УДК 697.1:621.019.3

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https://doi.org/10.32347/2409-2606.2026.58.137-152

# FACTORS AFFECTING THE RELIABILITY OF ENGINEERING SYSTEMS FOR INDOOR MICROCLIMATE CREATION

***Abstract.*** *The article analyses and systematises the factors affecting the reliability of engineering systems for creating indoor microclimates (heating, ventilation and air conditioning - HVAC) and directly influencing indoor environmental parameters in the presence of building envelope defects under conditions of military ecocide. A systems analysis, a comparative study and a scientific generalisation of domestic and foreign regulatory and literature sources in the field of reliability and the extreme operation of critical infrastructure were carried out. A multi-level classification of the factors influencing the reliability of HVAC systems was developed, in which two principal groups are distinguished: objective factors (climatic, anthropogenic, biological and ecological consequences of military ecocide) and subjective factors (errors in design, manufacturing, installation and operation by personnel). The specific features of the operation of process equipment under conditions of a destructive external environment, power supply interruptions, high aerosol, dust and chemical loads, as well as destruction of the building envelope, were investigated. The principal factors affecting the reliability of heating, ventilation and air conditioning systems are the operating conditions and a carefully designed system of maintenance, redundancy and enhancement of the resilience of life-support systems, in particular the implementation of multi-level adaptive filtration, local redundancy and autonomous power supply.*

***Ключові слова:*** *reliability, microclimate, heating, ventilation and air conditioning, military ecocide, building envelope defects, hardware factors, cascade failures, fault tolerance, IoT monitoring, BMS, AFDD, energy efficiency, limited power supply.*

**Introduction.** The full-scale military aggression and the military ecocide it has caused in Ukraine have created unprecedented challenges for the functioning of critical engineering infrastructure, in particular heating, ventilation and air conditioning (HVAC) systems. Ecocide may manifest itself not only in the physical destruction of facilities (residential buildings, combined heat and power plants, water mains), but also in the long-term contamination of territories with toxic substances and with the

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products of combustion and of explosives. Traditional approaches to the calculation and provision of microclimate system reliability do not fully account for the combined action of such factors as:

- physical destruction of system components (blast wave, fragments);
- prolonged interruptions in power and water supply;
- chemical and aerosol contamination of the air and soil, leading to corrosion and failure of equipment (for example, filters and heat exchangers);
- shortage of resources and the impossibility of prompt maintenance in hazardous zones.

This calls for the development of new, resilient engineering solutions capable of ensuring a high-quality microclimate (particularly in shelters, hospitals and temporary modular settlements) under high-risk conditions. The use of multi-level filtration, autonomous power sources and local redundancy, together with video surveillance and automatic control, provides management bodies with up-to-date data for making effective decisions on maintaining the operation of HVAC systems, which is critically important for increasing the resilience of HVAC systems under conditions of military ecocide.

**Relevance of the Study.** Heating, ventilation and air conditioning (HVAC) systems, which are widely used today, account for a significant share (20 – 40 %) of energy consumption and are vital systems under conditions of military ecocide. Malfunction or degradation of HVAC system components leads to a reduction not only in comfort, on the one hand, and to approximately 15 - 30 % of energy losses, but also in the ability to maintain the parameters required for the functioning of buildings such as hospitals or shelters. The development of effective strategies for preventive maintenance, for improving reliability and for restoring the operation of HVAC systems during military ecocide is of great importance. There is therefore a need to systematise all risk factors in order to create fault-tolerant systems of a new generation. Improving the reliability and energy efficiency of HVAC systems is a priority direction and one of the conditions for achieving the sustainable development of Ukraine.

**Recent Research and Publications.** The issues of assessing the reliability, failure-free operation and energy efficiency of engineering systems have been addressed in the works of many domestic and foreign researchers. In most existing studies, the main attention is paid to natural and climatic fluctuations (temperature peaks, seasonal humidity) or to the natural physical wear of equipment components. The analysis of publications shows the direction of research and of the regulatory, legal and standardisation frameworks of Ukraine relevant to the stated problem, in which the action of synergetic (cascade) factors would be considered, where a rise in the concentration of harmful impurities in the outdoor air, destruction of the building envelope and of HVAC systems, and a deterioration of the quality and parameters of

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the power supply occur simultaneously.

Reliability, stability and assessment. Reference [11] governs the methodology for the inspection and determination of the mechanical resistance and stability of buildings, while the sets of documents [2] and [3] establish the principles of structural safety, environmental protection and civil protection throughout the entire life cycle of facilities. Functional purpose and civil safety. Reference [4] sets out the requirements for civil protection structures (shelters), [6] for healthcare establishments, [5] and [7] for public and residential buildings, and [1] establishes general fire prevention requirements. Microclimate parameters, HVAC and energy efficiency. References [8] and [9] set out modern requirements for HVAC design, thermal insulation and energy efficiency.

Reference [10] regulates the sanitary and hygienic limits of the microclimate in the industrial sphere. Standards [14], [12] and [13] specify indoor air quality and thermal comfort indicators and methods for calculating air exchange with allowance for infiltration. The dissertations [16] and [17] address the problems of ensuring the microclimate during emergency heat supply outages and the assessment of the dynamic operating regimes of building envelopes and systems. Experimental studies [15] are devoted to the thermal regime of rooms when alternative ceramic heating panels are used. Foreign studies [18], [22] and [23] address the application of machine learning algorithms, data analytics and combined models for the real-time detection of HVAC system faults. The works [20], [19] and [21] investigate the influence of long-wave and optical radiation, the urban heat island and global warming on building energy consumption and on the physical condition of the human body.

The analysis of the literature indicates the absence of comprehensive studies in the field of the reliability of heating, ventilation and air conditioning systems, particularly under conditions of military ecocide, which provides the basis for formulating the objectives of the article with a view to developing a structural diagram of a multi-level classification of the factors affecting the reliability of heating, ventilation and air conditioning systems.

**Statement of the objectives of the article.** The aim of the article and the scientific novelty of the work consist in carrying out a systems analysis and a systematisation of the factors that affect the reliability of engineering systems for creating indoor microclimates (HVAC) and directly influence indoor environmental parameters in the presence of defects of the building envelope and of HVAC systems under conditions of military ecocide, and in developing a detailed structural diagram of a multi-level classification of the factors affecting the reliability of HVAC systems.

**Main body.** The reliability of engineering systems for creating a microclimate is their ability to perform specified functions while maintaining their performance indicators within established limits over the required period of time [3].

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A probable disruption of normal living conditions lasting more than three days constitutes a potential hazard to human life and activity, in accordance with [3].

The set of factors that determine the reliability of engineering systems for creating indoor microclimates is conventionally divided into two large groups: hardware (technical) factors, which depend directly on the condition of the equipment itself and its components, and non-hardware factors, which arise outside the sphere of equipment design and manufacture but critically affect its functional reliability. According to another classification, these factors are divided into objective factors (external and internal environmental conditions), including military ecocide, and subjective factors (human error at the design, manufacturing or operation stages).

In the context of microclimate systems, reliability comprises the following key aspects:

Continuity of operation: the ability of the system to maintain microclimate parameters (temperature, humidity, air velocity) without unplanned shutdowns, which is particularly important for engineering systems that create indoor microclimates. Fault tolerance is the minimisation of the risk of failure through the use of multi-level redundancy of components and autonomous power sources.

Diagnostics and forecasting: the modern approach to reliability envisages not only recording damage, but also forecasting the risks of its development by means of IoT (Internet of Things) systems, AFDD (Automated Fault Detection and Diagnostics) and BMS (Building Management System).

All factors affecting the reliability of HVAC systems may be subdivided into two groups: objective factors and subjective factors. The group of objective factors includes operational, climatic and biological factors. The group of subjective factors includes human errors during design, manufacture and operation. The factors that determine the reliability of HVAC systems at the design and manufacturing stages include: the choice of circuit and schematic solutions, the choice of components and their operating regimes, the choice of structural solutions, the selection of and adherence to the manufacturing technology, the automation of production, the burn-in of components and equipment, quality control, and so forth.

The reliability of engineering systems for creating a microclimate is affected by the codes and rules with which they must comply. The design, installation and operation of engineering systems for creating indoor microclimates (heating, ventilation and air conditioning - HVAC) in Ukraine are governed by a comprehensive hierarchical system of regulatory documents. Modern HVAC engineering calculation, which affects the reliability of engineering systems for creating indoor microclimates, is based on obtaining the initial architectural data, selecting the target comfort category according to the European classification, integrating the specific requirements associated with the intended use of the building, and mandatory compliance with fire

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safety restrictions and with the other challenges posed by military ecocide [1 - 14].

According to statistical data, 30 % of the decline in reliability is attributable to such factors as: operating time, electrical regimes, ambient temperature, humidity and atmospheric precipitation, reduced pressure, solar and other types of radiation and various kinds of airborne impurities, mechanical loads (overloads, impacts and vibrations, explosions), biological factors (fungi, mould, insects and rodents), the activity of maintenance personnel (qualifications, the performance of preventive measures, the organisation of operation, the availability of operating instructions for the given type of equipment), and so on.

Operating time is one of the principal factors determining reliability at all stages of the project life cycle. Technological and design deficiencies most often become apparent during the initial period of operation, when the failure rate is many times higher than during the normal operating period. Thus, during the burn-in period, many explicit and latent defects of HVAC systems as a whole and of their components are revealed. At the stage of intensive operation, after several hundred or thousand hours, an increase in the failure rate and irreversible changes in the parameters and characteristics of components set in.

The extended list of design factors determining the reliability of modern engineering microclimate systems may also include: the spatial and modular survivability of system interconnections; the vibration isolation compatibility of units; the level of data provision by primary sensors for integration with artificial intelligence algorithms and Digital Twins; and the structural conformity with the actual condition of the building envelope in accordance with [11].

Manufacturing factors comprise the factors that arise in the course of production preparation, manufacture and in-process inspection of products:

- incoming quality control of materials and components received from supplier enterprises;
- organisation of the technological process of equipment manufacture;
- product quality control at all stages of the technological process;
- qualifications of the manufacturers;
- quality assurance and inspection of the installation and commissioning of system equipment;
- system operating conditions.

Operational factors comprise the factors that arise outside the sphere of design and manufacture of the facilities. They reduce the operational reliability of engineering systems for creating indoor microclimates when the maintenance of such systems is carried out with insufficient competence or is impossible (the effect of military ecocide), and when their operating regime does not correspond to the regime established for operation. With a high quality of maintenance, operational reliability

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may increase in comparison with that predicted at the design and manufacturing stages. According to the nature of their action on the facility in operation, these factors may be divided into objective factors (the action of the external environment) and subjective factors (the action of maintenance personnel). The objective factors affecting the reliability of facilities may be classified into two groups: external and internal factors.

External factors comprise the influences determined by the external environment and the conditions of application, in particular the operation of engineering systems for creating a microclimate in hazardous areas and the impact of military ecocide. These are, first of all, climatic factors, mechanical actions (vibration, impacts, dust, aerosol contamination), electromagnetic and ionising radiation, and so forth. Internal factors are associated with changes in the parameters of the facility and of the structural materials (ageing, corrosion, etc.). These changes occur over time under the influence of external factors.

Subjective operational factors affecting reliability are understood to mean:

- the qualifications of the maintenance personnel;
- the organisation and quality of technical maintenance and scheduled servicing;
- the methods and means of organising the operation of facilities;
- the organisation of the collection and analysis of data on the reliability of facilities.

The non-hardware factors that affect system reliability and arise outside the sphere of design and manufacture of digital equipment include:

- the quality of the algorithms and software for products and for engineering systems with software control that create indoor microclimates;
- the qualifications of the maintenance personnel and the quality of equipment maintenance;
- the operating conditions of the equipment, including temperature, humidity, interference, and so forth.

The climatic factors include the following.

The thermal effect of the ambient air acts continuously on all constituent parts of engineering systems for creating indoor microclimates or on their products, irrespective of whether the system or product is operating or is in storage (not operating, or mothballed). The ambient temperature depends on the climatic zones in which the technical facility is operated. At low temperatures, the properties of many materials change substantially: plastics lose strength, rubber products become brittle and crack, cast iron and spring steels become brittle, and tin-bearing solders at temperatures below - 30 °C are prone to separation from the soldered joints. At low temperatures, greases and oils thicken, as a result of which failures occur in hydraulic systems and the moving parts of a product seize. High temperatures lead to overheating of the device and to its failure.

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A distinction is drawn between elevated (above 80 %) and reduced (below 40 %) relative air humidity, which depends on the climatic zone. Ukraine is located in a zone with moderate humidity (closer to elevated). Both elevated and reduced air humidity have an adverse effect on technical devices. Reduced humidity in combination with a high temperature leads to the drying out of certain materials, as a result of which the ageing processes of parts made from these materials are accelerated. Elevated humidity is one of the factors with the most adverse effect on technical facilities. It accelerates the corrosion of metals. Humidity also alters the properties of dielectrics. The moistening of insulating materials in various units and control panels leads to the occurrence of failures and malfunctions in them. The cause of moisture formation in units, control panels, gearboxes, enclosures and vessels may be the condensation of vapour on the cold surfaces of parts during significant temperature fluctuations. Moisture is the principal cause of the unreliable operation of transformers, chokes and similar components.

Reduced pressure, which occurs at altitudes of 150 m and above, causes a deterioration in the starting and operation of internal combustion engines. In addition, under conditions of military ecocide, damage to main air ducts is possible, which likewise affects the reliability of engineering systems for creating indoor microclimates. A reduction in pressure also affects the working capacity of maintenance personnel to a certain extent.

During military ecocide, the reliability of engineering systems for creating indoor microclimates is strongly affected by the contamination of the air with mechanical and chemical impurities. Dust, penetrating into microcracks in insulating materials, significantly reduces their insulating properties. Dust, and especially airborne sand, destroys paint and other protective coatings; moreover, entering the moving joints of mechanical assemblies and mechanisms, they cause accelerated wear of the friction surfaces. In addition to dust, the atmosphere may contain various harmful chemical impurities (salts, oxides, acids), particularly during military ecocide, which enter the air during explosions and are emitted by vehicles and industrial enterprises. These gases increase the corrosion of metals and accelerate the ageing process in plastics, filters and other non-metallic materials. The degree of influence of these impurities increases considerably in the presence of elevated humidity.

During the operation of engineering systems for creating indoor microclimates in the open air, all their external surfaces are exposed to direct sunlight, which carries thermal and ultraviolet radiation. Thermal radiation leads to an increase in the temperature of all constituent parts of technical facilities; the action of this temperature factor was considered above. The effect of ultraviolet radiation leads to the activation of the physico-chemical ageing processes of many parts made of rubber and plastic, as well as of paint coatings and various operating and preservation materials. Thus, as a

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result of the action of sunlight, the dielectric properties and colour of plastics change, a number of plastics become brittle, and a crust forms on rubber products, the surfaces of which then crack. Painted surfaces begin to fade and to peel.

Biodeterioration is a particular type of material destruction associated with the influence of biological factors such as microorganisms (bacteria, fungi), insects, rodents and birds.

Biological factors may manifest themselves in the form of:

- the direct use of various materials as sources of nutrition;
- the direct effect of the metabolic products of microorganisms on materials;
- the formation of substances that catalyse corrosion reactions.

Biodeterioration may be physical or chemical. Physical biodeterioration is caused by mammals, birds and the like, whereas chemical biodeterioration is caused by the enzymatic reactions that underlie the action of microorganisms. The activity of microorganisms is influenced by external physical and chemical factors.

The physical factors are the humidity of the environment, the concentration of substances in aqueous solutions, osmotic pressure, ambient temperature and radiation. The chemical factors are the composition and reaction of the environment, as well as its oxidation–reduction action. The environment may contain substances that either stimulate or inhibit the vital activity of microorganisms.

The biological factors include the following.

Fungi and mould. Of all the biological factors, these are the most hazardous for equipment. Fungi may develop on the surface of any materials if a layer of organic dust is present on them. The most favourable conditions for the development of most types of mould are high relative humidity (above 85 %), a temperature of 20 - 30 °C and still air. These conditions correspond to a hot tropical climate. When the temperature falls below 7 °C or rises above 40 °C, and also at a relative humidity below 75 %, the activity of mould growth and development decreases considerably.

The effect of fungi and mould on equipment components causes the following consequences:

- damage to or destruction of natural fibrous materials (textiles, yarn, cotton, wool, flax, jute, rubber, many plastics, wood, leather, paper and cardboard) and of optical components;
- destruction of paint coatings containing vegetable coverings or animal fats;
- acceleration of the corrosion process of metals;
- disruption of contacts, short circuits and insulation breakdown.

Products and their spare parts most frequently become covered with mould if they are stored in damp but warm and unventilated premises, or under tarpaulin in a warm and humid location.

Among insects, the most hazardous for components are moths and termites.

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Moths destroy plastics, wooden parts, leather and other organic materials. The moist decomposition products of insects, settling on the current-carrying parts of electrical equipment, may lead to current leakage and even to short circuits.

Rodents. They cause damage to various cables and wires, which leads to the disruption of electrical circuits and to the occurrence of short circuits.

Thus, the influence of external and internal factors on the operation of engineering systems for creating indoor microclimates must be anticipated as early as the design stage by incorporating preliminary protection schemes or strength improvements into the design and by properly drawing up operating recommendations. Personnel are required to comply with the operating recommendations and not to use devices for purposes other than those intended or under conditions not envisaged for their operation.

When designing engineering systems for creating indoor microclimates, the following factors must be taken into account.

External climatic and environmental factors, such as:

- outdoor air parameters;
- wind load and aeration;
- solar radiation;
- the quality of the external environment (the ecocide factor).

Internal process and operational factors:

- the intended use of the facility and its safety category;
- internal heat, moisture and gas gains;
- the air change rate.

Design factors:

- space-planning solutions;
- the thermal performance characteristics of the building envelope;
- the factor of physical wear and damage.

During the operation of engineering systems for creating a microclimate, the principal factors affecting their reliability are the operating conditions and a carefully designed system of maintenance and redundancy. Under the conditions of eliminating the consequences of hostilities, operational factors (the aerosol load of military ecocide and the destabilisation of power grid parameters) become dominant in the formation of microclimate system failures.

Proposed multi-level classification of the factors affecting the reliability of HVAC systems is shown in Fig. 1 and Fig. 2.

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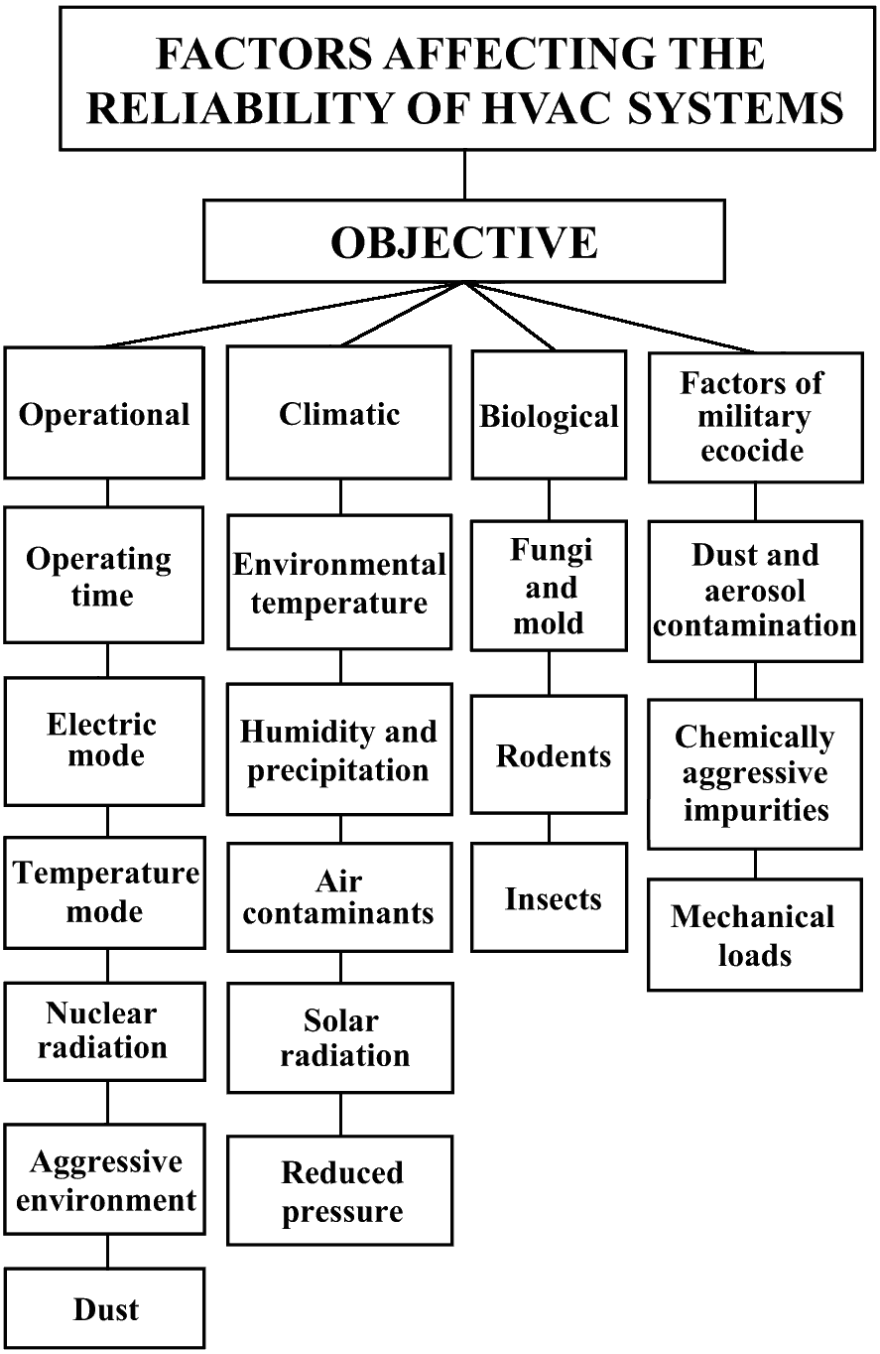



Fig. 1. Structural diagram of the multi-level classification of the factors affecting the reliability of HVAC systems

In practice, both a deterioration and an improvement of reliability indicators occur during manufacture and operation, particularly under conditions of military ecocide. The indoor microclimate depends on many factors. Their rather complex interaction with respect to comfort conditions has not to date been fully studied, especially under conditions that differ from the design ones.

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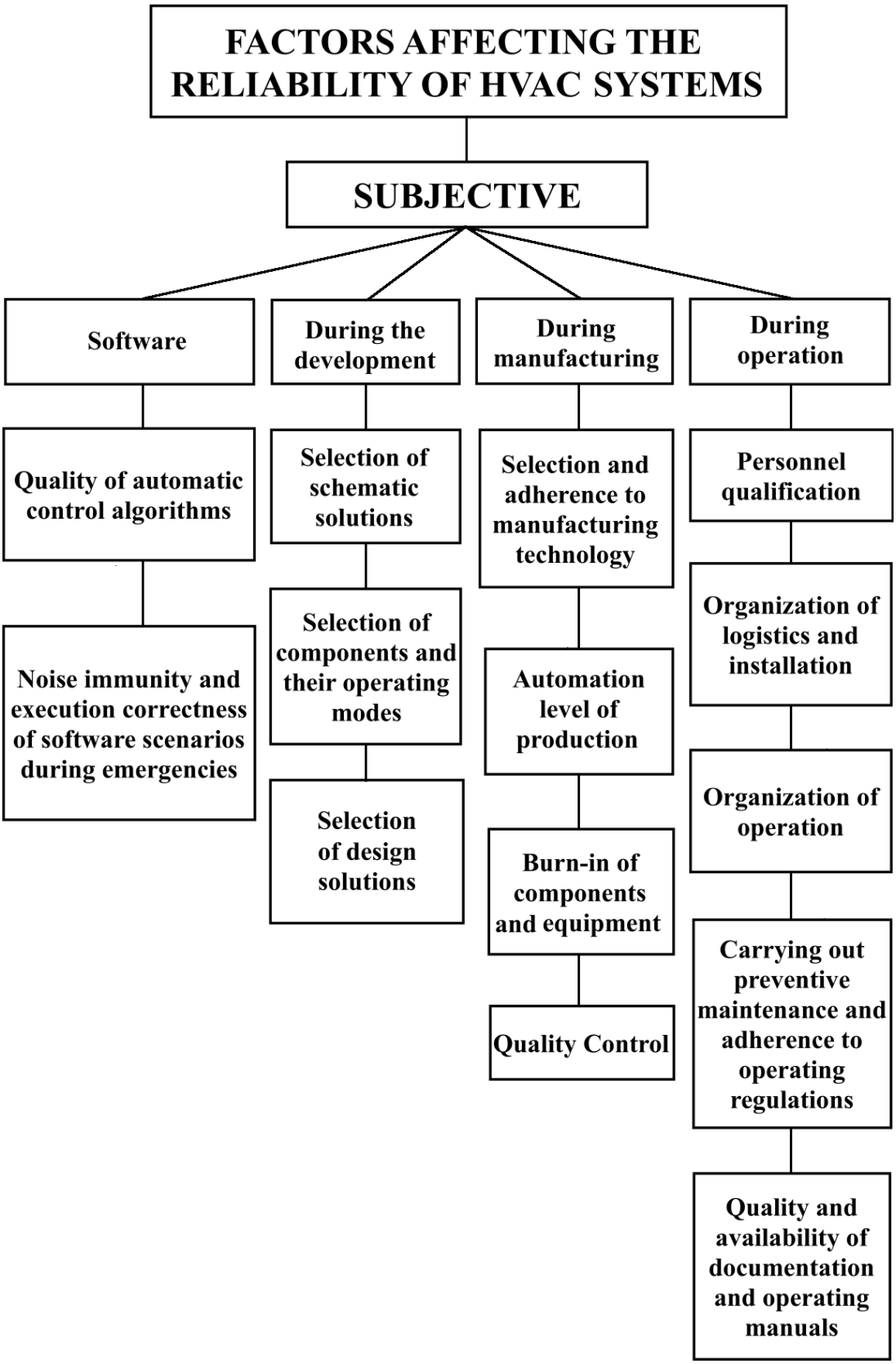



Fig. 2. Structural diagram of the multi-level classification of the factors affecting the reliability of HVAC systems

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**Conclusions.** In order to study and forecast the phenomena of the formation of microclimatic conditions in a room that has defects of the building envelope and of the HVAC systems, an analysis was carried out of the factors that affect engineering systems for creating indoor microclimates, their reliability and the variation of indoor microclimate parameters. The factors affecting the reliability of engineering systems for creating indoor microclimates have been investigated and systematised. A structural diagram of a multi-level classification of the factors affecting the reliability of HVAC systems has been developed. It has been demonstrated that, under conditions of military ecocide, traditional reliability models are inadequate, since they do not take into account the synergetic effect of building envelope destruction, aerosol and chemical contamination, and power outages. A comprehensive classification of factors (hardware/non-hardware, objective/subjective) has been formulated, which makes it possible to substantiate measures for increasing the resilience of HVAC systems as early as the design specification stage.

**Prospects for Further Research.** Further research will consist in developing a dynamic mathematical model for calculating the residual life of HVAC equipment in real time and in creating algorithms for the automatic switching of system operating modes in response to changes in the external environmental state during explosive aerosol contamination (the effect of military ecocide), as well as numerical parameters of the probability of failure-free operation of HVAC systems.

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UDC 697.1:621.019.3

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https://doi.org/10.32347/2409-2606.2026.58.137-152

# ФАКТОРИ ВПЛИВУ НА НАДІЙНІСТЬ ІНЖЕНЕРНИХ СИСТЕМ ДЛЯ СТВОРЕННЯ МІКРОКЛІМАТУ ПРИМІЩЕНЬ

***Анотація.*** *У статті проаналізовано та здійснено систематизування факторів, що впливають на надійність інженерних систем створення мікроклімату приміщень (опалення, вентиляції та кондиціювання повітря - ОВК) та безпосередньо на параметри внутрішнього середовища за наявності дефектів огороджувальних конструкцій в умовах воєнного екоциду. Проведено системний аналіз, порівняльне дослідження та наукове узагальнення вітчизняних і закордонних нормативних та літературних джерел у галузі надійності та екстремальної експлуатації критичної інфраструктури. Розроблено багаторівневу класифікацію факторів впливу на надійність систем опалення, вентиляції та кондиціювання повітря, у якій виділено дві основні групи: об'єктивні (кліматичні, техногенні, біологічні та екологічні наслідки воєнного екоциду) і суб'єктивні (помилки розробки, виготовлення, монтажу та експлуатації персоналом). Досліджено специфіку функціонування технологічного обладнання в умовах деструктивного зовнішнього середовища,*

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*перебоїв енергопостачання, високого аерозольного, пилового й хімічного навантаження, а також руйнування будівельної оболонки. Основними факторами, що впливають на надійність систем опалення, кондиціювання та вентиляції, є умови експлуатації та ретельно продумана система обслуговування, резервування, підвищення стійкості систем життєзабезпечення, зокрема впровадження багаторівневого адаптивного фільтрування, локального резервування й автономного живлення. Подальші дослідження полягатимуть у розроблянні динамічної математичної моделі для розрахунку залишкового ресурсу обладнання систем опалення, вентиляції та кондиціонування повітря в режимі реального часу, а також у створенні алгоритмів автоматичного перемикання режимів роботи систем у відповідь на зміни стану навколишнього середовища під час забруднення вибуховими аерозолями (наслідок воєнного екоциду). Крім того, передбачається визначення числових параметрів імовірності безвідмовної роботи цих систем.*

***Ключові слова:*** *надійність, мікроклімат, опалення вентиляція та кондиціювання, воєнний екоцид, дефекти огороджувальних конструкцій, апаратні фактори, каскадні відмови, відмовостійкість, інтернет речей, BMS, AFDD, енергоефективність, обмежене енергопостачання.*

Received/Надійшла до редакції 08.09.2026
Accepted/Прийнято 13.10.2026
Issued/Опубліковано 30.10.2026
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