine using multi-criteria optimization based on the Pareto principle

Decision-making tasks are usually multi-criteria and multi-alternative. It is necessary to compare all alternatives with each other and choose the most optimal one among them.

Let's assume that all properties of the alternatives have a numerical value, i.e., they are criteria. We denote these criteria $C_i(\chi)$, $i = \overline{1, n}$. In this case, any alternative χ can be matched with a point of the n- dimensional space E^n, the coordinates of which are the values of the corresponding criteria (n is the number of criteria used). Such a space is called a criterion space. In order to clarify this, we assume that the higher the value of the of the i-th criterion $C_i(\chi)$, the more superior this alternative is in terms of property i to other alternatives compared by the same criterion. Let us consider two arbitrary alternatives.

There are two possible situations:

1. One alternative is not worse than the other by all criteria:

$$C_i(\chi_2) \geq C_i(\chi_1),\ i = \overline{1, n} \quad (4)$$

(and at least one inequality is satisfied as a strict inequality).

2. This is not the case.

Condition (4) is the condition that alternative χ_2 is superior to alternative χ_1. Thus, transition from χ_1 to χ_2 improves our choice. Are there alternatives that cannot be improved? Yes, and almost always - this requires only the limitation of the values of the criteria $C_i(\chi)$, $i = \overline{1, n}$.

The set of non-improving alternatives is called the Pareto set for the given problem [15].

For further formalization of the choice, more specific and often rather controversial methods are introduced.

The method of criterion constraints is as follows: a set of numbers (levels, constraints) A_i, $i = \overline{2, n}$, and look for an alternative in which all criteria except one are constrained by $C_i(\chi) \geq A_i$, and the criterion C_1 is maximized. Of course, taking C_1 as the main criterion is conditional; it, like the important levels of A_i, in this problem, is subject to special selection. This technique is called the method of the main criterion or the method of criterion constraints.

Let's define the Pareto set for this problem according to the flowchart of the algorithm shown in Figure 18.

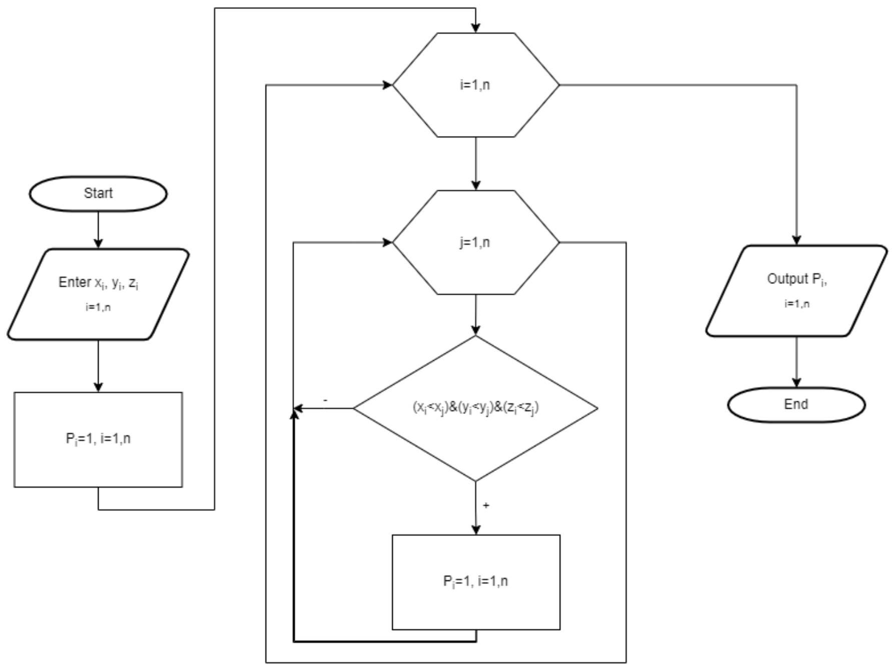

Figure 18: Block diagram of the Pareto set synthesis algorithm

Where x_i, y_i, z_i are the numerical values of the criteria of the i-th alternative. The Pareto set includes alternatives for which $P_i = 1$.

The input of the problem name, criteria, and alternatives into the program in order to make Pareto optimal decision related to the smartest city selection is shown in Figure 19.

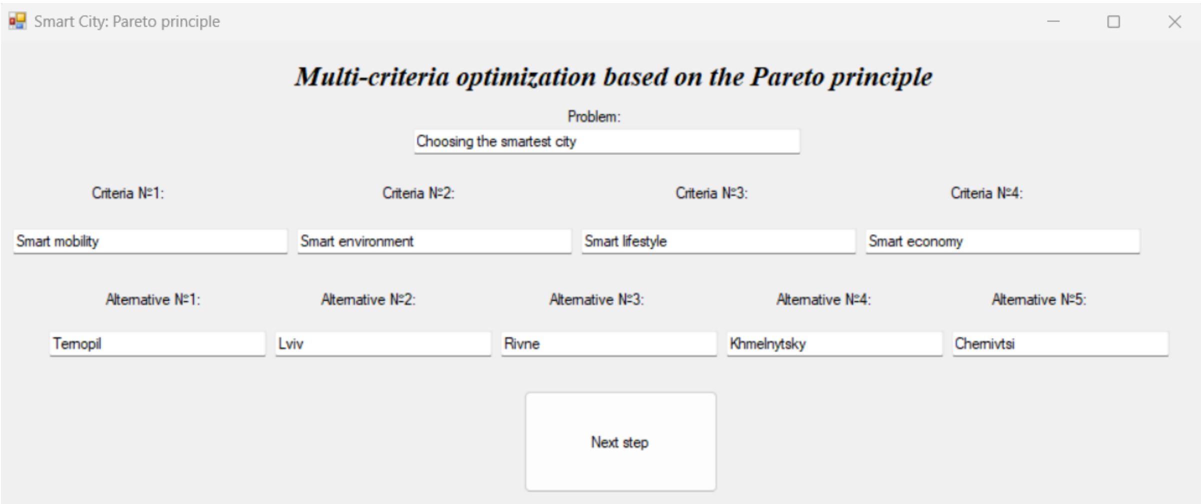

Figure 19: Entering input data

The criteria are as follows:

1. smart mobility;
2. smart environment;
3. smart lifestyle;
4. smart economy.

The next stage of the developed software is to determine the Pareto set (the set of non-improvable alternatives).

The program will display the text message about the alternatives that are in the Pareto set (the set of non-improvable alternatives) and they will be highlighted in green in the program dialog box (Figure 20).

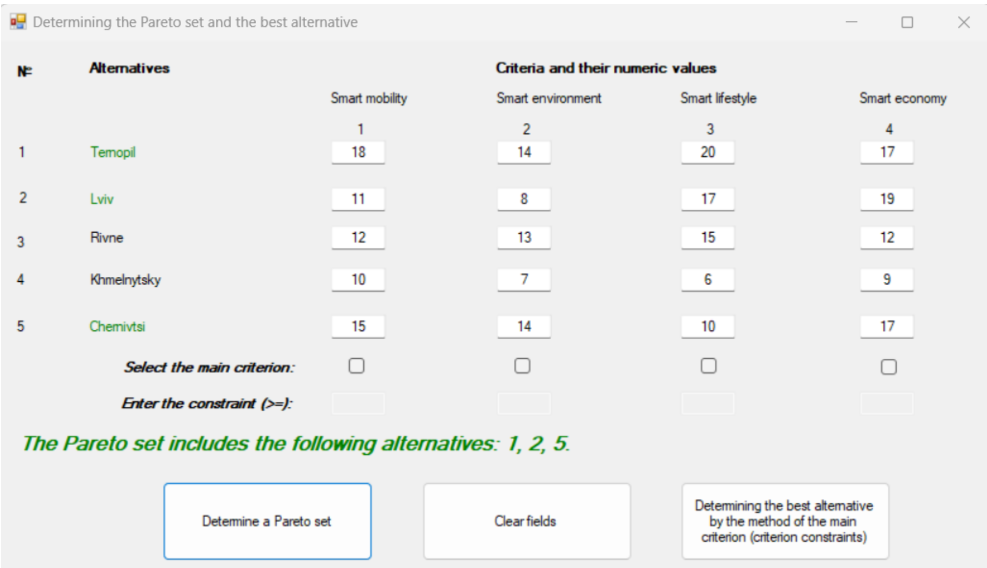

Figure 20: Programmatic definition of the Pareto set

The Pareto set is determined for each alternative in accordance with the criteria under condition (4), i.e. when at least one numerical value or point of the criteria for the given alternative is better or equivalent to the numerical value or point of another alternative. For example, for Chernivtsi alternative (see Figure 20), the test is carried out in the following way (5):

$$
\begin{gathered}
Chernivtsi - Lviv\text{: } 15 \geq 11,\ 14 \geq 8,\ 10 < 17,\ 17 < 19\ -\ 1; \\
Chernivtsi - Rivne\text{: } 15 \geq 12,\ 14 \geq 13,\ 10 < 15,\ 17 \geq 19\ -\ 1; \\
Chernivtsi - Khmelnytsky\text{: } 15 \geq 10,\ 14 \geq 7,\ 10 \geq 6,\ 17 \geq 9\ -\ 1; \\
Chernivtsi - Ternopil\text{: } 15 < 18,\ 14 \geq 14,\ 10 < 20,\ 17 \geq 17\ -\ 1.
\end{gathered} \tag{5}
$$

The final stage of multi-criteria optimization based on the Pareto principle is the selection of one alternative on the Pareto set using the method of criterion constraints (the main criterion method), which is carried out in the program mode. The user selects the main criterion and enters constraints on other criteria, and the best alternative is displayed in the text box and is highlighted in red (Figure 21).

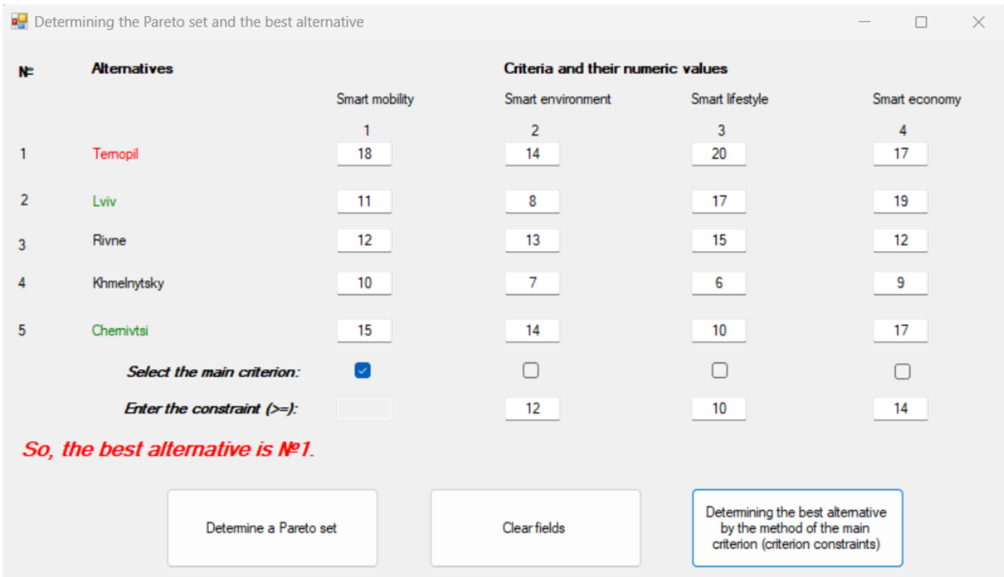

Figure 21: Evaluation of the best alternative by the main criterion method

Thus, the best alternative obtained as the result of the selection by the criterion constraint method from the Pareto set (non-improvable alternatives) is Ternopil.

5. Determination of the smartest city in Western Ukraine using Bayes' rule

Let us suppose that it is necessary to conduct differential diagnosis between the states of the investigated object (hereinafter referred to as hypotheses) $A_1, A_2, \ldots, A_n$. Each of these hypotheses is characterized by a distribution of conditional probabilities $P(B_i|A_j)$ of the occurrence of a particular feature (hereinafter referred to as a symptom) or symptom complex (group of symptoms) B_i – possible symptoms.

If specified:

1. conditional probability distributions $P(B_i|A_j)$;
2. a priori probabilities of hypotheses $P(A_j)$.

Then the problem of differential diagnosis is reduced to the statistical problem of choosing hypotheses, the optimal diagnostic rule for which is easy to construct using the well-known Bayes' rule, which for the a posteriori probability of the hypothesis A_j is as follows (6):

$$
P(A_i|B_j) = \frac{P(B_j|A_i)P(A_i)}{\sum_{i=1}^{n} P(B_j|A_i)P(A_i)}, \quad i = \overline{1, n}, \quad j = \overline{1, m}, \tag{6}
$$

where $P(A_i)$, $i = \overline{1, n}$ is a priori probability of the hypothesis A_i, $\sum_{i=1}^{n} P(A_i) = 1$;

$P(A_i|B_j)$ – is the probability of the hypothesis A_i provided that the symptom or symptom complex B_j occurred;

$P(B_j|A_i)$ – is the probability of occurrence of a symptom or symptom complex if the hypothesis A_i is true.

If for any hypothesis A'_j: the probability $P(A'_i|B_j) \gg P(A_i|B_j)$ for the other $j \neq j'$, then the optimal rule assigns the hypothesis A'_j to the investigated object [16].

Often, probabilities $P(A_i)$ are called a priori probabilities because they characterize the degree of probability of event A_i before the occurrence of event B_j. The occurrence of event B_j obviously results in the change in the measure of the probability of event A_i occurring, so the probabilities $P(A_i|B_j)$ are called a posteriori.

The task to be defined is to identify the criterion (symptom) and the smartest city (hypothesis).

So, there are the following 5 hypotheses to make a decision:

1. A_1 – Ternopil;
2. A_2 – Lviv;
3. A_3 – Rivne;
4. A_4 – Khmelnytskyi;
5. A_5 – Chernivtsi.

Criteria that will be referred to as symptoms:

1. B_1 – smart mobility;
2. B_2 – smart environment;
3. B_3 – smart lifestyle.

Let's set the a priori (before the experiment) probabilities of the hypotheses for the given problem ($\sum_{i=1}^{n} P(A_i) = 1$). Since all the cities can equally be the smartest, they are:

$P(A_1) = P(A_2) = P(A_3) = P(A_4) = P(A_5) = \frac{1}{5}$.

Now let's determine the distribution of conditional probabilities $P(B_j|A_i)$ of the symptom complex occurrence. In order to do this, let's turn to the statistics on the use of criteria in these cities (we will distribute probabilities according to the development of criteria in the city).

Thus, we get the following distribution of conditional probabilities $P(B_j|A_i)$.

You can enter the problem name, hypotheses, and symptoms in order to solve the problem with 5 hypotheses and 3 symptoms.

How to enter the problem name, hypotheses, and symptoms into the program to make a decision about the smartest city is shown in Figure 22.

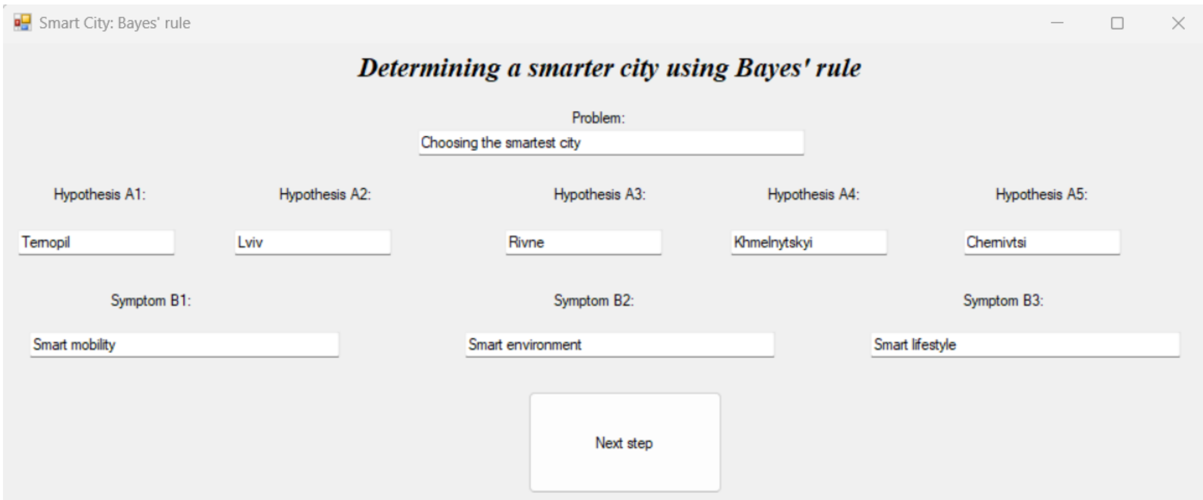

Figure 22: Entering input data

The next step is to enter the a priori probabilities of the hypotheses and the conditional probabilities of the symptom complex (Figure 23).

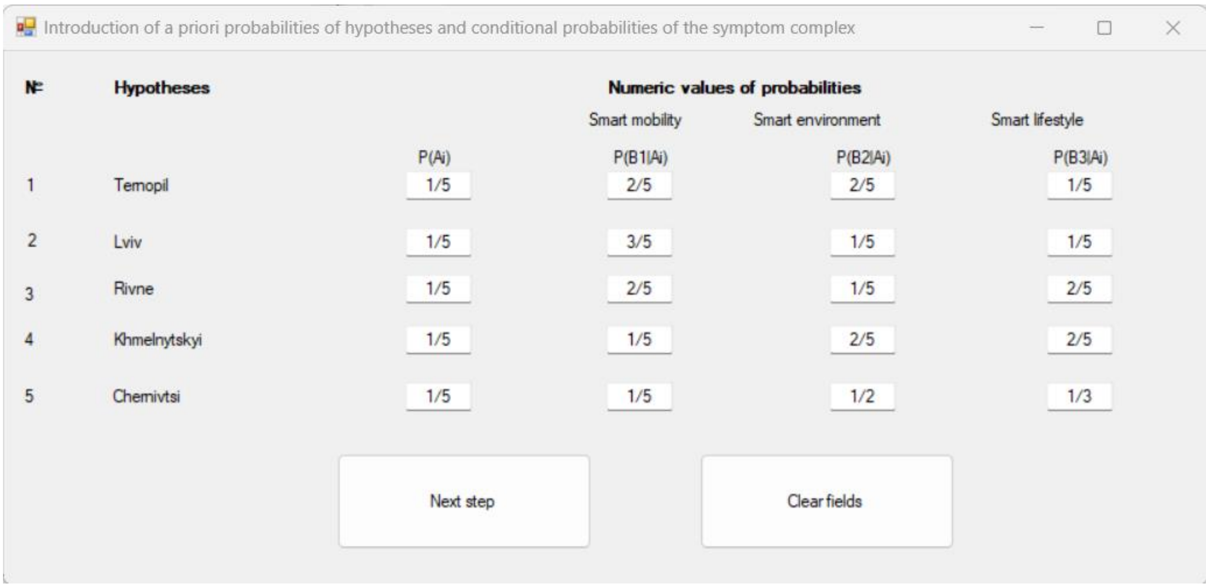

Figure 23: Entering of a priori probabilities of hypotheses and conditional probabilities of the symptom complex

Since each of the symptoms affects the problem of determining the smartest city, we take all of them into account in further calculations.

The final stage of the developed software is the search for a posteriori (after the experiment) probabilities according to Bayes' rule (6) and the selection of the best hypothesis (Figure 24).

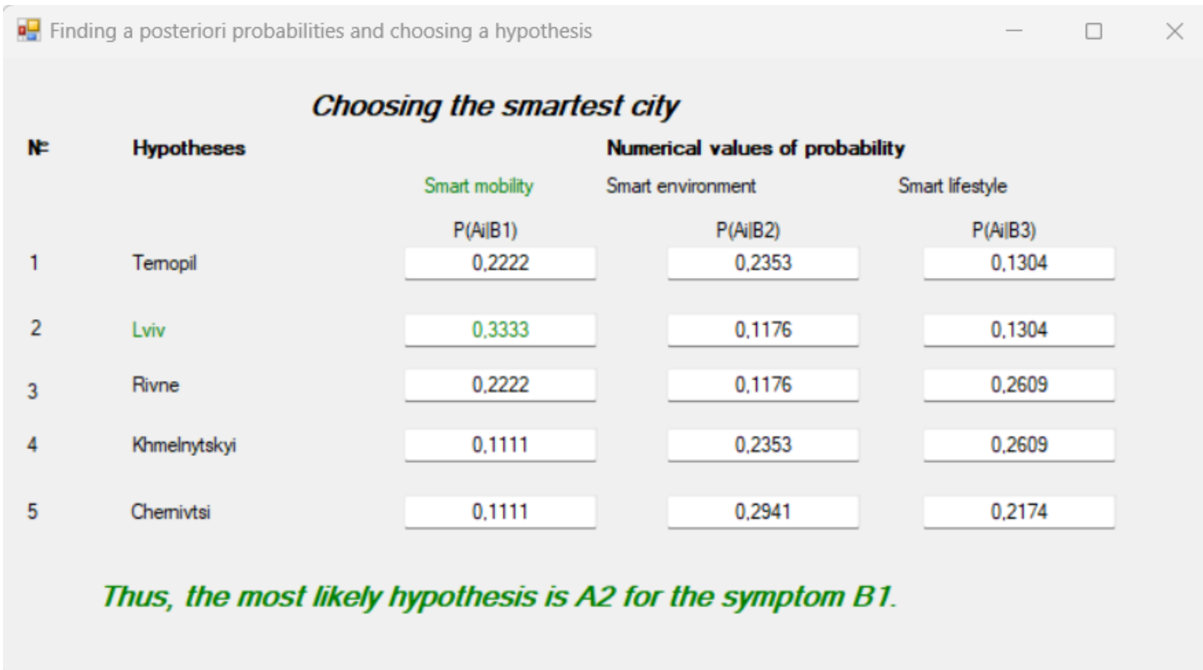

Figure 24: Choosing one hypothesis among the set of specified ones

The program will display the text message about the best hypothesis that is true for a particular symptom, and it and the a posteriori probability of this event (the maximum value among all probabilities) will be highlighted in green in the program dialog box.

6. Creating the information system for evaluation of the smartness of Ukrainian cities

With the development and application of smart city architectures and platforms, there is the need to check their implementation in particular city. In order to do this, let's look at the methodology that we propose to use to evalluate cities in Ukraine. The criteria have the hierarchical structure, and the overall city index is based on 6 characteristics, 25 factors, and 50 indicators (Figure 25).

The smart economy includes 3 factors and 5 indicators, among which it is worth paying attention to the level of self-employment of city residents and the unemployment rate, as these factors are crucial for attracting investors and building a business.

Smart mobility includes 3 factors and 8 indicators that make it possible to check the level of satisfaction with transport services in the city and the level of computerization of the population (availability of PCs and Internet access).

Smart environment involves creating comfortable and environmentally friendly living conditions for city residents and is based on 3 factors and 5 indicators.

Smart people (6 factors and 13 indicators) should be researched and analyzed in detail, because it is experienced and successful people who will be able to ensure the process of maintaining and developing the elements of the city smartness.

Smart living has the hierarchy of 7 factors and 11 indicators that are responsible for the life quality of city residents.

Smart governance is based on 3 factors and 8 indicators and involves identifying the level of commitment to the government and the services it provides.

#	Name of indicator
1	Level of self-employment
2	New businesses are registered
3	GDP per employee
4	Unemployment rate
5	Specific gravity in part-time employment
6	Public transport network per capita
7	Satisfaction with access to public transport
8	Satisfaction with the quality of public transport
9	International availability
10	Computers in households
11	Broadband Internet access in households
12	Traffic safety
13	Use of economical cars
14	The availability of sunny hours
15	Green space share
16	Solid particles
17	Deadly chronic diseases of the lower respiratory tract
18	Individual efforts for nature conservation
19	The importance of knowledge centers
20	Foreign language skills
21	Availability of books per inhabitant
22	Participation in lifelong learning
23	Participation in language courses
24	Share of foreigners
25	Proportion of citizens born abroad
26	Share of people working in creative industries
27	Voter turnout in elections
28	Immigration environment (Attitude towards immigrants)
29	Knowledge about Europe, countries
30	Voter turnout in local elections
31	Participation in voluntary work
32	Attendance of cinema / museums / theaters by one resident
33	Doctors and hospital beds per inhabitant
34	Satisfaction with the quality of the healthcare system
35	Crime rate
36	Mortality from assault
37	Satisfaction with personal safety
38	Satisfaction with personal housing situation
39	Satisfaction with the quality of the educational system
40	Importance as a tourist location (overnight, sights)
41	Perception of personal risk of poverty
42	Poverty rate
43	Number of city representatives per capita
44	Political activity of residents
45	Importance of policy for residents
46	Municipality expenditures per capita in purchasing power standards
47	Share of children in kindergarten
48	Satisfaction with the quality of schools
49	Satisfaction with the transparency of bureaucracy
50	Enjoy the fight against corruption

Figure 25: List of all indicators

The values of each of the indicators can be obtained from the open data sources (e.g., the Unified State Web Portal of Open Data [17]).

The calculation stage starts with the indicator weights calculation (7).

$$W = 1 \cdot P_1 + 2 \cdot P_2 + 3 \cdot P_3 + 4 \cdot P_4 + 5 \cdot P_5 \quad (7)$$

The result of calculating the weights is within the range from 1 to 5, thus we scale them into the value between 1 and 2 in order to make the weights more reasonable according to the following formula (8).

$$newW_i = \frac{w_i - \min(w)}{\max(w) - \min(w)} + 1 \quad (8)$$

In the equation w_i – is the initial weight, $\max(w)$ – is the maximum value, and $\min(w)$ – is the minimum weight.

In order to compare different indicators, we need to standardize their values. We use the Z-transform standardization method (9).

$$Z_{score} = \frac{x_i - \mu}{\sigma} \quad (9)$$

In this formula, x_i – is the original value of the sample data, μ is the mathematical expectation, and σ – is the standard deviation calculated using formula (10).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \quad (10)$$

The values of the factor are calculated using the formula (11).

$$F = \frac{1}{N}\sum_{x=1}^{N}(Z_x \cdot W_x) \quad (11)$$

In the equation, N – is the number of indicators belonging to a given factor, Z_x – is the Z_{score} of the value of the indicators belonging to that factor, and W_x is the weight of the indicators.

Characteristic values are calculated as the arithmetic mean of the factors related to a given characteristic using formula (12).

$$\mathrm{C} = \frac{1}{N}\sum_{x=1}^{N} F_x \quad (12)$$

The comprehensive city score or city smartness index is obtained by aggregating the values of the characteristics (13).

$$I = \sum_{x=1}^{6} C_x \quad (13)$$

This methodology assumes that each characteristic has an equal impact on the overall result of the city.

It is decided to implement the information system to the above mentioned methodology for the automated process of determining the city smartness.

For the correct operation of IS and data storage, the database with all user data, indicator scores, and results of the investigated cities will be used.

The result of its work is shown in Figure 26.

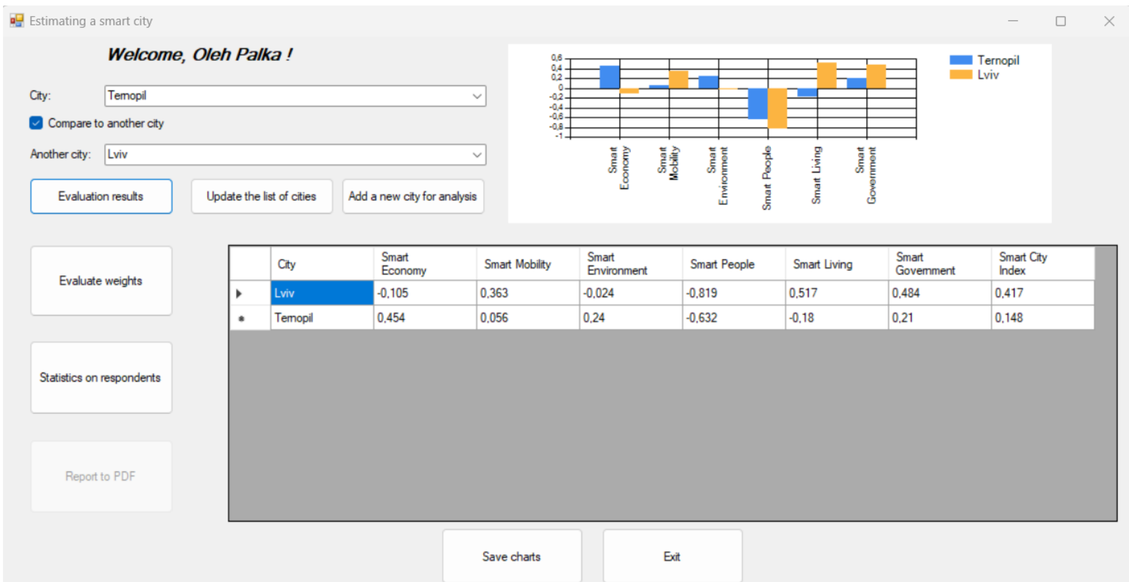

Figure 26: Implementation of the designed information system

The possibility of generating the results of all calculations and determining the city's evaluation by creating PDF file with detailed information has been implemented (Figure 27).

table_of_results_Ternopil_EN

ID	Indicators	X	W	Z_score	Factors	F	Characteristics	C	Smart_City_Index
1	Level of self-employment	85,65	2	1,116	Entrepreneurship	1,769	Smart Economy	0,454	0,148
2	New businesses are registered	83,21	1,333	0,979	Productivity	-0,678	Smart Mobility	0,056	
3	GDP per employee	56,67	1,333	-0,508	Labor market flexibility	0,27	Smart Environment	0,24	
4	Unemployment rate	41,32	1,222	-1,369	Local and international accessibility	0,632	Smart People	-0,632	
5	Specific gravity in part-time employment	95,36	1,333	1,66	Availability of ICT infrastructure	-0,304	Smart Living	-0,18	
6	Public transport network per capita	98,02	1,111	1,809	Sustainable, innovative and safe transportation systems	-0,158	Smart Government	0,21	
7	Satisfaction with access	49,46	1,111	-0,912	Attractive natural	0,509			

Figure 27: PDF file with evaluation results

You can see that Ternopil is ahead of Lviv in terms of evaluation. However the accuracy of the results depends directly on the number of surveyed city residents and their ratings for each criterion.

7. Conclusions

Thus, these methodologies and the designed information system make it possible to evaluate the cities smartness for their comparison and determination of their strengths and weaknesses of each of them.

As we can see from the results of the investigation, almost all system analysis methodologies and the designed information system make it possible to carry out comprehensive or almost comprehensive evaluation of the city smartness, and Ternopil is the winner.

Further investigations will be focused on the surveys of Ukrainian cities residents and obtaining more accurate results, on the basis of which the information dashboard with analytics will be designed.

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