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PROBLEMS OF PRESERVATION, RECONSTRUCTION AND RESTORATION (ADAPTATION) OF OBJECTS OF CULTURAL HERITAGE OF INDUSTRIAL PURPOSE

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Abstract

Industrial heritage buildings present a dual challenge: interventions must meet contemporary safety and performance requirements while preserving the authenticity that underpins heritage value. This article proposes a metrics-based approach to adaptive reuse by synthesising recent international research in architecture, structural engineering, geotechnics, and environmental assessment. A systematic review and evidence mapping of studies published between 2015 and 2025 link key project questions to measurable indicators structured around four pillars: authenticity, structural performance, monitoring and digital twins, and geotechnical and adjacent-construction risk. The synthesis defines operational targets, including volumetric and material retention thresholds for authenticity; performance-based deformation and drift limits for steel and masonry retrofits; traffic-light trigger values for settlement, vibration, and crack activation in early-warning monitoring systems; and life-cycle indicators such as retained-structure share, embodied-carbon balance, and carbon payback time. The article makes two principal contributions. First, it reframes authenticity as a quantifiable design boundary that can be optimized alongside structural and environmental objectives. Second, it consolidates dispersed international criteria into a concise, practice-oriented toolkit suitable for specification, procurement, and project control. The proposed framework supports transparent evaluation of trade-offs, prioritisation of minimal-intrusion strengthening, and use of digital monitoring as an active management tool. The article concludes with recommendations for pilot applications and standardisation pathways, positioning evidence-based metrics as a bridge between heritage values and contemporary safety, resilience, and sustainability goals.

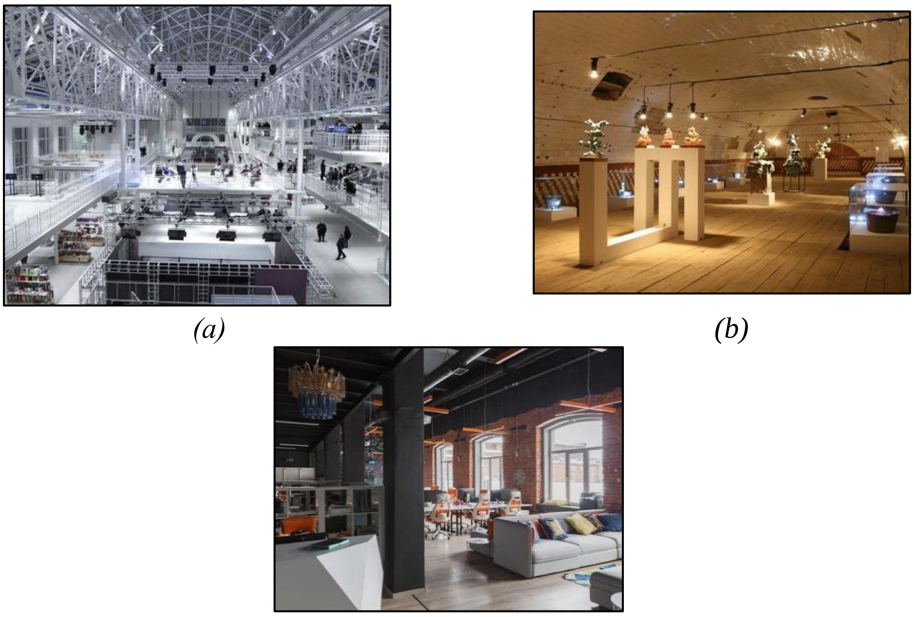
Keywords: Industrial heritage; Adaptive reuse; Authenticity metrics; Structural retrofitting; Digital monitoring.

I. Introduction

Objects of cultural heritage of industrial purpose were predominantly formed at the turn of the XIX-XX centuries. It is this time period that is singled out as the most significant in terms of quantitative and cultural value. From the functional point of view, this period includes factory buildings, manufactory shops, railway depots, factory complexes, combining stone (brickwork) vertical bearing structures with metal span solutions, which sets the problem of their preservation and adaptation.

According to the sampling data from the State Register of Cultural Heritage Sites (keywords «plant», «workshop», «factory», «manufactory», «depot» were used), 391 objects of cultural heritage of industrial purpose are registered, of which 247 objects have a direct purpose – «factory». The quantitative mapping of the objects on the map of the Russian Federation (see fig. 2 for details) demonstrates a pronounced concentration of industrial objects of cultural heritage in the European part of the country; east of the Urals, the density decreases and remains along the Trans-Siberian Railway. This territorial distribution reflects the historical industrialization of the turn of the century and at the same time underlines the imbalance in access to financing of restoration works: most objects are concentrated where the investment and tourist potential is the highest.

Some of the objects have already been adapted and brought into outstanding public spaces. Among the most prominent objects are the center of contemporary art in Moscow, GES-2 (fig. 1, a), the art cluster «Vinzavod» (fig. 1, b), as well as the buildings of the Otbelnyi and Gravernyi shops of the former Trichogornaya Manufactory (fig. 1, c), which now house office space and exhibition areas.



(a) *(b)*

(c)

Fig. 1. General view of the object of cultural heritage space (a - HPS2; b - Winzavod; c - Engraving shop of the Trichogornaya Manufactory).

Fig. 2. Distribution of industrial objects of cultural heritage across the territory of the Russian Federation.

II. Materials And Methods

The research material is foreign publications devoted to the preservation, reconstruction, and restoration of industrial objects of cultural heritage. The search strategy included combinations of keywords, namely:

- *industrial heritage*;
- *adaptive reuse*;
- *conservation*;
- *restoration*.

The materials referenced by the authors within the selected papers were also examined. A paper was accepted for analysis in the following cases:

1. the presence of a structural engineering or architectural aspect;
2. descriptions of implemented (or modeled) preservation practices for industrial structures;
3. the peer-reviewed nature of the publication. Texts devoted exclusively to archaeological or artistic analysis were excluded, as well as works without a clear methodological part.

III. Results

Adaptive reuse and preservation of authenticity

The study by F. Nepravisht examines the transformation of a 1940s Albanian industrial factory into an «open neighborhood» with office, residential, and public functions [VI]. The author applied GIS analysis to match the building density and historical morphology, and then checked the project for compliance with ICOMOS (International Council on Monuments and Sites) standards according to five authenticity criteria, namely:

- **spatial volume (shape) and composition.** Spatial layout, proportions, span spacing, and external appearance of towers and chimneys. The objects are surveyed by laser scanning, and then the BIM models are compared with the results of the design work before the intervention. This criterion of authenticity is characterized by an indicator called: «volume preservation ratio» (ratio of the original area to the design area) ≥ 0.75, which is considered acceptable;
- **material and texture.** Genuine brick, riveted steel, cast iron columns, patina of concrete. Capture the proportion of elements replaced. For early twentieth-century buildings, the international benchmark is no more than 30% complete replacement. Non-working units of «mothballed» machines are included in the exposition as material evidence of production;
- **traditions and technology of execution.** Method of stone (brick) masonry, types and kinds of joint filling, rivet joints, and manual molding of cast parts. Evaluated by laboratory analysis of metal/mortars, joint endoscopy, and 3D cavity endoscopy;
- **use and function.** The reasoning is based on the importance of preserving the parts of the Object that need to be preserved in order to retain an external industrial identity after the completion of the adaptation. This criterion is characterized by a «functional continuity coefficient» - the proportion of areas where the true functional purpose (industrial logic, e.g., light belt, crane girder) can be read;
- **spirit of place.** Intangible sensations: the acoustics of the workshop, the smell of oils, working signs or markings. Former factories are characterized by rhythmic sounds, vibrations, and specific light through cog lights. They are recreated through interactive installations and media, which increases the «identification index» of visitors. In the Albanian factory, the preservation of the noise background of compressors became a key «marker of authenticity» for local residents [VI].

The five criteria thus act as an interrelated matrix: physical parameters (form, material, technique) set the boundaries of acceptable intervention, while «function» and «spirit of place» provide a living link between the object and society. Quantitative evaluation techniques allow an objective balance between preserving authenticity and adapting the building to modern use.

In turn, the article by S. Samadzadehyazdi quantitatively assesses «engineering» and «social» authenticity on the example of three Iranian factories [VIII]. The authors form an 18-point scale and show that hybrid use (culture + creative spaces) gives, on average, 27% higher integral score than only museum scenarios, while the key remains the inviolability of the original rafter systems.

Structural safety and reinforcements.

P. Tartaglia et al. modeled three ways to seismically reinforce a 1965-built frame shop:

- X-bonding;
- local increase of column cross-sections;

- application of dissipative dampers [X].

The variant «bonds + dampers» provided the maximum reduction of relative displacements from 2.9 % to 1.6 % with an increase in metal capacity by only 6 kg/m². A. Formisano et al. tested a «DUO-system» in masonry: a 30-mm inner layer of glass mesh covered with plaster and a 20-mm outer insulating ceramic layer [III]. On the vibration bench, the building model withstood PGA = 0.35g without loss of bearing capacity, and the heat flux was reduced to 0.48 W/(m² K).

In this case, the probability of failure of 36% is significantly higher than the permissible level for cultural heritage sites (target value ≤ 0.1–1%); the reliability index $\beta \approx 0.36$ is much lower than the standard (required ≥ 3.0–3.7); the safety factor of 1.07 is insufficient (target value ≥ 1.5–2.0). These results indicate a critical condition of the structure and the need for urgent emergency measures, such as strengthening the load-bearing elements, limiting loads, or temporarily preserving the site. It is recommended to conduct a detailed survey and update the calculated parameters based on additional monitoring data.

Monitoring and numerical models.

P. K. Bhandari systematizes the sensitivity of classical sensors: strain gauges detect cracking with 5 times lower sensitivity than fiber optic «fiber Bragg gratings», which in turn is important for early warning [I].

The application of spatial state models for the structural behavior of cultural heritage sites and the creation of their digital twins includes the following steps in the case under consideration:

1. Formalization (determination of the physical condition of the structure, operational environment parameters, the condition of structural materials, and other deformation characteristics).

2. Kalman filtering for model prediction, which includes (prediction of the state, assessment of the uncertainty of the prediction, adjustment of the state estimate, and prediction of degradation).

3. Analysis of the system's observability.
4. Determination of the location of sensors.
5. Determining the possibility of restoring the system's state.
6. Developing practical recommendations for monitoring the technical condition of a cultural heritage site.

A complete recovery of the system state is possible with a properly selected mathematical model, an optimal sensor system, a high-quality Kalman filter configuration, and regular model verification. However, in practice, there is always some uncertainty that needs to be taken into account when making decisions for a cultural heritage site.

F. Carrara et al. trained the ResNet-50 convolutional network on 1.9 million artificial and 45 thousand real seismograms; the algorithm determines the beam damage and detects the manifestation of cracks up to 0.3 mm [II]. F. Niccolucci demonstrates a prototype of «heritage digital twin»: a cloud model of buildings «remembers» BIMgeometry and historical layers, which allows virtual observation of intervention options and immediately fixes their impact on the load-bearing scheme [V].

Environmental and economic sustainability.

For the renovation of a warehouse in Toronto, Opher T. and co-authors calculated and modeled the full life cycle. Retaining 65% of the structures reduced total CO_2-eq. emissions by 46% and energy costs by 41% compared to a new residential building of similar size [VII]. Gursel A. P. and his team generated 216 office/school to residential apartment conversion scenarios (USA, EU-27, China) [IV]. The median reduction in operating energy was 58%, and the carbon payback of major renovations comes at year 8, twice as fast as for new buildings. Szromek A. R. surveyed 17 public industrial museums in Europe and identified critical factors for achieving ESG status: the use of at least 20% recycled materials in current restorations [IX].

In this study, the LCA system boundaries included the materials used (slag-reinforced concrete and recycled steel), the transportation distance of building materials and structures from the supplier, and the greenhouse gas emissions from diesel-powered construction equipment. The operational forecast included a 75% reduction in energy consumption through the use of resource-saving systems. The carbon emission payback period was estimated to be 3-13 years, with a service life of 60 years. The sources of data for applying this approach are:

1) ISO 14040/14044 — general principles of LCA;

2) EN 15978 — specification for buildings (divided into stages A–D);

3) ISO 21930 — environmental declarations for construction products (EPD).

The distribution rules and selection of distribution are variable and depend on the availability of data on the cultural heritage object (sufficient statistical data → normal; expert assessments → triangular; lack of data → uniform), as well as on physical limitations and the goals of the analysis.

The uncertainty analysis of the LCA results, performed by Monte Carlo simulation, showed that with the following parameters of the base calculation (1250t of greenhouse gas emissions; application of a triangular distribution of the building's service life of 30, 60, 90 years; the distance of transportation of materials of 50-300 km – uniform distribution; the content of secondary raw materials in steel – normal distribution (90±5 %), the following values are observed. The greenhouse gas emissions were 980-1550 t (90% confidence interval). It is necessary to use regional databases: for example, the carbon intensity of electricity in Ontario differs from that in Europe, which affects accuracy. Increasing the service life to 90 years → +22% emissions; reducing it to 30 years → −23% emissions; transporting >300 km → +19% emissions.

A summary table was formed to visualize the methodological research directions of the ten publications analyzed. This table presents the problems raised by the authors of the papers, the research approaches applied, and the empirical findings, allowing us to relate the contribution of each source to the overall picture of industrial heritage adaptation (for more details, see the following table). Tab. 1.

Table 1. Problems and solutions of foreign researchers

№	Source of literature	Problematic	Methodological solution	Conclusions
1	Nepravishta F., 2024 [VI]	How to integrate a large Soviet factory into a modern urban environment while preserving authenticity	GIS-morphological analysis + master plan with multifunctional «pillars»	By retaining 82 % of the volume, the usable area can be increased by 24,000 m^2, and the local identity can be strengthened
2	Samadzadehyazdi S. et al., 2020 [VIII]	Quantifying Authenticity in Adaptive Use	18-point «engineering + social authenticity» scale	Hybrid «culture + creative industries» ↑ integral score by 27% vs. museum scenarios
3	Tartaglia R., 2022 [X]	Improving earthquake resistance of steel frames with minimum metal consumption	Models of three schemes (X-links, reinforcement nodes, dampers)	Combination «bonds + dampers» ↓ 2.9 %→1.6 % at +6 kg/m^2 steel
4	Formisano A., 2021 [III]	Simultaneous thermal and seismic conversion of historical masonry	"DUO-system" - 50 mm composite cladding	Heat loss -25%, pre-deformation +30%
5	Bhandari P. K., 2021 [I]	Simultaneous thermal and seismic transformation of historical masonry	«DUO-system - 50 mm composite cladding	FBG grids are 5 times more sensitive or detect crack formation earlier
6	Carrara F. et al. , 2022 [II]	Machine learning for monitoring historical sites	ResNet-50 for 1.9 million artificial seismograms	Fracture detection accuracy 94%, localization ±0.3 mm
7	Niccolucci F., 2024 [V]	Creating a «Digital twin» for predicting and testing interventions (external influences)	Cloud BIM + IoT sensor streams (EOSC)	Virtual scenarios ↓ survey costs and accident risk
8	Opher T. et al., 2021 [VII]	Full life cycle assessment of warehouse (industrial facility) renovation compared to new construction facilities	Cradle-to-grave Ecoinvent models	Preservation of 65 % of structures ↓ GWP (Global Warming Potential) by 46 %, and energy efficiency by 41 %
9	Gursel A. P. et al., 2023 [IV]	Energy and carbon balance of converting non-residential	Parametric LCA + EnergyPlus	E ↓ 58 %, GHG (greenhouse gas emissions) ↓ 65 %,

Table 1. Problems and solutions of foreign researchers

№	**Source of literature**	**Problematic**	**Methodological solution**	**Conclusions**
		buildings into residential buildings		«CO_2 payback» ≈ 8 years
10	Szromek A. R., 2025 [IX]	ESG metrics in public museums in Europe that are adapted to industrial facilities	Fin. analysis	«Green» status requires 20% recycled materials

Note: The above metrics are drawn from international case studies and standards; they provide objective targets (threshold values, performance improvements) that inform best practices in industrial heritage adaptation.

Geotechnical Stability and Construction-Adjacent Risks. One critical theme emerging from international practice – and requiring expansion – is the geotechnical and construction-adjacent risks involved in adaptive reuse of industrial heritage buildings. Often, historic industrial structures have shallow foundations and are situated in dense urban environments, making them vulnerable to damage from nearby excavation, dewatering, and vibration. The *underlying soil and groundwater conditions* thus become as important as the building's internal structure in preservation efforts.

Groundwater Dynamics: Lowering of the water table during adjacent construction can induce consolidation and differential settlement in heritage foundations. International best practice mandates close monitoring of groundwater levels and proactive control measures. For example, a case study of a deep excavation for a 3-level basement in Jakarta (adjacent to three 19th-century heritage buildings) maintained the pre-construction water table via artificial recharge whenever drawdown became excessive. By isolating the site with diaphragm walls and re-injecting water, engineers successfully lowered the water table from 1 m to 15 m depth without any observable cracks or deformation in the nearby historic structures. This remarkable outcome – *14 m groundwater drawdown with zero damage* – underscores the effectiveness of stabilizing groundwater as a preservation strategy. Generally, heritage projects establish a threshold for water table change (e.g., no more than a few meters drop); crossing this «yellow flag» triggers immediate countermeasures (such as on-site recharge wells) to prevent soil shrinkage beneath old foundations.

Excavation and Settlement: Deep excavations or tunneling next to historic factories can cause ground movements that propagate into adjacent buildings. Even a minor settlement can crack brittle masonry or disrupt centuries-old brick arches. International guidelines, therefore, call for preemptive structural support (underpinning, contiguous pile walls, etc.) and real-time deformation monitoring. For instance, the U.S. National Park Service recommends installing inclinometers and crack gauges on historic buildings before nearby excavation and enforcing a «no settlement» goal – essentially restricting even incidental movement. In practice, a commonly accepted limit is to keep differential settlement under ~1:1000 (0.1% strain) for vulnerable heritage masonry – roughly equivalent to a few millimeters over a 5–10 m span. Many projects adopt a tiered alert system: settlement <5 mm is *green* (negligible); >5–10 mm *yellow* (caution, initiate remedial actions); >10–15 mm *red* (work stoppage and structural intervention).

These values are stricter than for modern buildings, reflecting the lower tolerance of aged structures. For example, the Crossrail project in London (a large tunneling endeavor) set extremely conservative trigger levels for settlement and building tilt to protect historic buildings, with green triggers often as low as 3 mm and any movement beyond 10 mm requiring immediate engineering review. Likewise, a "quick response" monitoring regime is advised: automated levels or robotic total stations measuring key points on the façade daily or continuously, so that emerging trends are caught before substantial cracks form.

Vibration Protection: Construction vibrations – from pile driving, heavy trucks, jackhammers, or blasting – pose a serious risk to fragile industrial heritage, which often has unreinforced masonry and old mortar with limited damping capacity. International standards such as DIN 4150-3 (Germany) and research by preservation engineers have established guideline thresholds for peak particle velocity (PPV) to avoid cosmetic or structural damage. Typically, a PPV of 2–5 mm/s is recommended as a safe limit for very sensitive or historic structures. For comparison, modern concrete buildings can often tolerate 10–20 mm/s without issues, but a 19th-century brick mill with plastered walls may start cracking at vibrations well below that. Case studies illustrate the importance of tailoring these limits: at a museum in Ohio housing 1850s wall murals, engineers set a strict PPV limit of 0.12 in/s (≈3 mm/s), just above ambient vibration levels, to protect the priceless plaster artwork. In another instance, an Australian team established a 3 mm/s cutoff for a 1920s heritage church and adjusted construction techniques when monitors hit ~2.8 mm/s during piling. Mitigation measures include using smaller or manually operated equipment (e.g., replacing vibratory pile driving with hydraulic jacking), increasing distance from vibration sources, and temporary shoring of weak elements. Continuous vibration monitoring with geophones is now standard near heritage sites, with automated alerts (SMS/email) whenever vibrations approach the threshold. This real-time feedback enables contractors to pause or modify activities (for example, halting excavation blasting if vibrations exceed 3 mm/s and switching to a lower impact method).

Early-Warning Indicators: A common theme across groundwater, settlement, and vibration risks is the use of early-warning «traffic light» systems. International practice integrates multi-sensor data into a dashboard that classifies conditions as green, yellow, or red in real time. For example, if crack gauges on an industrial warehouse show a stable 0.1 mm width (green) that suddenly increases to 0.3 mm (yellow threshold for crack activation), engineers can be alerted to investigate before it widens further. If vibration monitors in a historic steel-framed shop consistently read under 2 mm/s (green) but a day of sheet piling pushes readings to 4 mm/s, a yellow alert would prompt immediate review of the construction activity and likely a temporary halt to prevent crossing into red (unsafe) levels. Threshold values for these alerts are often set at ~50–80% of the ultimate allowable limits so that there is a margin of safety.

The «red lines» for heritage structures are set very low compared to ordinary buildings. These stringent criteria, drawn from global experience, serve to preempt irreversible damage: by the time a crack is visibly gaping, or a wall is visibly tilting, it is often too late to fully preserve authenticity. Thus, the emphasis is on prevention and timely intervention, enabled by quantitative monitoring. In summary, addressing geotechnical and adjacent construction risks in adaptive reuse requires an interdisciplinary approach – geotechnical engineers, structural engineers, and conservation specialists working in concert – to design both protective measures (e.g., underpinning, cutoff walls) and an integrated monitoring system that safeguards the historical fabric throughout nearby construction activities.

IV. Discussion

The obtained results confirm that the current practice of handling (adaptation) of industrial cultural heritage objects is based on the following:

- authenticity (authenticity) of the Object;
- constructive safety;
- BIM-modeling (digital support);
- geotechnical conditions of the underlying environment.

Authenticity as a constraint on the depth of interventions. The objects of the Albanian mill and Iranian factories demonstrate that the integral «score» of authenticity (authenticity) increases when the new use continues the production logic (creative industries, public workshops) rather than leveling it by museum conservation [VI, VIII].

Structural modernization without rough interventions. The solutions «bonds + dampers» for steel frames and «DUO-system» for masonry demonstrate that it is possible to increase seismic resistance by 30-40% with a minimum increase in mass and without loss of historical connections [III, X]. Taking into account Russian SP 14.13330 «Seismic resistance of buildings», these technologies can become an acceptable alternative to the ubiquitous «wallpaper» reinforced concrete reinforcement, which actually deprives the material of authenticity.

From monitoring to control. The shift towards digital twins puts monitoring into the «early warning» mode, when a crack is detected at the first manifestations, rather than after a visual opening of 0.3 mm [I, II, V]. For the significant prevalence of Russian industrial cultural heritage sites (more than 391 units), this is a way to optimize the budget: with an average annual funding deficit, remote monitoring allows to reallocate resources to objects with the highest risk of failure of the load-bearing scheme.

Climate Benefits of Adaptation. Comparative analysis of the life cycle of the Canadian warehouse and parametric modeling of 216 conversions show that the «carbon payback» of major renovation comes on average after 8 years, while for new buildings this period exceeds 15 years [IV, VII]. In the context of the gradual introduction of carbon regulation in Russia, foreign experience becomes an additional economic argument in favor of preservation rather than demolition [IX].

The above analysis confirms that successful adaptive reuse of industrial heritage internationally is underpinned by four key pillars: (a) authenticity of the object; (b) structural safety; (c) digital support (BIM and monitoring); and (d) geotechnical risk management. Each pillar is associated with quantitative metrics and techniques as documented in global practice. A pertinent question is how these international metrics and practices can translate to Russia's regulatory and standards landscape – in particular, where gaps or misalignments exist in current GOST (Russian Federal Standards) and SP (Building Codes).

Authenticity Metrics vs. Russian Standards: International charters (e.g., ICOMOS) and studies often quantify authenticity through measures like volume retention ratios and material preservation percentages. For instance, retaining ≥75% of original structural volume and ≥70% of original material (≤30% replacement) is considered a benchmark for acceptable intervention. In Russia, by contrast, heritage protection regulations (e.g., laws on cultural heritage) emphasize preservation of *appearance* and *significant elements* in qualitative terms, but do not specify numeric thresholds. There is currently no direct equivalent to a «volume preservation ratio» in Russian restoration norms – decisions on how much of an industrial building can be removed or altered are left to expert judgment and individual project approvals (often via the Ministry of Culture's commissions). The lack of quantitative criteria can lead to variability in practice. Adopting international authenticity metrics into Russian guidelines could introduce more objectivity – for example, stipulating that any adaptive reuse of a listed industrial OCH (object of cultural heritage) should strive to keep at least, say, 70% of the historic fabric. It would also align with global trends and facilitate clearer evaluation of projects. A potential mismatch here is that Russian regulations traditionally differentiate between *restoration* and *reconstruction* in a binary way, whereas adaptive reuse is a spectrum. Introducing metrics (like functional continuity coefficients or authenticity scores) would help bridge this by quantifying outcomes between pure restoration and full reconstruction.

Structural Retrofit Techniques: Russian seismic and structural codes (e.g., SP 14.13330.2018 «Construction in Seismic Regions») ensure safety but often default to conventional strengthening methods – such as adding reinforced concrete jackets or shear walls – which can compromise authenticity (encasing historical steel or masonry in concrete «shells»). International practice shows viable alternatives: Tartaglia *et al.* demonstrated that steel mill frames can meet seismic requirements by adding discrete steel bracings and dampers with only a 6 kg/m² increase in mass. Such techniques maintain the original structural system's legibility. Currently, Russian codes do not explicitly encourage innovative devices like viscous dampers or fiber-reinforced polymers for heritage retrofit – these might fall under «experimental» methods requiring case-by-case approval. There is an alignment opportunity: performance-based design approaches (common internationally) could be gradually incorporated into Russian standards, allowing engineers to use advanced simulations to prove that minimal interventions achieve the required safety level. For example, rather than mandating a blanket addition of concrete walls for an unreinforced masonry factory, codes could accept designs that use a «DUO» composite coating or internal steel ties if they are validated to provide a target % increase in load capacity or drift reduction. The discussion in the Results noted that applying the «bonds + dampers» scheme from Italy could be an *acceptable alternative* to the ubiquitous concrete jacketing in Russia – realizing this would likely require updates to technical manuals and pilot projects to build local confidence. In summary, Russian structural codes currently contain gaps regarding modern retrofit materials and energy-dissipating devices; closing these gaps by referencing international case studies (perhaps via a national guideline for heritage structures) would promote both safety and authenticity.

Digital Twin and Monitoring Adoption: A notable difference is the integration of digital monitoring into the lifecycle of heritage projects. Internationally, as seen, the concept of a *heritage building digital twin* is emerging – continuous data collection (from sensors) combined with BIM to inform maintenance. Russian practice in monitoring of buildings (GOST R 53778–2010 for structural health monitoring, for instance) still relies largely on periodic manual inspections and simple instruments (crack gauges, visual surveys) at set intervals. Real-time IoT-based monitoring is not yet codified in Russian standards – there is no mandate that a reused factory museum must have accelerometers or moisture sensors installed, for example. Furthermore, while BIM use is growing in new construction in Russia, its application in restoration is nascent; a standardized «HBIM» (Historic BIM) template for industrial heritage is lacking. The Discussion of findings suggests that Russia's 391 documented industrial cultural heritage sites could greatly benefit from remote monitoring to optimize maintenance budgets. To translate this, Russian authorities could issue recommendations or add non-mandatory appendices to codes encouraging digital monitoring for valuable heritage, with thresholds for action. For example, similar to how the Venice Charter 1964 called for continuous monitoring in principle, Russian guidelines might encourage creating a digital model for any major adaptive reuse, where sensor data (cracks, tilt, vibrations) are fed in. Alignment example: if Russian building stock monitoring rules were updated to allow sensor data as a legitimate basis for decision (rather than waiting for visible damage), it would align with the early-warning philosophy seen abroad. A mismatch currently is the regulatory mindset: Russian codes tend to be prescriptive (what method to use) rather than performance-based (what outcome to achieve). Digital twin approaches are performance-oriented – detecting anomalies and managing by outcomes. Bridging this will require not just code changes but training and awareness so that project stakeholders trust sensor data and simulation outputs in making conservation decisions.

Geotechnical and Vibration Criteria: In Russian practice, vibration limits and allowable settlements for buildings are addressed in general construction standards (e.g., SP 22.13330.2016 for foundations, which might allow settlements on the order of 50 mm for new buildings). However, there is no dedicated standard for historic structures that tightens these tolerances. The international metrics highlight much lower thresholds for heritage. For instance, Swiss Standard SN 640312 and DIN 4150 allow only 3 mm/s PPV for ancient buildings, whereas Russian norms such as SanPiN (sanitary standards) historically permitted higher vibrations for residential/historic alike, not distinguishing sensitivity. This is a gap: adopting a differential approach (like a category for «especially valuable historical buildings» with strict vibration limits) would be prudent. Similarly, while Russian codes demand project-specific geotechnical studies, they do not set alert criteria during construction – it is usually the contractor's responsibility to prevent damage, without quantified trigger values. International practice, as summarized, uses trigger values as contractual and safety tools. Russia could incorporate «traffic light» schemes into technical regulations for any construction near heritage sites. For example, Moscow city authorities might issue guidelines that if excavation is within X meters of a cultural heritage site, the project must implement monitoring with defined green/yellow/red thresholds (perhaps referencing Table 2 values or relevant international norms).

Translating international metrics to the Russian regulatory landscape will involve updating existing GOST/SP documents to include quantitative benchmarks and modern techniques, as well as developing new guidance specific to adaptive reuse of cultural heritage. Russian standards historically excel in ensuring structural safety; the challenge is to broaden their scope to explicitly include *authenticity conservation and innovative monitoring* as integral parts of the design criteria. There is encouraging movement – for instance, Russia's gradual introduction of carbon accounting in construction is noted, aligning with the global emphasis on life-cycle carbon benefits of reuse. By acknowledging gaps (like the absence of vibration limits for heritage, or missing BIM guidelines) and filling them with proven international practices, Russian authorities and professionals can better balance preservation with development. Not only would this protect cultural legacy, but it would also foster international collaboration, as engineers and architects could more easily communicate using a shared set of metrics (e.g., talking in terms of «carbon payback» or «authenticity index» which are universally understood). The adaptations must be done carefully, piloted through *examples of alignment or mismatch*: for instance, comparing an earthquake retrofit done to Eurocode vs. to Russian code on a similar factory to illustrate differences in outcome. Such comparative pilots and joint research (possibly through ICOMOS or UNESCO programs) could smooth the integration of these advanced metrics into Russia's regulatory framework, ultimately raising the standard of industrial heritage adaptive reuse domestically.

V. Conclusion

The conducted analysis of foreign studies has shown that successful adaptation of industrial heritage is based on the following:

- authenticity (authenticity) of the Object;
- structural safety;
- BIM modeling (digital support);
- geotechnical conditions of the underlying environment.

Thus, the integrated application of foreign techniques - when adapted to the Russian regulatory framework and climatic conditions - provides not only authenticity, but also economic, environmental, and social efficiency of adaptation projects. Further research should be focused on the experimental implementation of the described technologies in Russian cities, the development of domestic BIM templates for industrial heritage, and the formation of national methodological recommendations for assessing the carbon footprint of restoration solutions.

This extended analysis of foreign studies and best practices has reinforced that successful adaptation of industrial heritage buildings rests on an integrated approach – one that values authenticity, ensures structural integrity, leverages digital tools, and mitigates environmental and geotechnical risks. International experience shows that careful, evidence-based interventions can harmoniously integrate historic factories into modern use, preserving the «spirit of place» while delivering economic and social benefits. Crucially, the quantitative benchmarks (thresholds, indices, performance metrics) provide a common language to evaluate and guide such projects objectively.

When adapted to the Russian regulatory framework and climate, these techniques offer significant improvements over traditional approaches. For example, applying seismic dampers and composite materials in lieu of heavy concrete jackets can boost safety by 30–40% without sacrificing authenticity. Implementing remote monitoring and early-warning systems can optimize resource allocation across Russia's vast territory of industrial heritage sites. Embracing life-cycle carbon assessment aligns industrial reuse with Russia's emerging carbon regulation policies, bolstering the economic case for preservation over demolition.

Overall, the findings underscore that adaptive reuse is not at odds with development – it is a catalyst for sustainable development. By investing in modern methods (BIM, sensors, advanced materials) and updating standards to reflect proven international metrics, Russia can unlock the full potential of its industrial cultural heritage site assets. These monuments of past industry can become pioneers of innovation in conservation, demonstrating how heritage adaptation contributes to urban revitalization, resilience, and reduced carbon footprint. Further steps should include pilot projects in Russian cities applying the described techniques, the creation of localized BIM libraries for historic industrial types, and the formulation of national guidelines (methodological recommendations) for evaluating interventions – including a «carbon footprint» assessment protocol for restoration solutions. Such measures will facilitate knowledge transfer from international research into Russian practice, ensuring that the country's industrial heritage is not only preserved in form but also remains living heritage, actively integrated into the cultural and economic life of communities.

The limit state criteria for structures in cultural heritage objects are based on standard construction regulations, but are supplemented with specific requirements aimed at preserving the historical and cultural value of the asset. These functions define clear threshold values: once exceeded, the structure either loses its load-bearing capacity or fails to meet operational standards.

First group of limit states. This category is associated with a sharp deterioration in load-bearing capacity and a real risk of complete collapse. For architectural monuments and historic buildings, it includes:

1. Various types of structural failure — ranging from plastic and brittle damage to fatigue failures caused by long-term load exposure.
2. Loss of stability — affecting either individual components or the entire structure. This may manifest as overturning, lateral displacement, or distortion of the original structural form.
3. Critical deformations — excessive deflections, shifts, crack propagation, or weakening of connections caused by material ageing or external impacts. Such changes lead to exhaustion of the load-bearing capacity.
4. Chain-reaction failure — a sequential damage process in load-bearing elements that may trigger the collapse of a significant part or the entire building.

For cultural heritage assets, even local damages can be critical if they affect elements protected as part of the heritage value. In such cases, the structural condition may be classified as a limit state.

Second group of limit states. This group covers situations where normal operation is disrupted, service life is reduced, or usage conditions deteriorate. In the context of architectural monuments, this manifests as:

1. Exceeding permissible deformations — unacceptable deflections or rotation angles of structural elements that distort the historical appearance of the building or impair its functionality.
2. Excessive vibrations — oscillations in the foundation or load-bearing components that cause discomfort for visitors, interfere with operation, or threaten the integrity of finishes and decorative details.
3. Crack formation — damage that does not lead to immediate collapse but reduces operational performance, degrades visual appearance, or accelerates further deterioration.
4. Material degradation — weathering, biological attack (mould, mildew), and corrosion of metal components. These processes gradually reduce the durability of structural elements.

Failure of waterproofing and drainage systems — moisture ingress into structural components, which accelerates material deterioration, promotes mould growth, and causes rot in wooden elements.

Special limit states. These arise under the influence of extreme factors — natural disasters or man-made incidents. For cultural heritage objects, this may include:

1. Damage due to natural disasters — earthquakes, floods, landslides, hurricanes, or fires- can cause severe structural damage.

2. Damage from man-made impacts — vibrations from traffic, construction work in protected zones, industrial emissions, or changes in groundwater levels due to urban development.
3. Damage from unauthorised actions — vandalism, illegal alterations, or unapproved restorations leading to irreversible changes in the appearance or structural integrity of the asset.

Specific features of cultural heritage objects. When assessing limit states for such buildings, a number of key features must be taken into account:

1. Historical and cultural value — even minor damage to protected elements may be considered critical, as it affects the authenticity of the asset.
2. Restrictions on restoration methods — any interventions must preserve original materials, construction techniques, and architectural solutions.
3. Impact of external factors — special attention is paid to protection against atmospheric exposure, biological attack, environmental pollution, and other adverse processes.
4. Regulatory requirements — compliance with current heritage protection regulations, including regular monitoring of technical condition, control of foundation deformations, and assessment of geotechnical conditions.

Upon detection of signs of a limit state, it is essential to promptly notify the relevant heritage protection authorities and take measures to stabilise the structure — including the implementation of emergency anti-response and anti-collapse measures.

1. Uncertainty management is based on three principles:
2. Collection of heterogeneous data (direct measurements, analog information, and historical archives).
3. Conservative modeling, which involves calculating loads with a safety margin and using reduced material properties.
4. Adaptability, which involves regularly updating models based on monitoring data and new surveys.

This approach ensures the safety of the facility even when the initial data is incomplete, minimizing risks through proactive measures and conservative assumptions. When signs of a critical condition (critical cracks, rolls, and shifts) are detected, an emergency intervention is initiated, followed by a detailed analysis of the causes.

Conflict of Interest:

The authors declare that there is no conflict of interest regarding this article.

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