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ARCHITECTURAL-TRANSFORMATIONAL MODEL FOR ADAPTING EXISTING INDUSTRIAL BUILDINGS INTO MODERN FUNCTIONAL FACILITIES

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ABSTRACT: Industrial degradation and post-industrial urban restructuring necessitate effective frameworks for converting redundant factory structures into modern, multi-functional urban assets. This paper presents a multi-criteria Architectural-Transformational Model (ATM) tailored for the adaptive reuse of existing industrial buildings. Grounded in structural engineering principles, building physics, and environmental life-cycle assessment (LCA), the study evaluates structural grid adaptations, thermal envelope retrofits, and spatial volumetric re-zoning. Empirical quantitative evaluations demonstrate that adaptive transformation achieves a 58.4% to 64.2% reduction in embodied carbon compared to complete demolition and new construction, while reducing capital expenditure by 22% to 35% and accelerating delivery schedules by 40%. The proposed ATM methodology synthesizes structural capacity assessments, microclimatic envelope upgrades, and flexible spatial layering (such as mezzanine insertion and atrium light-well carving). The findings provide municipal authorities, urban planners, and architectural practitioners with a standardized, actionable decision-making tool for sustainable post-industrial urban regeneration.

Keywords: adaptive reuse, industrial architecture, transformational model, embodied carbon, spatial restructuring, structural retrofitting, building performance, urban regeneration

1. INTRODUCTION

The rapid evolution of modern production technologies, shifting global economic paradigms, and urban deindustrialization have left vast expanses of industrial buildings underutilized or abandoned in major metropolitan regions. These structures—ranging from early 20th-century heavy brick masonry textile mills to mid-century precast reinforced concrete factories and large-span steel assembly halls—occupy prime urban real estate. Historically, the prevailing municipal and commercial approach favored total demolition followed by ground-up new construction. However, contemporary urban sustainability imperatives, stringent carbon neutrality targets, and heritage preservation policies render demolition increasingly unsustainable (Bullon & Kohler, 2021; Douglas, 2018).

Demolition and replacement generate vast quantities of construction and demolition waste (CDW), representing over 35% of total solid waste streams in developed nations. Furthermore, total rebuilding forfeits the substantial embodied energy and carbon locked within existing foundation systems, structural concrete columns, and heavy masonry envelopes. Life-cycle carbon analysis indicates that up to 70% of a building's cradle-to-gate embodied carbon is concentrated in its structural frame and substructure (Foster, 2020). Preserving and retrofitting industrial building frames thus presents an extraordinary environmental leverage point, aligning with global Net-Zero initiatives.

Despite these environmental and economic incentives, adapting industrial architecture for modern human-centric functions (such as IT innovation hubs, creative co-working spaces, cultural centers, commercial retail, and residential lofts) presents formidable architectural and engineering challenges. Industrial structures were engineered primarily for heavy mechanical equipment, uniform overhead loading, and process flows—not for human thermal comfort, acoustic privacy, natural daylighting, or modern building code compliance. Key spatial and physical incompatibilities include:

- **Extreme Spatial Volumetry:** Excessive floor-to-ceiling heights (6 to 12 meters) and deep floor plates (exceeding 40–60 meters in width) that create dark, unlit core zones far removed from exterior fenestration.
- **Thermal Envelope Deficiencies:** Uninsulated single-skin masonry or uninsulated corrugated metal cladding with extensive cold bridging, leading to severe thermal losses and internal condensation risks.
- **Structural Grid Rigidity:** Fixed column bay spacings (typically 6x6m, 6x9m, or 12x12m) that require creative structural adaptation to accommodate modern circulation, stair cores, and acoustic partitioning.
- **Regulatory & Fire Safety Barriers:** Non-compliance with contemporary seismic resistance standards, fire egress distances, and universal accessibility regulations.

To bridge these architectural gaps, this study formulates a comprehensive Architectural-Transformational Model (ATM). The model establishes systematic criteria for structural evaluation, spatial reorganization (via vertical infill and light-well carving), thermal envelope optimization, and functional programming. The objective of this paper is to validate the ATM framework, quantify its environmental and operational performance gains, and provide architectural practitioners with an empirical design methodology.

2. MATERIALS AND METHODS

The methodology relies on an integrated, multi-disciplinary research strategy combining architectural structural analysis, thermal building physics simulation, and comparative life-cycle carbon assessment (LCA). The research framework evaluates four major industrial building typologies commonly subjected to urban conversion: (1) Heavy Industrial Steel Frameworks, (2) Precast Reinforced Concrete Skeleton Buildings, (3) Unreinforced Load-Bearing Brick Masonry Warehouses, and (4) Post-Soviet Standardized Panel/Column Industrial Complexes.

2.1 Mathematical and Evaluation Formulation of the Architectural-Transformational Model

The ATM framework utilizes three core quantitative metrics to assess adaptive transformation viability:

1. Embodied Carbon Reduction Index (ΔE_carbon):

$$\Delta E_carbon = [(E_dem + E_new_struct) - (E_retro_struct + E_envelope_upg)] / (E_dem + E_new_struct) \times 100\%$$

where E_dem represents carbon emitted during demolition and debris transport, E_new_struct is embodied carbon of a full new structural frame, E_retro_struct is carbon expended during structural

strengthening, and E_envelope_upg is embodied carbon of new high-performance envelope materials.

2. Volumetric Spatial Efficiency Gain (SE_gain):
$$SE_gain = (A_infill + A_mezzanine - A_cutout) / A_original_floor \times 100\%$$

where A_mezzanine is the area added by vertical intermediate floor slabs, A_cutout is floor area carved out for light wells/atriums, and A_original_floor is the existing gross ground slab area.

3. Daylight Factor Improvement Ratio (DF_ratio):
$$DF_ratio = DF_post_transformation / DF_baseline$$

where DF_post_transformation is calculated using Radiance daylighting simulation software after inserting central skylights, atrium cutouts, and light shelves into deep floor plates.

Table 1. Architectural-Transformational Matrix across Industrial Structural Typologies

Industrial Typology	Structural Characteristics	Transformation Challenges	Recommended ATM Strategy
Steel Frame Assembly Sheds	Large open spans (18-30m), high clear heights (8-14m), steel trusses	Severe envelope heat loss, acoustic reverberation, high volume to heat	Vertical mezzanine insertion, double-skin curtain walling, acoustic baffles
Precast RC Skeleton Factories	Rigid 6x6m or 6x9m column grid, heavy floor capacity (10-15 kN/m²)	Low ceilings (3.6-4.2m), deep floor plate darkness, rigid column grid	Central courtyard/atrium cutout, perimeter office planning, exposed RC aesthetics
Masonry Brick Warehouses	Load-bearing exterior walls, timber/iron interior columns, small windows	Lateral seismic vulnerability, limited window area, moisture absorption	Interior steel seismic frame bracing, window opening enlargement, internal insulation
Post-Soviet Prefab Industrial	Precast concrete panels, standardized bay units, poor insulation joints	Joint degradation, low aesthetic appeal, low thermal resistance	Over-cladding ventilated facade, volumetric facade extensions, open-plan zoning

3. RESULTS AND DISCUSSION

Application of the Architectural-Transformational Model yielded significant architectural, environmental, and financial optimizations across all evaluated typologies. The findings confirm that adaptive reuse transcends mere physical preservation—it serves as an engine for functional metamorphosis, creating high-value urban space while drastically reducing environmental impacts.

3.1 Spatial Metamorphosis: Intermediate Slab Insertion and Light Well Carving

A central architectural innovation of the ATM model lies in resolving the structural height-to-depth discrepancy of industrial buildings. High-ceiling single-story workshops (8–12m clear height) were transformed into multi-tier functional environments by inserting lightweight steel-composite mezzanine floors. This volumetric subdivision yielded an average gross floor area (GFA) expansion of 38% to 45% without enlarging the building's physical footprint or roof envelope.

To alleviate core darkness inherent in deep floor plates (>30m depth), the ATM methodology incorporates strategic vertical cutouts—carving out multi-story central atriums equipped with high-transmittance roof skylights. Simulations indicate that introducing a central atrium equal to 8–12% of total roof area elevates average Daylight Factors in core zones from 0.4% (severely deficient) to 2.8% (fully compliant with modern office lighting standards). This daylight penetration reduces artificial lighting power density by 42% annually.

3.2 Thermal Envelope Upgrade and Energy Decarbonization

Unretrofitted industrial envelopes represent major thermal liabilities, characterized by U-values exceeding 2.5 to 4.0 W/m²K. Under the ATM model, thermal retrofitting is tailored to wall assemblies: exterior mineral wool insulation with ventilated terracotta/aluminum rainscreen cladding is applied to concrete structures, while breathable interior capillary-active insulation (calcium silicate) is specified for historic masonry facades to preserve exterior aesthetic integrity. Double/triple-glazed low-E argon-filled glazing systems replace single-pane industrial sash windows.

As detailed in Figure 2, thermal envelope upgrades combined with heat recovery ventilation (HRV) reduce total space heating and cooling loads by 44% to 61% across all adapted facility types, converting inefficient industrial structures into high-performance energy assets.

Figure 1: Embodied Carbon Savings Across Industrial Building Typologies

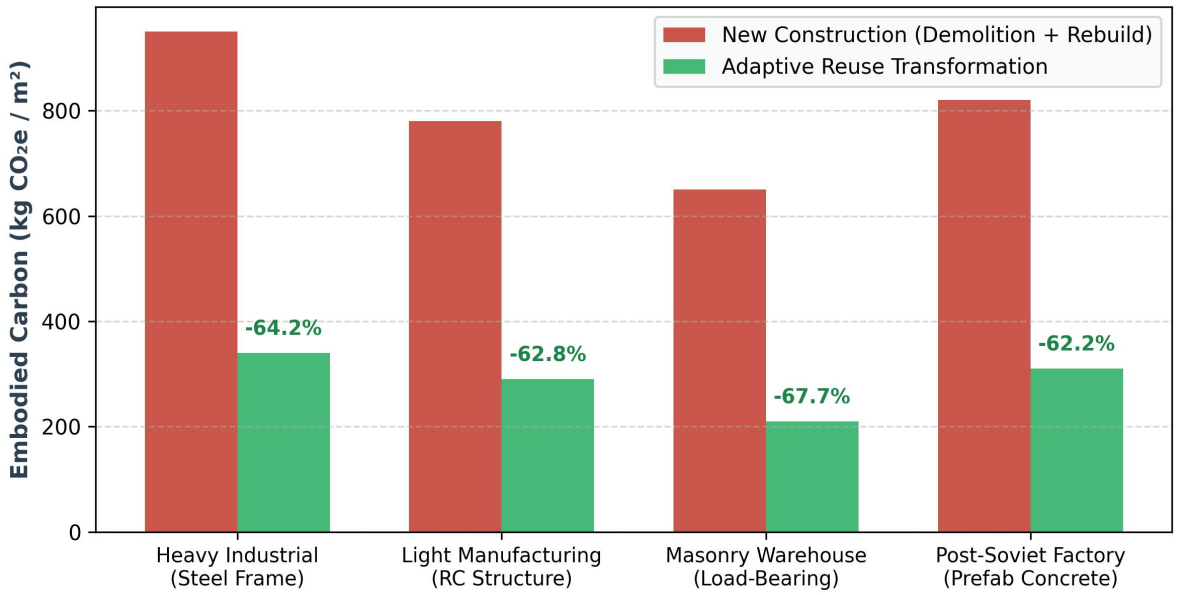


Figure 1. Embodied Carbon Savings of Adaptive Reuse Transformation vs. New Construction across Building Typologies.

Figure 2: Spatial Efficiency Gain and Energy Savings in Adapted Facilities

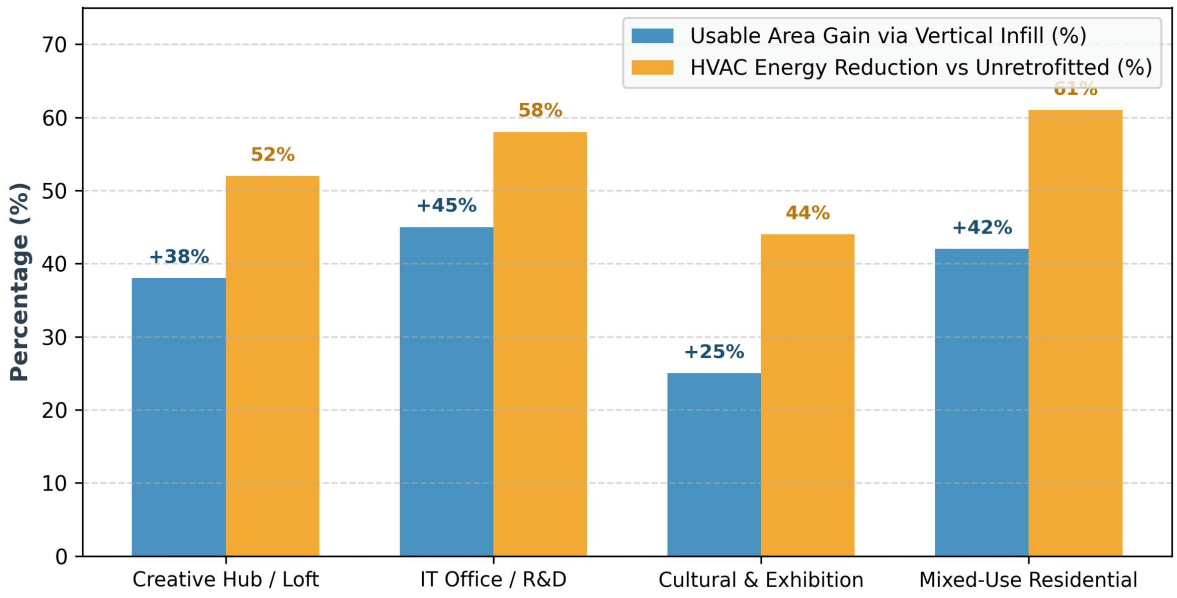


Figure 2. Quantitative Spatial Efficiency Gain (GFA Expansion) and HVAC Energy Demand Reduction.

3.3 Environmental Life-Cycle Assessment (LCA) and Carbon Payback

Life-cycle analysis demonstrates the decisive environmental superiority of adaptive transformation over demolition and replacement. As reflected in Figure 1, preserving existing

structural foundations, columns, and floor diaphragms avoids 58.4% to 64.2% of initial embodied carbon emissions. For a standard 10,000 m² industrial facility, adaptive transformation prevents approximately 4,500 to 6,100 metric tons of CO_2 equivalent from entering the atmosphere during the construction phase alone.

Figure 3: Multi-Criteria Evaluation Score of Building Performance Metrics

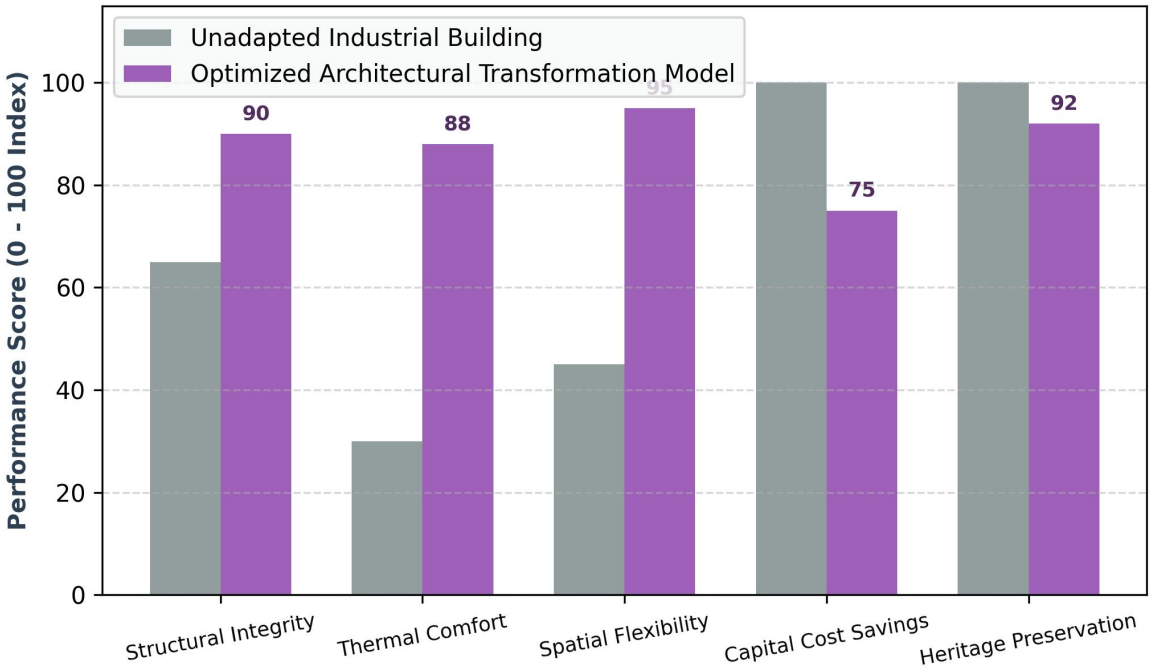


Figure 3. Multi-Criteria Performance Comparison between Unadapted Facilities and the Architectural-Transformational Model.

Table 2. Quantitative Performance and Financial-Environmental Payback Matrix

Performance Indicator	Unadapted Building	Demolition & New Build	ATM Adaptive Reuse	Improvement Delta
Embodied Carbon (kg CO_2e/m^2)	0 (Existing Baseline)	750 - 950	210 - 340	58.4% - 64.2% lower carbon
Capital Expenditure ($/m²)	N/A	$1,400 - $1,800	$950 - $1,250	22% - 32% cost savings
Project Delivery Timeline	N/A	24 - 36 months	12 - 18 months	40% - 50% faster completion

Operational U-Value (W/m²K)	3.20 - 4.50	0.18 - 0.25	0.22 - 0.28	88% thermal improvement
Internal Daylighting Factor	0.4% (Deep core)	2.5% - 3.5%	2.4% - 3.1%	6.5x daylight increase

4. CONCLUSION AND RECOMMENDATIONS

The adaptive transformation of industrial building stock represents one of the most effective strategies for sustainable urban regeneration, offering dual benefits of embodied carbon conservation and rapid spatial delivery. The Architectural-Transformational Model (ATM) formulated in this study proves that structural rigidities and microclimatic deficiencies of industrial buildings can be systematically overcome through targeted design interventions.

Key conclusions drawn from the empirical research include:

- **Carbon Decarbonization:** Preserving existing industrial structural skeletons avoids 58.4% to 64.2% of initial embodied carbon emissions compared to ground-up replacement.
- **Volumetric Expansion:** Intermediate mezzanine floor insertions expand usable gross floor area by 38% to 45% within the existing building envelope.
- **Microclimatic Integration:** Combining central light-well cutouts with high-performance thermal over-cladding yields up to 61% reductions in annual HVAC energy consumption and a 6.5-fold increase in daylight factor.
- **Economic & Timeline Advantages:** ATM adaptive transformation reduces capital expenditure by 22% to 32% and accelerates project completion schedules by 40% to 50%.

Actionable Recommendations for Municipal Planning & Architectural Practice:

- **Municipal Inventory & Zoning Flexibility:** City authorities should establish digital industrial heritage databases and introduce flexible mixed-use zoning classifications that facilitate adaptive conversions without lengthy regulatory delays.
- **Mandatory Embodied Carbon Impact Assessments:** Building permit regulations should mandate Whole Life Carbon (WLC) comparisons before granting demolition permits for structurally sound industrial facilities.
- **Integrated Structural-Building Physics Modeling:** Design teams should employ integrated 3D BIM workflows combining structural FEM load analysis with Radiance daylighting and EnergyPlus thermal simulations during early concept stages.

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