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A CONCEPTUAL MODEL FOR QUALITY ASSESSMENT OF FRAME STRENGTHENING DURING BUILDING RECONSTRUCTION

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The strengthening of frame buildings during reconstruction is a complex engineering task that requires the coordinated consideration of structural reliability, technological efficiency, and long-term sustainability. In practice, the selection of structural-technological solutions is often based on expert judgment and fragmented criteria, which limits transparency and increases uncertainty in decision-making, especially under constrained reconstruction conditions.

This paper proposes a conceptual model for quality assessment of frame strengthening as a core component of a decision support system. The model is based on a systemic and life-cycle-oriented approach and integrates three interacting groups of criteria: reliability, efficiency, and sustainability. Quality is interpreted as an integral result of the interaction between these criteria rather than as a single performance indicator.

The proposed structure formalizes the hierarchy of criteria and indicators, allowing the assessment process to account for structural performance, technological feasibility, resource efficiency, environmental impact, and organizational stability throughout the life cycle of the building. The model does not represent a comparative optimization algorithm but provides a methodological framework for ensuring logical consistency and transparency in the evaluation and substantiation of strengthening solutions.

The developed conceptual model creates a theoretical basis for further implementation of digital decision support tools, multi-criteria analysis methods, and BIM-based quality management systems in building reconstruction projects.

Keywords: structural strengthening, quality assessment, decision support system, structural-technological solutions, reliability, efficiency, sustain ability, building reconstruction, life-cycle approach.

1. Problem statement

Modern conditions of building operation – such as changes in functional use, increased load demands on structural frames, aging of materials, and, in the case of Ukraine, large-scale damage caused by military actions – necessitate systematic strengthening, rehabilitation, and reconstruction of existing frame buildings [7, 14]. Frame structural systems are widely used in industrial, public, and civil buildings, forming a significant part of the building stock and construction heritage.

During long-term operation, frame buildings under go both physical deterioration and functional obsolescence, which of ten requires structural upgrading to meet current safety, performance, and regulatory requirements. Reconstruction processes in evitably include strengthening of individual load-bearing elements orentire structural frames. As a result of strengthening, the properties of structural elements are modified, including geometric parameters, spatial configuration, load-bearing capacity, durability, cost, and operational reliability [6, 12].

Despite the availability of numerous strengthening techniques, the selection of optimal structural-technological solutions (STS) remains a complex and weakly formalized task. Strengthening is typically performed under constrained conditions-limited space, ongoing building operation, safety requirements for users, and environmental restrictions – which significantly complicates decision-making. In practice, the choice of strengthening methods often relies on expert judgment rather than on a transparent, systematic evaluation of quality, efficiency, reliability, and sustainability [1, 12].

Current regulatory frameworks primarily define safety and performance requirements for structural products and construction works but do not provide integrated decision-support mechanisms for selecting optimal strengthening strategies during reconstruction [5, 7]. This creates a gap between normative requirements and practical implementation, especially when multiple technological, economic, environmental, and organizational factors must be simultaneously considered.

Therefore, there is a need for a comprehensive decision support system that integrates reliability, efficiency, and sustainability criteria to ensure quality assurance of frame strengthening during building reconstruction. Such a system should support rational selection of constructive-technological solutions, reduce subjectivity in decision-making, and improve long-term performance of reconstructed buildings.

2. Analysis of Recent Achievements and Publications

Modern construction science and practice have developed extensive systems for quantitative quality assessment of construction products and processes. These systems are reflected in national standards (DSTU), European regulations, ISO standards, and technical specifications governing construction quality, safety, durability, and environmental performance [5, 6, 12].

The European Construction Products Regulation (EU) No. 305/2011 establishes harmonized conditions for placing construction products on the market, requiring compliance with essential performance characteristics such as mechanical resistance, stability, safety, environmental protection, and durability. It also introduces a system for assessment and verification of performance based on harmonized standards and European Technical Assessments (ETA), including testing, inspection, and production control procedures.

In the context of strengthening structural frames, traditional quality indicators must be adapted to reflect the specific nature of reconstruction processes. Unlike new construction, strengthening does not aim to create a new product but rather to modify and improve the performance characteristics of existing structures. Consequently, functional indicators focus on the increase of load-bearing capacity and durability of both individual elements and the overall structural frame.

Reliability indicators for strengthening solutions are primarily associated with durability and long-term performance, defined as the ability of structural elements to maintain required parameters over time under specified operating conditions [7, 11]. Technological indicators play a critical role, as they characterize the efficiency of constructive-technological solutions in terms of labor productivity, resource consumption, and feasibility under constrained site conditions [1].

A significant body of research has addressed technological efficiency, labor intensity, and time consumption in construction and reconstruction processes. Previous studies have analyzed labor norms, construction cycle duration, and organizational aspects of building works, demonstrating their substantial influence on overall process performance and project outcomes [15].

In parallel, research on Lean construction principles has confirmed their potential to reduce process waste, improve productivity, and enhance operational reliability under constrained construction conditions, which is particularly relevant for reconstruction projects [17, 19].

Ergonomic and safety indicators are also recognized as essential quality parameters, reflecting human interaction with construction processes and equipment. These include physical effort, environmental conditions (lighting, temperature, noise, vibration), and occupational safety during strengthening operations.

Economic indicators remain mandatory criteria, encompassing capital costs, labor costs, material consumption, transportation, and long-term operational expenses. In parallel, environmental performance indicators – such as emissions, waste generation, and resource efficiency – are increasingly emphasized in the context of sustainable construction and life-cycle assessment [4].

International standards and guidelines, including ISO-based quality management systems, Eurocodes, and fire design standards, provide methodologies for assessing existing structures and designing strengthening interventions [2, 3, 8–10]. However, these documents primarily address structural safety and calculation principles rather than integrated decision-making frameworks that combine reliability, efficiency, sustainability, and organizational factors.

Despite extensive research on individual aspects of reconstruction – structural behavior, materials, labor efficiency, and risk management-insufficient attention has been given to holistic decision support systems for selecting optimal strengthening solutions for frame buildings. In particular, issues related to multi-criteria evaluation, integration of life-cycle considerations, and reduction of subjectivity in decision-making remain under explored.

This gap highlights the necessity of developing an integrated decision support system for quality assurance of frame strengthening during building reconstruction, capable of combining technical, technological, economic, environmental, and organizational criteria into a unified evaluation framework.

3. Research Methodology

The research methodology is based on a systemic and life-cycle-oriented approach to the assessment and substantiation of structural-technological solutions (STS) for strengthening frame buildings during reconstruction. The proposed methodology integrates structural reliability, technological efficiency, and sustainability into a unified framework that supports informed decision-making and quality assurance [1, 2, 11].

The methodological concept does not aim at direct optimization or ranking of predefined alternatives. Instead, it focuses on the formalization of the quality assessment structure, ensuring logical consistency between evaluation criteria and the actual technical, technological, environmental, and organizational conditions of reconstruction.

3.1. Conceptual Model of Quality Assessment for Frame Strengthening

Quality assurance of frame strengthening during building reconstruction requires a multidimensional assessment model capable of integrating heterogeneous criteria related to structural performance, construction technology, resource efficiency, and long-term sustainability.

In this study, a conceptual model of quality assessment is proposed as a core component of a decision support framework for substantiating STS for frame strengthening. The model is based on a systemic and life-cycle perspective, in which quality is interpreted not as a single indicator but as an integrated result of interacting criteria groups.

The model introduces a general quality assessment function (*QAF*), defined as:

$$QAF = f(N_i, R_i, A_i),$$

where N_i represents reliability criteria; R_i represents efficiency criteria; A_i represents sustainability criteria.

Each criterion group forms a hierarchical subsystem consisting of generalized criteria and detailed indicators. This structure enables flexible adaptation of the assessment model to different reconstruction scenarios, building types, and strengthening strategies.

Unlike comparative optimization models, this conceptual framework is not intended to rank alternatives at this stage, but to establish a transparent and logically consistent structure for quality evaluation that can later be embedded into a decision support system.

The overall hierarchical structure of the proposed quality assessment model for frame strengthening is shown in Figure 1, where the interrelation between reliability, efficiency, and sustainability criteria within the *QAF* is illustrated.

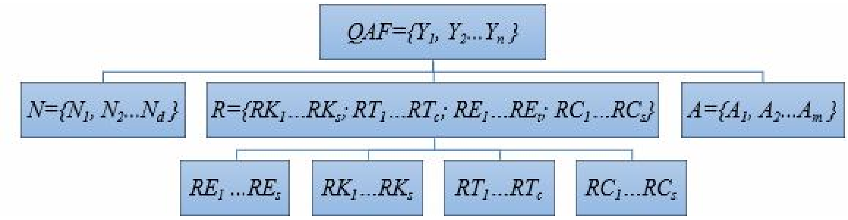

Fig. 1. Hierarchical structure of the quality assessment function for frame strengthening, integrating reliability, efficiency, and sustainability criteria

3.2. Formalization of Quality Criteria and Indicators

The reliability criteria (*N*) within the reliability subsystem define the ability of the strengthened building frame to maintain its load-bearing capacity, safety, and functional performance over time under real operating conditions [7–11, 21-28].

Reliability is treated as a multi-level concept, incorporating structural, material, probabilistic, and process-related aspects. The hierarchical structure of the reliability criteria subsystem is presented in Figure 2.

The collection and analysis of reliability-related information are represented in the form of a criteria matrix:

$$N = \{N_1, N_2, ..., N_d\}.$$

Each reliability criterion is quantified using physically interpretable indicators, such as probability of failure-free operation, increase in load-bearing capacity, stiffness parameters, durability time, and sensitivity to degradation mechanisms. This hierarchical representation allows the separation of global reliability objectives from detailed performance indicators while preserving their logical interconnection.

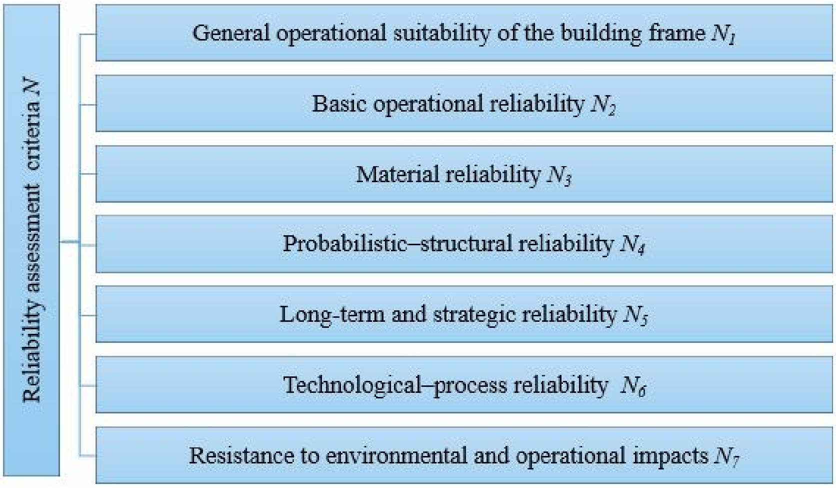

Fig. 2. Hierarchical structure of the reliability quality subsystem

Efficiency Criteria (R) characterize the rationality of structural-technological solutions from the standpoint of resource consumption, labor intensity, time, and capital investments [23, 25, 29-32].

To avoid overlap with sustainability considerations, efficiency is interpreted primarily as process-oriented performance, focusing on the organization and execution of strengthening works [1, 12]. The efficiency subsystem is decomposed into four functional groups, as illustrated in Figure 3.

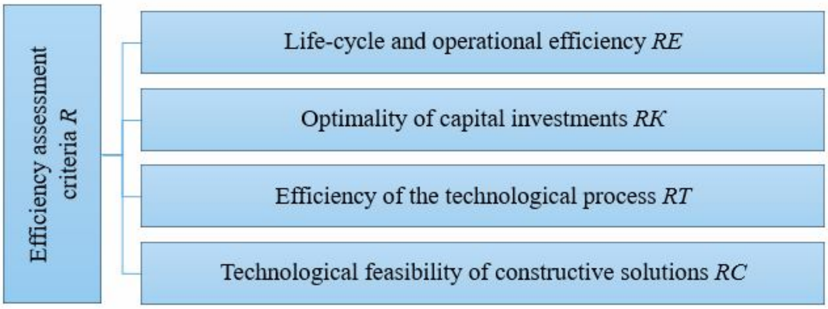

Fig. 3.Hierarchical structure of the efficiency quality subsystem

The corresponding efficiency criteria matrix is defined as:

$$R=(RK_1 \ldots RK_k;\ RT_1 \ldots RT_c;\ RE_1 \ldots RE_l;\ RC_1 \ldots RC_s).$$

Such decomposition enables separate evaluation of productivity, investment rationality, technological controllability, and construct ability, while maintaining their integration within the overall evaluation framework.

Sustainability Criteria (A) reflect the long-term consequences of adopted STS throughout the building life cycle and represent the balance between technical performance, resource efficiency, social impact, and organizational stability [21, 25, 29].

The hierarchical structure of the sustainability subsystem is shown in Figure 4. The collection and analysis of sustainability-related information are expressed as:

$$A=\{A_1, A_2, \ldots, A_m\}.$$

Unlike efficiency criteria, sustainability indicators are oriented toward long-term effects, such as service life extension, environmental footprint reduction, continuity of building operation during reconstruction, and adaptability of strengthened structures to future functional changes. Sustainability criteria aggregate relevant indicators from the reliability and efficiency subsystems, forming an **integrative layer** that links short-term technological decisions with long-term life-cycle performance.

Fig. 4.Hierarchical structure of the sustainability quality subsystem

3.3. Integration of the Model within a Decision Support Framework

The proposed quality assessment model is embedded within a broader conceptual decision support framework that links the diagnosis of the current structural condition with the formation of strengthening strategies for frame buildings.

As illustrated in Figure 5, the process begins at the initiation stage, driven by the causes of reconstruction, such as changes in functional requirements, increased operational loads, structural damage, or long-term degradation. At this stage, the current state assessment of the building frame is performed, taking into account external change factors E_k, internal change factors C_r, identified defects D_i, observed damage P_i, and operating conditions I_i.

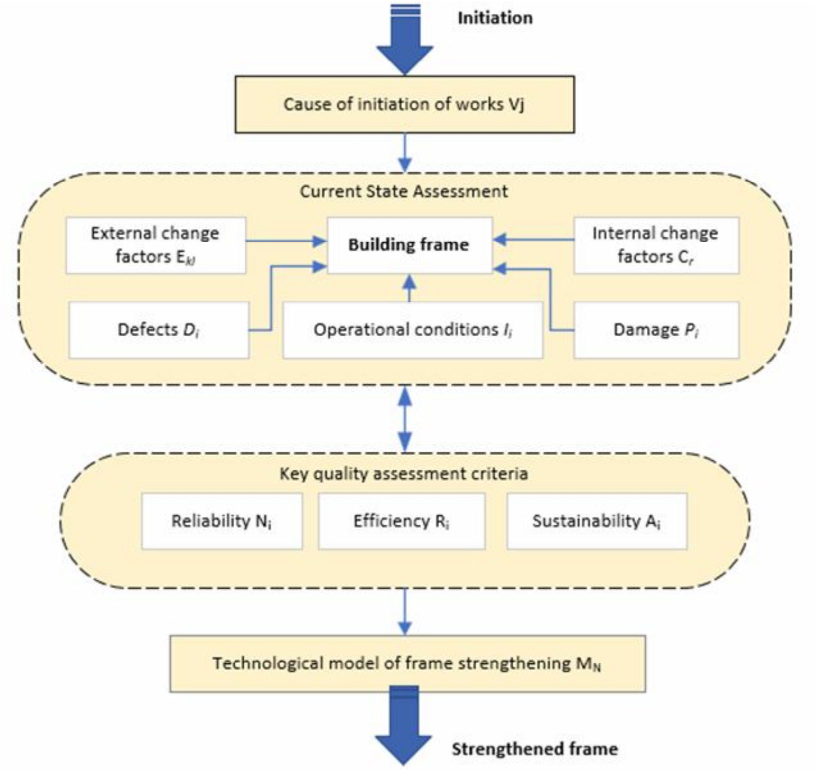

Fig. 5. Conceptual framework linking current state assessment, quality criteria, and frame strengthening

At the subsequent stage, the quality assessment criteria (*QAC*), reliability (N_i), efficiency (R_i), and sustainability (A_i), are applied to structure the evaluation of potential structural-technological solutions. These criteria form the analytical link between the diagnosed condition of the structure and the selected technological strengthening model M_N .

The outcome of this process is a strengthened building frame, whose quality characteristics are determined not only by structural load-bearing capacity but also by technological feasibility, resource efficiency, and long-term sustainability throughout the building life cycle.

It is important to emphasize that Figure 5 does not represent an optimization algorithm or a finalized decision-making procedure. Instead, it provides a conceptual representation of the role and position of the quality assessment model within the overall reconstruction process, ensuring methodological transparency and logical consistency for further development of decision support tools.

4. Conclusions

The proposed conceptual model establishes a unified theoretical basis for quality assessment of frame strengthening during building reconstruction. By separating reliability, efficiency, and sustainability into interacting but non-duplicating subsystems, the model overcomes the limitations of single-criterion or cost-driven approaches commonly applied in engineering practice.

Unlike prescriptive standards or narrowly focused optimization models, the proposed framework provides a flexible and extensible structure suitable for integration into digital decision support systems, BIM-based workflows, and multi-criteria analysis tools. This makes the model particularly relevant for reconstruction projects carried out under complex conditions, including limited spatial constraints, ongoing building operation, and heightened uncertainty caused by structural damage or degradation.

Future research may extend the conceptual framework by introducing weighting procedures, uncertainty modeling, and scenario-based decision analysis, while preserving the fundamental structure and logic of the proposed quality assessment model.

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КОНЦЕПТУАЛЬНА МОДЕЛЬ ОЦІНЮВАННЯ ЯКОСТІ ПІДСИЛЕННЯ КАРКАСНИХ БУДІВЕЛЬ ПІД ЧАС РЕКОНСТРУКЦІЇ

Підсилення каркасних будівель у процесі реконструкції є складною інженерною задачею, що потребує узгодженого врахування показників надійності конструкцій, технологічної ефективності виконання робіт та довгострокової сталості прийнятих рішень. На практиці вибір конструктивно-технологічних рішень часто ґрунтується на експертних судженнях і фрагментарному використанні окремих критеріїв, що знижує прозорість та обґрунтованість прийняття рішень, особливо в умовах обмеженого простору, безперервної експлуатації будівель і підвищеного рівня невизначеності.

У статті запропоновано концептуальну модель оцінювання якості підсилення каркасних будівель як ключовий елемент системи підтримки прийняття рішень. Модель базується на системному та життєво-цикловому підходах і інтегрує три взаємопов’язані групи критеріїв: надійності, ефективності та сталості. Якість підсилення інтерпретується як інтегральний результат взаємодії зазначених критеріїв, а не як окремий техніко-економічний показник.

Запропонована структура формалізує ієрархію критеріїв і показників, що дозволяє комплексно враховувати несучу здатність і довговічність конструкцій, технологічну здійсненність робіт, раціональність використання ресурсів, екологічні наслідки та організаційну стабільність процесу реконструкції протягом життєвого циклу будівлі. Модель не є алгоритмом оптимізації альтернатив, а створює методологічну основу для забезпечення логічної узгодженості та прозорості оцінювання і обґрунтування конструктивно-технологічних рішень.

Розроблена концептуальна модель формує теоретичне підґрунтя для подальшого впровадження цифрових інструментів підтримки прийняття рішень, методів багатокритеріального аналізу та BIM-орієнтованих систем управління якістю в проєктах реконструкції будівель.

Ключові слова: підсилення конструкцій, оцінювання якості, система підтримки прийняття рішень, конструктивно-технологічні рішення, надійність, ефективність, сталість, реконструкція будівель, життєво-цикловий підхід.

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Tabl. 0. Fig. 5. Ref. 32.

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