Universal Library of Engineering Technology Research Article

ISSN: 3064-996X

Open Access | PP: 17-22

DOI: https://doi.org/10.70315/uloap.ulete.2023.003

Aspects of the Restoration and Maintenance of Architectural Structures Taking into Account Fire Risks

Valentyn Ishchenko

Expert in Fire Safety, Emergency Rescue Operations and High-Altitude Engineering and Technical Works, Ukraine.

Abstract

Fires at cultural heritage sites (OKH) result in irreplaceable losses of civilizational significance. The problem is complicated by a fundamental contradiction between the necessity of integrating a modern suite of fire safety measures and the requirement to preserve the historical authenticity of forms, structures, and materials. The aim of this study is to develop and theoretically substantiate an integrated three-level fire risk management model applicable at all stages of the OKH life cycle, with targeted attention to the stages of restoration and scheduled maintenance. The methodological basis includes a systems analysis of the scholarly literature, content analysis of key international standards (primarily NFPA 914) and guidelines (UNESCO, ICOMOS), as well as a retrospective study of emblematic fire incidents using a case-study approach. As the principal result, a conceptual model is proposed, integrating processes at the strategic level (risk identification and assessment, formulation of targets), the tactical level (engineering and technical solutions and their adaptation to heritage specifics), and the operational level (management of procedures, competencies, and personnel discipline). The central linking mechanism of the model is interdisciplinary expertise, which ensures continuity and coherence of decisions across levels. The conclusions confirm that a systemic, risk-oriented approach makes it possible to achieve a balance between safeguarding the authenticity of OKH and attaining the regulatory level of fire safety required, overcoming the limitations of purely prescriptive requirements. The information presented will be of interest to restoration specialists, fire safety engineers, managers of OKH, and representatives of supervisory authorities.

Keywords: *Fire Safety, Cultural Heritage Sites, Restoration, Risk Management, Integrated Approach, Historic Buildings, Passive Fire Protection, Active Fire Suppression Systems, Interdisciplinary Expertise, NFPA 914.*

INTRODUCTION

Objects of cultural heritage serve as irreplaceable material witnesses to historical experience, cultural practices, and the collective identity of communities [1]. Their destruction as a result of fire is a loss that cannot be compensated: the consequences extend far beyond property damage and affect symbolic, scientific, and social dimensions [2]. Despite significant progress in fire safety, major incidents at historic sites continue to occur with alarming regularity, indicating persistent systemic defects in current protection regimes [2]. Statistical observations, including data from national emergency services, confirm the persistently high level of fire risk for buildings, primarily in the housing stock, which often includes historic structures [3]. Particular vulnerability is observed during periods of restoration, repair, and conservation, when an increased share of combustible materials, the use of temporary engineering solutions, and the performance of hot work create a combination of heightened risk factors.

The research gap in this area is defined by a fundamental contradiction known as the compliance paradox (compliance paradox). On the one hand, historic buildings are subject to bringing into compliance with modern, predominantly prescriptive building and fire regulations. On the other hand, literal adherence to such prescriptions often requires invasive interventions: installation of large-scale equipment, routing of utilities through authentic structures, and replacement of historical materials with modern fire-resistant analogues. Such actions can cause irreversible damage and destroy precisely those elements, spatial structures, and details that constitute the true value of the object [6, 18]. As a result, the attempt to ensure formal safety may in fact lead to a reduction of heritage. At the same time, existing practices remain fragmented: they either focus on isolated technical solutions or are limited to administrative measures and do not form a unified methodology linking engineering, restoration, and managerial aspects into a continuous process.

The aim of the study is to develop a conceptual model of integrated fire risk management applicable at all stages of the life cycle of OKH, with particular emphasis on periods of restoration and maintenance.

The scientific novelty lies in the proposal of a three-level system architecture in which fire safety is considered not as the sum of disparate measures, but as a continuous controlled process with the distribution of functions across the strategic, tactical, and operational levels.

The author's hypothesis is that effective provision of fire safety for OKH is achieved not so much through the implementation of the most advanced and costly technologies as through the application of a comprehensive risk-oriented approach. Its core is the synergy of in-depth assessment of specific threats, adaptive engineering solutions, and competent operational management carried out by specialists with interdisciplinary training in fire safety, engineering, and restoration.

MATERIALS AND METHODS

The body of literature on the restoration and operation of architectural assets with regard to fire risks consists of several intersecting strands: methodological foundations and quantitative risk assessment models; normative and organizational foundations of risk management and authenticity preservation; economic and infrastructural solutions for mitigating vulnerability; post-fire reconstruction practices and operational recovery. In studies on quantitative risk assessment, one can observe an evolution from survey and classification works toward hybrid probabilistic models. Thus, a comprehensive review of causal chains of ignition, mechanisms of progressive damage, and strategies for enhancing fire safety in buildings summarizes typical hazard identification methods (HAZID), risk matrices, and reformulates them into applied frameworks for fire safety engineering, underscoring the gap between universal prescriptions and the contextual constraints of historic fabric ([3]). At the next level of detail, performance-based principles for historic assets are systematized as a sequence: determination of value and permissible interventions, target safety indicators, selection of modeling methods, and verification of measures, with the declared key being the balance between the preservation of material substance and achieving an equivalent level of safety to contemporary assets ([4]). Chen J. et al. [1] demonstrate iterative tuning of prior probabilities to local heritage contexts, which is critical for rare but catastrophic events. Interdisciplinary guidelines within European cultural heritage resilience initiatives, by contrast, keep the focus on the processuality of risk management: from identification of value and threats to preparedness plans, monitoring, and feedback, linking fire as one scenario within multi-hazard frameworks alongside climatic impacts ([14]). Studies applied to historic urban centers propose an econo-engineering operationalization, modeling block-level vulnerability and comparing cost–benefit for bundles of measures (fire-resistant barriers, compartmentation, modernization of electrical networks, automatic detection) with attention to intangible value and constraints on intervention ([5]).

The normative and organizational layer establishes a compromise between prescriptive and performance-based regimes. The guidance of the US National Trust, addressed to heritage asset managers, translates the language of codes into the practice of inventories, minimally invasive interventions (concealed wiring, reversible systems), evacuation planning for challenging layouts, and staff training, thereby demonstrating that organizational measures can offset some technical constraints ([6]). A study of historic Delft demonstrates case-oriented application of such principles: it details block geometries, fire spread paths through timber structures, deficits of the hydrant network, and the vulnerability of attic spaces; on this basis it proposes locally adapted measures, including separation of roof voids and early detection ([7]). At the level of a regulatory constitution, NFPA 914 formalizes the idea of equivalent safety through the justification of alternative solutions, documentation of value, and reversibility of interventions, providing designers with a roadmap for evaluating acceptable risk for historic structures [9, 11]. In parallel, international framework documents on risk management for World Heritage emphasize the integration of fire safety into the cycles of preparedness, response, and recovery, with a focus on stakeholder coordination and embedding procedures in site management plans ([13]).

Economic and infrastructural approaches to reducing vulnerability aim to link technical solutions with budgetary and value constraints. Cost–benefit models in historic contexts essentially serve as a mechanism for legitimizing performance-based measures before regulators and owners, allowing transparent comparison of intervention bundles with expected reductions in damage and downtime ([5]). Review papers on fire hazards in buildings, although focusing primarily on contemporary construction, are important as a repository of standard measures (early detection systems, fire protection of load-bearing elements, passive compartmentation) which, when adapted to heritage, pass through a filter of reversibility and material compatibility ([3]).

Post-fire reconstruction and operational recovery form a distinct domain in which managerial, legal, and technical decisions are closely intertwined with the ethics of authenticity. A study of reconstruction practices after destructive fires notes that the early phase—stabilization, documentation, temporary shelters—shapes the space of subsequent decisions between authentic conservation and value-justified replacement, and imposes high demands on insurance and contract support ([2]). From a more applied perspective, analysis of the operational challenges of fire aftermath mitigation points to chronic issues: contamination by salts and combustion products, dampening of masonry, degradation of lime binders, the need for rapid yet reversible stabilization and documentation, and a shortage of contractors competent in restoration standards ([16]). The international ICOMOS-ICCROM research program emphasizes that the success of recovery depends on recovery governance: transparency of decision-making, role allocation, mechanisms for community participation, and readiness to revise objectives as new survey data arrive ([12, 13]). Historical cases—from Windsor Castle to the Libušín log complex—exhibit diverse trajectories: in the former, reliance on meticulously documented restoration with innovative engineering solutions and significant organizational lessons for royal residences ([15]); in the latter, a rethinking of fire protection for traditional wooden architecture, where the compatibility of modern fire-retardant treatments and concealed building services with the asset's value becomes a central technical constraint ([17]). Practical guides on building adaptation summarize a set of constructive strategies (compartmentation, redundancy of egress routes, localized fire protection), emphasizing the principle of minimal sufficient intervention and phased implementation ([18]).

Taken together, the literature constructs a coherent methodological staircase: ethical and value calibration of conservation goals ([10]), integrated risk assessment grounded in data and expert knowledge ([1, 14]), regulatory legitimization of alternative solutions ([9, 11]), economic justification of measure bundles ([5]), and readiness for post-fire recovery governance ([2, 12, 16]). Nevertheless, contradictions persist. First, there is tension between prescriptive codes and the performance approach: standards provide mechanisms of equivalency, but enforcement practices and insurance requirements often pull solutions toward excessive technologization that conflicts with authenticity. Second, methodological divergences concern sources of probabilistic information: Bayesian networks promise transparent integration of knowledge but depend on expert priors and sparse incident data, which limits model transferability across assets, whereas survey-based and qualitative frameworks avoid this problem at the cost of aggregation. Third, in the post-fire phase, emphases diverge between speed of stabilization at any cost and reflective recovery, where institutional expectations (timelines, budgets, public symbolism) conflict with restoration principles of reversibility and minimality.

RESULTS AND DISCUSSION

Built cultural heritage as a type of building stock is characterized by a specific set of properties that substantially increase its sensitivity to fire-hazard impacts. It is appropriate to subdivide the set of vulnerabilities into three classes: structural-material, operational, and human-factor related.

Historic structures, in contrast to the modern stock, were constructed outside the framework of current fire safety regulations [2]. Their load-bearing and enclosing systems are often formed of combustible materials: wood (beams, floors, roof truss systems, decorative elements), textiles (tapestries, draperies), and other organic composites [18]. Hidden cavities, ventilation ducts, and complexly configured interstory and attic spaces are typical for such objects; they function as natural corridors for the rapid and unseen spread of fire and smoke, turning a local incipient stage into a large-scale fire [6]. Nonstandard layout solutions, the absence of standard evacuation routes and smoke removal systems further complicate the rescue of occupants and the work of firefighting units.

The etiology of fires in historic buildings is multifactorial. Most typical are faults and overloads of obsolete electrical wiring, careless handling of sources of open flame (including the use of candles in places of worship), as well as deliberate arson and acts of vandalism. A separate cluster of risks emerges during restoration and repair interventions: the performance of hot work (welding, cutting, use of open flame), installation of temporary electrical networks, and storage of combustible construction materials and solvents greatly increase the probability of fire initiation.

Insufficient awareness and preparedness of regular staff, as well as employees of contracting organizations, predetermine the likelihood of critical errors. Violations of equipment operating regulations, disregard of precautionary requirements during work, and untimely maintenance of engineering systems act as significant determinants of risk [7, 17].

For the purpose of overcoming the fragmentation of existing practices and resolving the paradox of compliance, an integrated three-level fire risk management model is proposed. This model (Fig.1) organizes all aspects of fire safety into a hierarchical architecture in which each subsequent level sequentially specifies and operationalizes the decisions made at the preceding one.

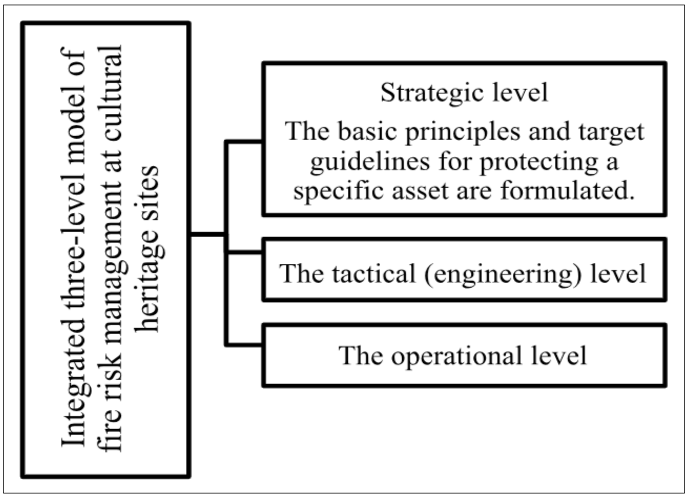

Fig.1. Integrated three-level model of fire risk management at the window (compiled by the author based on [4, 11, 12]).

The strategic level is the supporting framework of the entire system. The key tasks of this level are:

- Comprehensive risk assessment. Instead of formally following universal regulations, an in-depth analysis of vulnerabilities specific to the given building is carried out using both qualitative and quantitative methods. Index-based approaches acquire particular importance here, in particular the Historic Fire Risk Index (HFRI), which make it possible to reduce a multicriteria assessment (fire protection, evacuation routes, historical significance, etc.) to a single numerical indicator. This format ensures controlled weighting and transparency of decisions, surpassing rigid prescriptions in flexibility [1, 9].

- At the outset it is necessary to establish what must be ensured as a priority. The commonly accepted hierarchy is as follows: life and health of people; integrity of load-bearing structures; preservation of unique finishing elements and movable valuables (collections) [4]. Based on the results of the risk assessment and priority setting, a single document is compiled — the Fire Safety Plan, which serves as a strategic guideline for all subsequent measures.

The tactical (engineering) level is intended to translate strategic goals into specific design and technical solutions. Its task is to provide the required level of protection with minimal intervention in the historical fabric of the asset.

Passive fire protection measures are solutions that limit the spread of fire without active actuation. Fire protection of structures: the use of modern fire-retardant treatments (impregnations, varnishes, paints) that preserve the appearance and texture of historical materials, primarily timber.

Compartmentation: the formation of fire compartments to localize the seat of fire. In historic buildings this is achieved predominantly by a delicate enhancement of the fire resistance of existing walls, floors, and door openings, rather than the erection of new separating barriers [2, 10].

Active fire protection measures are systems that require actuation to perform their functions. Detection and alarm systems: the use of modern aspirating or multi-sensor detectors with concealed installation that provide early fire detection. Automatic fire suppression systems: the choice is critically important, since the secondary damage from the extinguishing agent may be comparable to the damage from fire; for OKN, solutions that minimize such damage are preferable (Table 1).

Table 1. Comparative analysis of automatic fire suppression systems for OKN (compiled by the author based on [13, 14]).

System type	Principle of operation	Advantages for OKN	Disadvantages	Application area
Water mist (TRV)	Cooling of the combustion zone and displacement of oxygen by finely dispersed water droplets.	Minimal water consumption and, consequently, minimal secondary damage. High efficiency.	High cost. Stringent water quality requirements.	Exhibition halls, public spaces, structural protection.
Gaseous (inert gases, halons)	Reduction of oxygen concentration in the protected volume below the level required for combustion.	No secondary damage to materials. Penetrates into hard-to-reach areas.	Requires room airtightness. Hazardous to people (inert gases). High cost.	Archives, collection storages, server rooms, libraries.27
Aerosol	Inhibition (retardation) of chemical reactions in the flame by finely dispersed particles of alkali metal salts.	High efficiency. Compactness. Does not require sealing and piping.	Formation of a solid deposit on surfaces that requires cleaning. Potential corrosive impact.	Electrical switchrooms, technical rooms, enclosed volumes.

The operational level encompasses the administrative and organizational framework that ensures the functioning of the system and the correct actions of personnel in the event of a fire. This is the most dynamic layer of management, requiring continuous monitoring and prompt intervention:

- Development of regulations. The establishment of clear, practically applicable instructions for employees and contractors, primarily the hot work permit system, which explicitly defines the preparation of the work area, the mandatory readiness of primary fire extinguishing means, and continuous supervision [15].The key tasks of this level are:

- Training and drills. Systematic briefings and practical evacuation exercises, and for museums and libraries, procedures for rescuing the most valuable objects.

- Maintenance and audit. Scheduled preventive maintenance of all engineering subsystems, regular inspections of the facility, and monitoring of compliance with fire safety regulations.

The proposed three-level model, flawless in theory, risks failing in practice if its implementation is entrusted to narrow specialists acting in isolation. The effectiveness of the integrated approach is directly linked to the presence of an integrator — an expert who understands the tasks of each level and is able to connect them. The existing sectoral fragmentation — when fire safety engineers are unfamiliar with the subtleties of scientific restoration, and restorers lack knowledge of fire dynamics and the logic of engineering protection — remains a key obstacle to the actual safety of cultural heritage sites.

The decisive condition for success is not the technology itself, but the professional capable of correlating the selection, adaptation, and operation of solutions with the unique parameters of a historical building. From this arises the urgent need for the targeted training of a new generation of specialists and the launch of educational pathways aimed at forming such integrators for the heritage preservation industry [7, 8].

The fire at Windsor Castle, which occurred on November 20, 1992, is a striking example of how a combination of seemingly minor managerial and organizational shortcomings can escalate into a catastrophe of national scale.

The source of the fire originated in Queen Victoria's private chapel as a result of an overheated spotlight pressed against a combustible curtain [16]. The fire then rapidly spread through hidden cavities in the roof and inter-floor structures, resulting in the destruction or serious damage of 115 rooms, including nine state halls. Examining this incident through the lens of the proposed three-level model demonstrates its practical verifiability and analytical productivity (Table 2).

Table 2. Lessons from the Windsor Castle fire in the context of the Integrated Risk Management Model (compiled by the author based on [5, 15, 16]).

Identified deficiency (Windsor, 1992)	Model level	Corrective action within the model
Carrying out work (installation of a floodlight) in close proximity to combustible materials (curtain) without a risk assessment.	Operational	Implementation of a strict procedure and a permit-to-work system for any work (not only hot work) with a fire risk assessment. Mandatory briefing and supervision of personnel.
Absence of an early fire detection system at the point of ignition.	Tactical	Design and installation of a modern, possibly concealed, automatic fire alarm system in all rooms, especially in areas with elevated fire load.
Rapid spread of fire through extensive concealed voids in the roof and floor assemblies.	Tactical	Analysis of the structures and development of a design for concealed compartmentation — installation of fire barriers within voids to limit the extent of fire spread.
Absence of a unified, comprehensive, and regularly updated fire safety plan for the entire castle.	Strategic	Development, approval, and regular updating of a unified Fire Safety Plan based on a comprehensive risk assessment and defining overall policy, objectives, and procedures.
Insufficient staff preparedness and absence of a clear plan for the rescue of works of art.	Operational	Development and regular rehearsal of evacuation plans not only for people but also for the most valuable items of the collection, with clear allocation of roles and areas of responsibility.

The conducted analysis indicates that the disaster could have been avoided or its consequences significantly limited if an integrated risk management system had been in place at the facility. At the strategic level, this would have meant the existence of a coherent, coordinated plan. At the tactical level — the implementation of effective early detection means and passive fire protection (including compartmentation). At the operational level — the elimination of work performed in violation of basic safety requirements. Thus, this example convincingly demonstrates that the safety of OKH is not the result of implementing a single magical technology, but the outcome of continuous, systematic activity structured and maintained simultaneously at the strategic, tactical, and operational levels.

CONCLUSION

The analysis carried out indicates that ensuring the fire safety of cultural heritage sites is a complex and inherently interdisciplinary task that does not tolerate mechanical adherence to prescriptive codes and requires a flexible, risk-oriented approach. Historic built fabric, owing to the uniqueness of structural solutions, materials, and functions, is by its nature irreducible to a typical facility. Attempts to fit it to standard regulations generate a compliance paradox, in which measures that are formally correct themselves become a source of loss of genuine historical value.

The key finding of the work is that effective resolution of these contradictions is possible only within the logic of systems management. The developed conceptual three-level model (strategic, tactical, operational levels) serves as a tool for structuring such an approach: from the formulation of target benchmarks and risk assessment at the strategic level. Through the justified selection and design of gentle engineering solutions at the tactical level. To the regulation of procedures, personnel training, and continuous monitoring at the operational level.

The aim of the research—the creation of a conceptual model of integrated fire risk management—has been achieved. The proposed hypothesis that the effectiveness of protecting OKN is determined not by a set of separate technologies but by a coherent management architecture based on the synergy of risk analytics, adaptive engineering measures, and professional administration was confirmed both within the framework of theoretical consideration and in the analysis of the fire at Windsor Castle. Separately emphasized is the decisive role of interdisciplinary expertise that brings together the experience of a practicing firefighter, an engineer, and a conservator as a necessary condition for the successful implementation of the proposed model.

The practical significance of the results lies in their applicability for OKN managers, restoration organizations, design engineers, and supervisory authorities as a methodological basis for the development and implementation of more effective, balanced, and economically justified fire safety systems. Application of the model makes it possible simultaneously to raise the level of protection of unique monuments and to ensure the preservation of their authenticity for future generations.

REFERENCES

1. Chen J. et al. A combined method to build Bayesian network for fire risk assessment of historical buildings //Fire Technology. – 2023. – Vol. 59 (6). – pp. 3525-3563.
2. Kincaid S. After the fire: reconstruction following destructive fires in historic buildings //The Historic Environment: Policy & Practice. – 2020. – Vol. 11 (1). – pp. 21-39.
3. Kodur V., Kumar P., Rafi M. M. Fire hazard in buildings: review, assessment and strategies for improving fire safety //PSU research review. – 2020. – Vol. 4 (1). – pp. 1-23. https://doi.org/10.1108/PRR-12-2018-0033.
4. Torero J. L. Fire safety of historical buildings: principles and methodological approach //International Journal of Architectural Heritage. – 2019. – Vol. 13 (7). – pp. 926-940.
5. Neto J. T., Ferreira T. M. Assessing and mitigating vulnerability and fire risk in historic centres: A cost-benefit analysis //Journal of Cultural Heritage. – 2020. – Vol. 45. – pp. 279-290.
6. Fire Safety in Historic Buildings [Electronic resource]. - Access mode: https://savingplaces.org/files/fire-safety-and-historic-buildings (date of access: 20.07.2023).
7. Fire safety aspects in cultural heritage – a case study in historical Delft [Electronic resource]. - Access mode: https://heronjournal.nl/50-4/9.pdf (date of access: 15.07.2023).
8. Heritage on Fire – Complexities, Potential Solutions and Current Regulations: An Exploratory Study [Electronic resource]. - Access mode: https://lup.lub.lu.se/student-papers/record/9051087/file/9051111.pdf (date of access: 15.07.2023).
9. NFPA 914, Code for the Protection of Historic Structures [Electronic resource]. - Access mode: https://www.nfpa.org/product/nfpa-914-code/p0914code (date of access: 20.07.2023).
10. Torero J. L. Fire safety of historical buildings: principles and methodological approach //International Journal of Architectural Heritage. – 2019. – Vol. 13 (7). – pp. 926-940. https://doi.org/10.1080/15583058.2019.1612484.
11. NFPA 914 [Electronic resource]. - Access mode: https://atapars.com/wp-content/uploads/2021/01/atapars.com-NFPA-914-2007.pdf (date of access: 20.07.2023).
12. Kealy L., Marchand T. H. J. The ICOMOS-ICCROM Studies Project on Post-disaster Recovery and Reconstruction Situations //Post-trauma and the Recovery Governance of Cultural Heritage. – Singapore : Springer Nature Singapore, 2022. – pp. 175-197.
13. Managing Disaster Risks for World Heritage [Electronic resource]. - Access mode: https://www.iccrom.org/sites/default/files/2018-07/managing_disaster_risks_for_world_heritage_en.pdf (date of access: 20.07.2023).
14. Ravankhah M. et al. Risk assessment and risk management for the protection of cultural heritage //Cultural heritage resilience against climate change and natural hazards: Methodologies, procedures, technologies and policy improvements achieved by Horizon 2020–700191 STORM project. – 2019. – pp. 55-88.
15. The fire at Windsor Castle - Royal Collection Trust [Electronic resource]. - Access mode: https://www.rct.uk/visit/windsor-castle/the-fire-at-windsor-castle (date of access: 27.07.2023).
16. Kincaid S. Practical challenges in mitigating the aftermath of fire in historic buildings //The Historic Environment: Policy & Practice. – 2021. – Vol. 12 (1). – pp. 77-96.
17. Vidholdová Z., Dˇatelinka A. Libušín–historical building fire //Delta. – 2021. – Vol. 15 (1). – pp. 92-100.
18. Building Adaptation - Union of civil engineers in Bulgaria [Electronic resource]. - Access mode: https://www.uceb.eu/DATA/CivBook/08.%20Building%20Adaptation.pdf (date of access: 05.08.2023).

Citation: Valentyn Ishchenko, "Aspects of the Restoration and Maintenance of Architectural Structures Taking into Account Fire Risks", Universal Library of Engineering Technology, 2023; 17-22. DOI: https://doi.org/10.70315/uloap.ulete.2023.003.