The use of the Analytic Hierarchy Process in Determination of the Design Solution for Vertical Gardening

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Abstract. The researches cover the methodological basis for formation of vertical gardening (landscaping) of building facades in the concept of landscape architecture, ecology of vertical gardening, green construction technologies and measures aimed at the improvement of the energy efficiency of buildings. The ‘Tree of Objectives’ is substantiated, which determines contemporary fields of development of green facades. For the first time, a methodology for choosing variants of the project design and technology solution of vertical gardening is proposed. In the work, multi-factor landscape ecological analysis is used; the analytical method of system analysis – the Analytic Hierarchy Process – is discussed. The author of the method is Thomas L. Saaty (USA), who represents the structure of a practical decision as a hierarchy, with further decomposition of the problem into more simple elements, and further, in the processing of the sequence of judgments of a decision maker on the basis of comparing elements to each other two at a time. In result, the intensity of interaction between elements in the hierarchy is described, and then, the judgments are expressed numerically. The method includes the procedures of synthesis of multiple judgments, of obtaining priority ranking of criteria, and finding alternative solutions. The proposed method for evaluation of a group of factors is universally applicable and can be easily used in practice, and also is the basis for preliminary selection of urban environment factors for creation of a comfort environment in the course of realization of landscape ecological properties of vertical gardening. The use of the system analysis method allows solving the analytical problem of choosing a design solution for vertical gardening system.

1. Introduction
Considerable experience has been gained in the world practice of engineering, construction and operation of buildings in the direction of Energy Performance of Buildings using elements of architectural planting.

The use of landscape solutions for vertical gardening of buildings’ panes attracts interest, because it can reduce energy costs and improve the environment. For regions with a sharply arid climate, including the city of Volgograd, the aim to improve environment is becoming an important energy-saving measure, where green construction takes an active role. Techniques for vertical gardening of panes (shading, wall cooling) are directed to creating favorable living conditions for citizens, and can be significantly increased by a reasonable plant selection.
In modern cities, vertical gardening is widely applicable both for the panes of low-rise and medium-rise buildings, as well as for high-rise buildings and structures and their internal spaces – atriums. Landscaping techniques for the walls of buildings and structures may vary - complete, partial and accent wall coating. The choice of techniques depends on the project challenge, architectural design of the building and the environmental conditions of the territory.

Various design and technology solutions of buildings facades are used for arrangement of vertical gardening. With the purpose of choosing an optimum design solution, it is possible to use the analytical method of system analysis – the analytic hierarchy process.

1.1. Research objectives
The purpose of the research is the substantiation of the use of the analytical method of system analysis – the analytic hierarchy process – in choosing the project design and technology solution of a building’s facade for arrangement of living walls in the concept of vertical gardening.

Research objectives:

- development of objectives of landscape-ecological approach in the designing of a vertical surface gardening model with the use of the ‘tree of objectives’;
- development of the structural model of choosing a variant of design and technology solution for building’s facade vertical gardening;
- choosing a variant of design solution with the use of the analytic hierarchy process.

1.2. Practical and theoretical foundation of research
The research of the general and complex problems of the formation of the green concept of the city, development of vertical gardening systems (VGS) is based on scientific research from the different perspectives. In this paper, the architectural planting is considered as the basis for sustainable development of the city. The authors recognize the concept of architectural planting or sustainable architecture as the style of buildings constructed in accordance with the principles of environmental protection. Scientists note that architectural planting seeks to minimize the amount of resources consumed during the construction and operation of a building. Living wall techniques can become a part of a sustainable city strategy, and green vertical surfaces bring significant environmental, social and economic benefits to urban areas [1, 2].

The issues related to the application of energy-saving technologies and methods for improving the energy efficiency of buildings attract attention when using landscape solutions (vertical gardening of the southern panes of buildings and landscaping of roofs), which can reduce energy costs [3]. Vertical gardening is considered here as a passive tool for energy saving of a building. The aspects that should be taken into account when working with VGS (classification systems, various working mechanisms, green storm infrastructure) are being clarified [4]. The examples of design proposals for energy saving due to landscaping cladding, green spaces and for historic buildings are made [5, 6].

The multiplicity of design solutions variants sets the objective of considering alternative variants in different aspects of the formation of a comfort environment in the realization of landscape and ecological properties of vertical gardening: improvement of the microclimate; high rain water accumulation capacity; mitigation of the insular heat accumulation effect; energy saving thanks to insulation against wind, heating or cooling effect in the process of evaporation, absorption of noise; improvement of the air quality (some plants can partially capture fine dust); optical valorization of unattractively looking facades and walls; contributes to the decrease of the stress level; protection against graffiti; creation of a living space for fauna and flora, etc.

The use of the system analysis method allows solving the analytical problem related to choosing a design solution for vertical gardening system.

2. Materials and Methods
2.1. Creation of the “objective tree” for the vertical gardening

The theoretical part of the research is to develop the tasks of landscape-ecological approach of designing a model of the vertical greening plane, to define the concept of comfortable landscaped environment when choosing the types of formation of vertical gardening of the panes of the building and the selection of dendrological content in plants for landscaping.

Firstly, the environmental problems of high-rise construction (consumption of excess amount of energy, expulsion of vehicles attracted by a high-level object, collection and disposition of garbage, negative hydraulic impact, artificial lighting at night, influence on changing climatic conditions, shading of a large area, influence on the person, change of the wind conditions, negative influence of panes on birds) were analyzed and the property package which are neutralized by vertical gardening is defined.

Further research actions were aimed at solving the problems of development of the “objective tree”, required for the formation of a comfortable environment in the implementation of landscape-ecological properties of vertical gardening: improvement of the microclimate, high cumulative capacity of rain water; reducing the effect of island heat accumulation; energy efficiency due to isolation against wind, thermal insulation or cooling effect during evaporation; noise absorption; improved air quality (some plants may partially catch fine dust); optical valorization of unattractive panes and walls; contribution to stress reduction; protection against graffiti; creation of life space for fauna and flora, and etc.

The discovered objectives and tasks allow us to determine the whole range of measures for the formation of comfort of the environment using various technologies of vertical gardening Figure 1.

![Figure 1. The “objective tree” for development of the vertical gardening of the buildings.](image)

When choosing a design and technology project solution, the problem of identification of a multiplicity of factors and of the selection of significant factors is solved.

With the purpose of choosing an optimum design solution, the analytical method of system analysis – the analytic hierarchy process – is used. This method was used by the author in the scientific work [7] dedicated to the study of the impact of transport noise on the formation of acoustic environment in the area of transport intersections, in particular, to the development of a structural model on the basis of the method, which enables to carry out the evaluation of a group of factors influencing the sound level, and to make adequate decisions related to the selection of significant factors.

The method lies in the decomposition of the problem into more simple elements, and further, in the processing of the sequence of judgments of a decision maker (DM) on the basis of comparing elements to each other two at a time. In result, the intensity of interaction between elements in the hierarchy is described, and then, the judgments are expressed numerically. The method includes the procedures of synthesis of multiple judgments, of obtaining priority ranking of criteria, and finding alternative solutions.
At the first stage, most important elements of a problem are identified, at the second, the best way for verification of observations, of testing and evaluation of elements is identified, and the next stage is the development of a way for implementation of a decision and for evaluation of its quality. The use of a mathematical model allows evaluating the results of making decisions and their consequences. The process of the search for an optimum solution is carried out according to the principle of hierarchy: results obtained at a level are used as input data for the next level. The analytic hierarchy process systematizes the process of finding a solution for such a multi-stage problem [7, 8].

The basis for modeling of the process is formed by principles of identity and decompositions, by principles of discrimination, comparative judgment and synthesis [8]:

Stage 1: The objective is formulated which defines the problem, and then the decomposition is made, its breakdown into smaller objectives.

Stage 2: Criteria are selected, according to which the optimum variant of problem solution is selected;

Stage 3: Generation of alternatives: a certain set of alternatives (objects) is selected for further evaluation.

After the hierarchical description of the problem in the form of a structural diagram, it is necessary to set priorities of criteria and to evaluate each of the alternatives with taking into consideration all criteria, and to identify the important one.

After the decomposition is made, the problem of choice is divided into three hierarchic levels. The hierarchy is considered to be full if each element at a given level functions a criterion for all elements of the lower level [7, 8]. After the problem is hierarchically described in the form of a structural diagram, priorities of criteria values are set, and each of the alternatives is evaluated with taking into consideration all criteria. As objects for carrying out the analysis, variants of design and technology solutions for vertical gardening were chosen. The hierarchical representation of the group of factors evaluation model is built from the top (the objective is set from the point of view of management), through intermediary levels to the lowest level which is a list of alternatives – variants of solutions for vertical gardening. In the model, a full dynamic hierarchy was created, in which each element of a given level functions as a criterion for elements of the lower level.

With the purpose of implementation of principles of discrimination and comparative judgments, elements of the problem are compared pair-wise using the comparison matrix (Figure 2).

![Figure 2. Matrix of binary comparisons.](image_url)

Let us assume that A_1, A_2, A_3,....., A_n is a set of n elements, and w_1, w_2, w_3,.....,w_n are their corresponding weights or intensities. Here, the i-th row represents the ratio between weights of i-th criterion and all criterions (that is, a binary ratio). This matrix has reversed symmetry properties. If values of w_1, w_2, w_3,.....,w_n are unknown in advance, binary comparisons of elements are carried out with the use of subjective judgments numerically evaluated according to a certain scale. For carrying
out subjective binary comparisons, the classic scale of comparative significance is used [8]. The number of comparison matrixes has to be equal to the number of criterions.

The next stage of implementation of the method is the procedure of synthesis of vectors of local priorities. From a group of binary comparison matrixes, a set of local priorities is formed, which represent the relative influence of a set of element on each element of the above adjacent level. Using known methods of analytical planning, it is possible to obtain a column of relative significances (or own vectors of priorities) of each criterion of the system in relation to all other criterions [8]. The last stage of the analysis is the application of the procedure of synthesis of integral priorities’ vectors. Local priority vectors are multiplied by priorities of relevant criterion at a higher level and are summarized for each element according to criteria influenced by relevant element. This procedure gives a global priority vector for each element.

The method lies in the decomposition of the problem into more simple elements, and further, in the processing of the sequence of judgments of a decision maker (DM) on the basis of pair-wise comparison of elements. In result, the intensity of interaction between elements in the hierarchy is described, and then, the judgments are expressed numerically. This method includes procedures of synthesis of a set of judgments, obtaining priorities of criteria, and identification of alternative solutions.

Alternatives, among which the best variant is chosen, are compared to each other with the use of comparison matrixes. It should be mentioned that such way of filling of matrixes is possible in case if there is a comparison scale in place, that is, there is a way for measuring criterions (as a rule, at the Level 3 of the hierarchic model).

When filling matrixes at Level 2, the cells are filled with evaluations obtained in result of subjective but thought-over numerical judgments of the author about qualitative characteristics of objects. But, often a part of structural components of a group of criteria cannot be given a quantitative description, and there only are qualitative methods of their evaluation. Because of that, classic scale of comparative significance is used for carrying out subjective binary comparisons.

When carrying out binary comparisons, it is necessary to give an evaluation, what is better, what is worse, and to what extent. Because quality characteristics of system elements will have to be compared, a value has to be assigned to a quality of an element and compared with that value of other elements which have numerical values. The efficiency and the relevance of the used nine-grade scale have been proven theoretically when it was compared with many other scales, and is successfully used by many researchers [8].

The next stage of implementation of the method is the procedure of synthesis of local priorities’ vectors. From a group of binary comparison matrixes, a set of local priorities is formed, which express the relative influence of a set of elements on an element of the above adjacent level. Using known methods of analytical planning, a row of relative significances (or own vectors of priorities) can be obtained for each criterion of the system in relation to all other criterions [8, 9].

One of the best techniques [9] is the calculation of the geometrical mean for a row corresponding to the criterion. Priorities are calculated using matrix rows according to the following algorithm:

1) all elements in matrix rows are multiplied together, and an n-th root is extracted from the product (where n is the dimension of the matrix), and the geometrical mean is obtained for each row

\[ \sqrt[n]{a_{11}a_{12}a_{13}...a_{1n}} = x_1 \]  

\[ \sqrt[n]{a_{21}a_{22}a_{23}...a_{2n}} = x_2 \]  

\[ \sqrt[n]{a_{n1}a_{n2}a_{n3}...a_{nn}} = x_n \]  

2) all \( x_i \) are summarized
\[ S = x_1 + x_2 + x_3 + \ldots + x_i + \ldots + x_n \]  

(2)

3) A normalized vector of priorities is obtained with elements \( X_1 = x_1 / S, X_2 = x_2 / S, \ldots X_n = x_n / S \).

Obtained values \( X_i \) are quantitative characteristics of hierarchy elements within relevant level, and are called components of local vector of priorities. They determine relative weights of elements of the system’s structure and are the numerical basis for description of the problem at this level of progress towards the goal.

The degree of consistency of the comparison matrix is determined by the Consistency Index (CI) which is calculated in the following way:

- first, each column of the judgment matrix is summarized;
- the sum of the first column of the matrix is multiplied by the value of the first component of the normalized vector of priorities;
- the sum of the first column is multiplied by the value of the second component, etc.;
- then, the values obtained are summarized.

\[
\begin{bmatrix}
    a_{11} & a_{12} & a_{13} & \ldots & a_{1n} \\
    a_{21} & a_{22} & a_{23} & \ldots & a_{2n} \\
    \vdots & \vdots & \vdots & \ddots & \vdots \\
    a_{n1} & a_{n2} & a_{n3} & \ldots & a_{nn}
\end{bmatrix}
\begin{bmatrix}
    X_1 \\
    X_2 \\
    \vdots \\
    X_n
\end{bmatrix} =
\begin{bmatrix}
    a_{11}X_1+a_{12}X_2+a_{13}X_3+\ldots+a_{1n}X_n \\
    a_{21}X_1+a_{22}X_2+a_{23}X_3+\ldots+a_{2n}X_n \\
    \vdots \\
    a_{n1}X_1+a_{n2}X_2+a_{n3}X_3+\ldots+a_{nn}X_n
\end{bmatrix}
\]  

(3)

In such a way, we receive an important characteristics of the judgments’ matrix \( L_{\text{max}} \). The consistency index is calculated as follows:

\[ \text{CI} = (L_{\text{max}} - n)(n-1)^{-1} \]  

(4)

where \( n \) is the number of compared elements.

Average random consistencies (SS) for average matrixes are shown in Table 1.

| Matrix Size | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  |
|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| SS          | 0.0 | 0.0 | 1.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45| 1.49|

If we divide the value of the CI by the number corresponding to the random consistency of a matrix of the same size, we will obtain the Consistency Ratio (CR). The value of the Consistency Ratio (CR) has to be 10% of the CI or lower. In certain cases, 20% can be assumed, but not more. The quality of judgments, their logical consistency is valuated according to the value of the Consistency Index (CI), of \( L_{\text{max}} \) or of the Consistency Ratio (CR). If there are no controversial statements, then \( L_{\text{max}} = n, \ CI < 0.3 \), and CR 10% IS [8, 9].

The next stage is the procedure of synthesis of local priorities’ vectors. Local priorities’ vectors are multiplied by priorities of relevant criterion at the upper level and summarized for each element according to criteria which are influenced by this element. This procedure gives a global priority vector for an element.

In such a way, the method for quantitative determination of relative significance of quality factors is determined, which is very important, because some of criteria of a group of factors practically cannot be numerically assessed, and that was the basis for the use of the Analytic Hierarchy Process for substantiation of the method for evaluation of a group of factors and parameters [10]. The proposed evaluation method of a group of factors is quite versatile and can be easily used in practice, and also is the basis for preliminary selection of factors and further selection of the project variant of the design and technology solution for vertical gardening of horizontal and vertical surfaces of buildings and constructions.

3. Results
Design task has been considered and solved for the urban territory of Volgograd as part of the solution to the problem of vertical gardening of building facades in the context of reconstruction of buildings and providing comfortable living conditions.

As a result of field surveys, observations and mathematical calculations, quantitative and qualitative estimates of the parameters of each group of factors are obtained. The obtained hierarchical model includes three levels, each of which is divided into sub-levels (Figure 2). A dynamic hierarchy is created in the model in which each element of a given level functions as a criterion for all elements of a lower level. As a result of the analysis, 16 matrices of judgments were obtained, in which the degree of influence of the components of the group of factors — natural and climatic, agrotechnological and safety factors — was assessed: at the sub-level 2.1 - 5, the criterion for assessing natural and climatic factors; at a sub-level 2.2 - 5 criteria for assessing agrotechnological factors; at sub-level 2.3 - 3 criteria for assessing safety factors and 3 types of design and technological solutions, which were compared in pairs according to each of the criteria. The correctness of the obtained characteristics, as well as the quality of the reasoning, their logical completeness are estimated by the value of the conformity index (CI) [7-9], the characteristic of the reasoning matrix Lmax and the conformity ratio (CR) which value does not exceed 10% of the CI [7-9]. Vectors of integrated priorities for environmental, climatic, agrotechnological and safety factors, calculated for each of the 3 types of design solutions, were the data for compiling matrices of significance pair relationships according to criteria of a group of factors at levels 2 and 3 of the hierarchy. Vector processing was carried out in Microsoft Excel, which allowed us to rank the objects under study (Table 2).

Table 2. Integral indicator of the influence of a group of factors on the choice of a design and technological solution for vertical gardening of the facade at the stage of its reconstruction.

| Bike lane objects | Assessment of a group of factors that influence the choice of design and technological solutions | Integrated priorities | Rank |
|-------------------|-------------------------------------------------------------------------------------------------|-----------------------|------|
| Design and technological solution 1 | 0.654 | 1 |
| Design and technological solution 2 | 0.112 | 3 |
| Design and technological solution 3 | 0.234 | 2 |

An assessment of the factors showed that the optimal design and technological solution for vertical gardening is design and technological solution 1 (rank 1), a group of natural and climatic, agrotechnological factors have the greatest influence on the choice of design solution, Figure 2. The optimal option is a bearing support with a metal grid - a system of metal mesh - a closely interwoven mesh of aluminum or light steel cables, attached to the facade using brackets.

Selection of vegetation for vertical gardening was carried out using the "green constructor" system, including the names of spaces that meet environmental, aesthetic and dendrological requirements (drought-resistant, beautifully flowering, with high phytoncide properties, effectively reducing noise levels, resistant to smoke and gas), used in the formation of a greened wall. Principles of plant selection: growth rate, unpretentiousness, drought and smoke resistance, winter hardness, light regime and the ability to survive the conditions of the city.

4. Conclusions
1. The design of city facades gardening is aimed at improving the living conditions, human health and the restoration of the ecological landscape;
2. The proposed method for assessing a group of factors is universal and easily applicable in practice; it can be the basis for preliminary selection of factors and determination of mathematical dependencies. The study has continued to address the issues of designing vertical gardening, focusing on the integrated use of various structural and technological
solutions for vertical gardening and assessing the degree of safety for human health of living conditions and stay in buildings and structures.

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