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CONCEPTUAL FOUNDATIONS OF THE EXPERT SYSTEM OF BIOCLIMATIC MODELING

The article is devoted to the theoretical substantiation of the structure of the Expert System for Bioclimatic Modeling and the disclosure of its functioning mechanisms. The main goal is to develop the conceptual framework of an expert system as an innovative tool to support analytical and creative decision-making in architectural design. The system is designed to integrate a variety of multi-parameter data, including climatic conditions, characteristics of architectural objects, etc. to generate optimal bioclimatic recommendations.

In the course of the study, a set of scientific methods was used to develop the structure of the expert system. System analysis was used to identify the key components of the system and their interrelationships. Cluster analysis was used to develop the structure of the knowledge base for effective organization and systematization of information. Information system modeling techniques were used to develop a model of interaction between the expert system modules, including the database, rule base, and solver. Expert evaluation methods were used to fill the knowledge base and evaluate the parameters of design decisions. A multi-criteria approach was used to process fuzzy data and make decisions in the face of the complexity and multiplicity of bioclimatic modeling criteria.

The results of the study present the conceptual structure of the expert system, where a hybrid knowledge base combining declarative and procedural knowledge, a modular database structure, the use of the heuristic method "IF-THET" in the rule base, and a hierarchical system based on a decision tree are proposed to effectively process complex information and generate optimal bioclimatic recommendations. Further research is planned to focus on the practical implementation and validation of the developed system, expanding its functionality by integrating with other design tools, and using machine learning methods to automatically update the knowledge base.

Keywords: expert system; bioclimatic modeling; knowledge base; energy efficiency; passive technologies; artificial intelligence.

Problem Statement. The formation of a global information environment - encompassing the entire sphere of activity for individuals, human groups [1], and artificial organisms (intelligent systems) [2] - is realized in design through the implementation of engineering technologies that significantly expand architects' capabilities. The shaping of bioclimatic buildings is based on a comprehensive analysis of climate adaptation to achieve an optimal balance between internal and external environments. The effectiveness of bioclimatic design solutions directly depends on detailed analysis of climatic parameters. To ensure reliability and convenience in modeling these parameters, developing specialized tools for optimizing their integration is essential. Modern design technologies (CAD, CAM, CAE) automate processes but inadequately integrate ecological and climatic aspects. Despite advanced BIM (6D, 7D) and GIS functionalities, their application to bioclimatic design tasks remains hindered by high costs and technical complexity. The advancement of artificial intelligence systems opens new possibilities for bioclimatic modeling. However, it requires systematization of expert knowledge and adaptation to designers' practical needs through creating a knowledge base and developing an architecture for expert bioclimatic modeling systems.

Analysis of Recent Research and Publications. Computer-aided design (CAD) systems are widely used in contemporary architectural design. Through network technologies, CAD systems gain real-time access to databases and automate the life cycle of construction projects. [3, 4] However, current CAD systems do not fully integrate eco-design functions such as energy efficiency or consideration of climatic conditions. Building Information Modeling (BIM) technology enables the creation of three-dimensional models of buildings with geometric, physical, and functional characteristics, as well as controlling construction in terms of time and costs. [5] Improvements in BIM include 6D modeling (energy efficiency and environmental performance) and 7D modeling (lifecycle management of a facility).[6] Despite this, the implementation of 6D and 7D dimensions faces challenges related to software realization, high costs, and insufficient consideration of natural and climatic factors. Geographic Information Systems (GIS) accumulate spatial data, and a modern trend is the attempt to integrate them with high-cost BIM solutions to account for local natural conditions. [7] However, in the practical work of designers, there is a need to create an accessible decision support system for analytical and creative tasks based on multiparametric data, which simultaneously integrates natural and climatic factors, eco-design, a comfortable environment, and energy performance for design needs. Artificial intelligence (AI) systems can serve as such systems, significantly expanding the possibilities for design automation.

Expert systems (ES), as a tool of artificial intelligence, are used to solve complex multiparametric problems. The definitions of concepts, principles, purposes, development stages, structure, and functioning of various expert systems have been considered in many specialized studies. Recent research highlights the effectiveness of ES in forecasting, classification, processing of imprecise information, and educational processes. [8, 9] The theoretical possibility of creating applied expert systems for design, for example, for landscape design, is discussed in [10]; for solving multiparametric modeling tasks in civil engineering [11]; in the field of energy conservation and sustainable natural resource use, it is presented in [12], where a model for deriving bioclimatic recommendations is also proposed. The practical application of ES in the educational process has been studied in [13, 14, 15].

Examples of software implementation of expert systems in construction include G2 Gensym ES; in environmental monitoring-Exsys Corvid ES; for selecting tree seeds based on climatic conditions-WebFlex ES. [16; 17; 18] However, existing expert systems do not cover the majority of aspects of bioclimatic modeling, which necessitates the creation of systems that utilize the results of theoretical research, design practice, and artificial intelligence systems as the foundation for the knowledge base and inference mechanism of a Bioclimatic Modeling Expert System (BMES), as well as the subsequent development of a functioning software product.

In summary, expert systems consist of a knowledge base and an inference engine, which, according to the aforementioned researchers, determines their effectiveness in solving complex problems. Despite progress in the development of expert systems and bioclimatic modeling, there remains a need for integrated solutions that provide comprehensive decision support. Many existing systems focus on individual aspects of design without considering bioclimatic factors. This study proposes an architecture for an expert system for bioclimatic modeling that integrates bioclimatic factor analysis with artificial intelligence tools to enhance decision-making.

Purpose of the Article. The aim of this study is to theoretically substantiate the structure of the Bioclimatic Modeling Expert System (BMES) and its operational mechanisms. The research relevance lies in developing the foundational principles of BMES decision support system for analytical and creative tasks that integrates multiparametric data (climate, architectural object elements, materials, environmental standards) to generate optimal bioclimatic recommendations. This integration aims to reduce resource costs and enhance design quality.

To achieve this goal, the following tasks have been defined:

1. Identify the key structural components of BMES (database, rules, and decision-making algorithms).

2.Justify the necessity of accounting for climatic, energy performance, and other interrelated factors.

3. Develop a model for system module interaction (database, rule base, inference engine).

4.Investigate the process of generating bioclimatic solutions.

The novelty of the research lies in the development of the BMES structure, capable of analyzing, classifying and predicting optimal bioclimatic solutions for architectural design tasks. The system's core comprises a knowledge base that structures data, facts, rules, and other information, alongside an inference engine used to solve bioclimatic modeling challenges. To address the scientific task of developing BMES's framework, the following methods were employed: systemic analysis, cluster analysis, information system modeling, expert evaluation methods. A multicriteria approach was applied to handle fuzzy data during the study of module interaction within the expert system.

Main Part. In the practice of design based on bioclimatic modeling principles, there is a clear need for an accessible decision support system that integrates multiparametric data, including natural and climatic factors, energy efficiency indicators, environmental performance, and functionality. One promising approach to addressing this challenge is the use of expert systems (ES).

An expert system is a software complex that, based on a knowledge base containing expert experience and rules for its application, can provide recommendations or solutions for complex professional tasks. The purpose of developing a Bioclimatic Modeling Expert System (BMES) is to create a tool for supporting optimal design decisions that take into account the requirements of bioclimatic modeling.

Conceptually, the Bioclimatic Modeling Expert System has a classical structure, comprising two main components: a knowledge base and an inference engine.

The BMES knowledge base has a hybrid structure that combines declarative and procedural knowledge. Declarative knowledge is presented as structured information about the subject area and includes facts, concepts, and relationships among them. This information is stored in a database organized according to a modular principle, with dedicated clusters for design. Procedural knowledge is represented as rules, algorithms, and procedures that describe how to use declarative knowledge to solve specific tasks and is stored in the rule base. The rule base contains a set of rules and heuristics that define logical relationships between facts in the database. These rules are used by the inference engine to derive new knowledge and make decisions. The inference engine analyzes facts and performs logical inference based on information from the database and rules from the rule base, using search strategies and inference methods to find solutions in a manner similar to expert reasoning.

In BMES, the decision selection algorithm narrows the search space using cluster analysis and aggregates criteria to rank alternatives. This structure enables the system to accumulate, update, and use expert experience necessary for bioclimatic modeling, thereby supporting decision-making with high accuracy and efficiency.

The database structure includes several clusters, each serving as a separate information block. The "Climatic Characteristics" cluster contains data about climate as the long-term weather regime observed in a specific area (combinations of temperature, humidity, precipitation, wind direction and speed, etc.). In bioclimatic design, it is advisable to assess climatic impacts and loads from generalized macroclimatic indicators (meteorological conditions over large planetary-scale areas with similar climatic characteristics) to background conditions-mesoclimate (climatic features of territories with relatively uniform conditions, such as regions, cities, or city districts)-with further refinement at the level of local site data assessment, i.e., its microclimate.

The "Design Objects" cluster provides for the classification of objects according to their functional purpose (residential, public, industrial, etc.) and the structural elements of architectural objects (walls, transparent structures, roofs, and others). This facilitates the systematization of data for further analysis and modeling in accordance with bioclimatic principles.

The "Design Solutions" cluster contains a list of possible design options to ensure efficiency under various climatic conditions. This cluster is divided into sections: building placement and spatial planning solutions; structural solutions and building materials; engineering systems; and natural elements. The following are examples of some sections within this cluster.

The "Building Materials" section includes data on materials and their parameters. Examples from the database include the thermal performance characteristics of building materials and regulatory requirements for thermal resistance in a given region. The database also contains recommendations for material usage (for example, in hot climates, materials with high thermal resistance coefficients are recommended for sun-facing orientations, while materials with low coefficients, such as glass, are suggested for northern orientations). The section encompasses information on the use of both traditional and modern building materials that are locally available and commonly used in specific regions.

An important section of the cluster is "Engineering Systems," which contains information on solutions for natural ventilation, passive and active heating and cooling systems. Examples from the database include natural ventilation systems (stack effect); Trombe walls, wind towers and their descriptions; double-skin facade systems and their effective use for ventilation; designs for open building elements (verandas, canopies) for additional natural cooling or solar heating in winter; and descriptions of traditional local passive system solutions (such as Chinese multifunctional courtyards as elements of heating, ventilation, and cooling systems).

The "Natural Elements" section of the cluster pertains to information regarding the use of natural features such as vegetation (trees, shrubs, green roofs and walls), water bodies, and more, as elements influencing climatic parameters for their improvement. Examples from the database include options for placing water bodies near buildings; the use of tall trees for shading and improving the site microclimate; the application of green roofs and walls that provide thermal insulation and create green spaces in any climate zone; and green facades that protect from sun and wind, produce moisture, serve as sound insulation, and increase local humidity.

The data on elements within the clusters are organized as interconnected tables, which enables rapid search and retrieval of the required information. For each element of the database cluster or its parameters, a special information assessment procedure is used with the involvement of subject-matter experts. The following methods are applied: analysis of bioclimatic project implementation experience; comparison of the proposed solution with existing standards and requirements; and expert evaluation of the cluster element based on their knowledge and experience. The qualitative parameters of cluster elements obtained in this way are encoded as numerical values for further processing. For example, the building form is encoded by a numerical value, where the highest score is assigned to the building that best aligns with the bioclimatic approach. Dynamic changes in the external environment (such as changes in wind speed, direction, or temperature) are encoded with additional values, allowing the system to adapt recommendations to climatic influences. The system also accounts for fuzzy concepts (for example, comfort or wind protection), which are difficult to assess precisely; this means that the "wind protection" parameter can range from "unprotected" to "fully protected," with each value assigned a specific numerical expression. Based on these data and combinations of rules, the inference engine determines the overall compliance of an object with bioclimatic requirements.

Thus, the structure of the bioclimatic modeling database corresponds to the generally accepted object-oriented programming template, particularly the concepts of multiple inheritance and nesting, which confirms the validity of the chosen approach for building the expert system. For example, there are base elements, and derivative elements can be formed that add new parameters to the base ones. In this case, the new element inherits all the main parameters of the base element, requiring only those parameters that distinguish it from the base. For instance, the main element in the "Design object" cluster -roof -has derivative elements such as geometric roof shapes: pitched, curvilinear, or others.

An important component of the expert system's knowledge base is the rule base, which describes the relationships between input data and output recommendations. The BMES rules define how to make decisions for different combinations of cluster element parameters in the database. The rules link climatic data and the characteristics of the design object by evaluating elements of the "Design solutions" cluster for compliance with bioclimatic modeling criteria, forming a unified decision-making chain.

At the core of the BMES rule base lies the heuristic "IF-THEN" method, where:

- "IF" defines a condition that is checked based on facts from the database;
- "THEN" specifies the action or conclusion to be taken if the condition is met.

Rules in BMES can be expanded with additional conditions and may be either forward or backward. For example: "IF – Condition 1 AND Condition 2, THEN – Conclusion" - a forward rule. Backward rules take the form: "IF – Conclusion, THEN – Conditions 1 AND 2 must be satisfied."

When forward rules are used, the system starts with existing facts in the database and applies rules to derive new conclusions until the final objective (a bioclimatic solution) is reached. An example of a forward rule: "IF the intensity of solar radiation exceeds Y W/m^2 AND the indoor temperature exceeds Z°C, THEN activate the window shading system to reduce solar gain, prevent overheating, and ensure a comfortable microclimate."

When applying backward rules, the system starts from the goal (the bioclimatic solution) and seeks facts that support this goal by using the rules in reverse order. An example of a backward rule in BMES: "IF it is necessary to achieve a comfortable microclimate under conditions of excessive insolation, THEN reduce the window area on the southern façade AND install sun-shading devices (blinds, canopies)."

BMES uses a combined approach, allowing the system to adapt to various situations and achieve optimal results. The rules in the knowledge base are structured to support both forward and backward reasoning, which ensures flexibility and efficiency in system operation. This approach enables the system to consider different scenarios and options for bioclimatic solutions, assess their effectiveness, and select the most optimal ones based on specific conditions and requirements. For instance, when designing buildings in a hot climate, the system may first consider passive cooling methods (natural ventilation, sun protection) and, if these prove insufficient, move on to active systems (air conditioning).

Rules are used by the inference engine to derive new knowledge and make decisions. The inference engine is the core of the system, performing logical reasoning based on information from the database and the BMES rule base, employing search strategies and inference methods to solve the task. It is based on logical expressions that describe the relationships between different parameters.

In the BMES, the concept of a decision tree is used to form a hierarchical inference system. This model predicts the value of a target variable based on input data and consists of "leaves" (target function values) and "branches" (attributes influencing the function). The BMES inference engine uses an attribute selection algorithm based on information gain. Each new attribute at a decision tree node is formed by adding new parameters, which increases or refines the information at each level. This process is inherently hierarchical. The task of selecting a bioclimatic solution during inference is broken down into a series of smaller sub-tasks, each solved at a specific level of the hierarchy. At the top level, the system considers general parameters such as climate zone, building type, material type, and equipment type. At subsequent levels, further detail is added, taking into account specific characteristics of the building, materials, equipment, environment, and other factors. Each decision tree node corresponds to a particular rule or criterion used to select among possible options. The connections are formed through analysis of the object's parameters and their comparison with existing knowledge and rules in the knowledge base. Depending on the result of applying a rule, the system moves to the next node, where other criteria and rules are considered. This process continues until the final node-the optimal bioclimatic solution for the specific design object-is reached.

Thus, the hierarchical inference system in BMES enables efficient organization of the decision-making process, consideration of many interrelated factors, and identification of optimal solutions for complex and multi-factor bioclimatic modeling tasks.

Conclusions and Prospects. As a result of the research, a conceptual structure for the Bioclimatic Modeling Expert System was developed, representing a promising approach to creating an effective decision support system for design based on bioclimatic modeling principles. The core of the system is a hybrid knowledge base that combines declarative knowledge about natural and climatic factors, energy efficiency, environmental performance, and the functionality of design objects with procedural knowledge in the form of rules and algorithms. The proposed modular database structure with the clusters "Climatic Characteristics," "Design Objects," and "Design Solutions" ensures systematic organization and convenient access to necessary information. The use of the heuristic "IF-THEN" method in the rule base enables efficient linking of input data with output recommendations, supporting both forward and backward logical inference. The application of a hierarchical inference system based on decision trees allows the consideration of a large number of interrelated factors and stepwise narrowing of the search space for optimal bioclimatic solutions.

Despite this conceptual foundation, practical implementation and validation of the developed BMES require further detailed study. In particular, the process of populating the knowledge base with expert data and rules are important. This involves expert analysis and integration of data from various sources, including scientific research, regulatory documents, and examples of successful projects, to ensure the completeness and relevance of the information used by the system and to improve the quality of recommended solutions.

Future research prospects include expanding the functional capabilities of BMES by integrating it with other design and modeling tools and adapting the system to different regional climatic conditions and building types. Of particular interest is the exploration of machine learning opportunities for automated updating and enhancement of the BMES knowledge base.

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КОНЦЕПТУАЛЬНІ ЗАСАДИ ЕКСПЕРТНОЇ СИСТЕМИ БІОКЛІМАТИЧНОГО МОДЕЛЮВАННЯ

Стаття присвячена теоретичному обґрунтуванню структури Експертної системи біокліматичного моделювання та розкриттю механізмів її функціонування. Головною метою є розробка концептуальних засад експертної системи як інноваційного інструменту підтримки прийняття аналітичних і творчих рішень в архітектурному проєктуванні. Система покликана інтегрувати різноманітні багатопараметричні дані, включаючи кліматичні умови, характеристики архітектурних об'єктів тощо з метою генерації оптимальних біокліматичних рекомендацій.

У процесі дослідження для розробки структури експертної системи застосовано комплекс наукових методів. Системний аналіз використовувався для визначення ключових компонентів системи та їх взаємозв'язків. Кластерний аналіз застосовувався при розробці структури бази знань для ефективної організації та систематизації інформації. Методи моделювання інформаційних систем були використані для розробки моделі взаємодії модулів експертної системи, включаючи базу даних, базу правил та вирішувач. Для наповнення бази знань та оцінки параметрів проєктних рішень залучалися методи експертних оцінок. Багатокритеріальний підхід застосовувався для опрацювання нечітких даних та прийняття рішень в умовах складності та множинності критеріїв біокліматичного моделювання.

Результати дослідження представляють концептуальну структуру експертної системи, де запропонована гібридна база знань, що поєднує декларативні та процедурні знання, модульну структуру бази даних, використання евристичного методу "ЯКЩО-ТО" в базі правил та ієрархічну систему на основі дерева рішень для ефективної обробки складної інформації та генерації оптимальних біокліматичних рекомендацій. Подальші дослідження передбачається спрямувати на практичну реалізацію та валідацію розробленої системи, розширення її функціональних можливостей шляхом інтеграції з іншими інструментами проєктування та використання методів машинного навчання для автоматизованого поповнення бази знань.

Ключові слова: експертна система; біокліматичне моделювання; база знань; енергоефективність; пасивні технології; штучний інтелект.