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CONSTRUCTING BIM-DRIVEN MULTI-HAZARD RESILIENCE INDICES COMBINING CLIMATE-STRESS SCENARIOS WITH SUSTAINABILITY-WEIGHTED CONSTRUCTION DECISION OPTIMIZATION TECHNIQUES.

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ABSTRACT
The increasing frequency and severity of climate-induced hazards have intensified the need for construction systems capable of demonstrating high resilience while meeting stringent sustainability requirements. Traditional risk assessment frameworks often evaluate hazards in isolation and lack the computational depth needed to integrate sustainability-based decision metrics. To address this gap, this study develops a BIM-driven methodology for constructing multi-hazard resilience indices that incorporate climate-stress scenarios and sustainability-weighted optimization techniques. At the broader level, the approach links Building Information Modeling with advanced environmental analytics, enabling the extraction, simulation, and integration of thermodynamic, structural, and ecological performance attributes directly from digital project models. These attributes are evaluated against projected climate loads including heatwaves, extreme precipitation, and wind intensification to quantify system vulnerabilities across temporal and spatial scales. The methodology narrows in scope by formulating resilience indices that blend hazard-response behaviors with sustainability criteria such as embodied carbon, operational energy use, and long-term resource efficiency. A multi-objective optimization engine assigns dynamic weights to sustainability indicators based on scenario severity, economic constraints, and construction sequencing requirements. Through this integration, BIM functions not only as a geometric repository but also as a computational platform for adaptive decision-making. The resulting indices allow project teams to evaluate trade-offs between resilience-enhancing interventions and sustainability goals, ensuring that mitigation strategies do not inadvertently increase lifecycle impacts. The research provides a novel pathway for embedding resilience and sustainability into a unified digital framework, offering actionable insights for planners, engineers, and policymakers confronted with climate uncertainty. It also establishes the foundation for advanced predictive analytics and decision-support systems capable of guiding sustainable construction choices under multi-hazard conditions.

Keywords:
BIM-driven resilience, multi-hazard assessment, sustainability optimization, climate-stress scenarios, construction decision-making, resilience indices

1. INTRODUCTION

1.1 Background: Climate hazards, resilience gaps, and the sustainability imperative

Climate-induced hazards such as extreme heat, intense rainfall, storm surges, and wind amplification continue to reshape global construction risk profiles, exposing infrastructure systems to unpredictable stressors that increasingly exceed traditional design envelopes [1]. These escalating threats reveal significant resilience gaps, particularly in how construction projects anticipate, absorb, and recover from multi-hazard disruptions. Conventional engineering models often treat hazards independently, overlooking compounding effects that arise when climate variables interact dynamically across spatial and temporal scales [2]. Sustainability considerations add an additional layer of complexity: projects must now meet stringent environmental expectations while simultaneously enhancing structural robustness, operational continuity, and lifecycle performance [3]. Integrating resilience with sustainability is therefore no longer optional but fundamental for achieving long-term infrastructure viability. This dual imperative underscores the necessity of computational tools capable of modeling hazard behaviors, assessing vulnerability pathways, and evaluating the environmental implications of protective interventions [4]. BIM emerges as a powerful catalyst for this transformation, offering a data-rich environment that centralizes geometric, material, operational, and environmental information. When properly leveraged, BIM can facilitate advanced simulations and decision analytics that bridge resilience theory with sustainability-driven design and construction practices [5].

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1.2 Problem statement: Fragmented hazard assessment and lack of integrated sustainability weighting

Despite notable advancements in modeling climate hazards, most assessment approaches remain fragmented, relying on isolated analyses that fail to capture interdependencies between structural exposure, operational performance, and sustainability outcomes [6]. Current resilience frameworks typically emphasize structural capacity or hazard intensity but rarely incorporate weighted evaluation of sustainability indicators such as embodied carbon, energy demand, water usage, or environmental degradation potential [7]. This omission limits the ability of project teams to select interventions that balance protective performance with ecological responsibility. Furthermore, hazard assessments are often disconnected from BIM environments, resulting in duplicated data, inconsistent assumptions, and reduced analytical transparency [8]. Without integrated sustainability weighting, decision-makers risk adopting resilience-enhancing measures that unintentionally increase lifecycle impacts or compromise long-term environmental goals [9]. Consequently, a unified methodology is needed one that blends multi-hazard simulation, resilience scoring, and sustainability-weighted optimization into a seamless digital workflow capable of guiding computationally informed construction decisions [10].

1.3 Research aim, scope, and contributions

This study aims to develop a BIM-driven computational framework for constructing multi-hazard resilience indices that incorporate climate-stress scenarios alongside sustainability-weighted decision optimization. The scope spans structural, environmental, and thermodynamic domains, enabling a holistic evaluation of how buildings respond to dynamic climate stressors and how sustainability metrics influence resilience-based choices [3]. The framework integrates hazard simulations, BIM-derived data, and multi-objective weighting models to quantify trade-offs among performance, risk, and ecological objectives [6].

Key contributions include:

(1) a unified formulation for resilience indices that account for both hazard intensity and sustainability impacts;

(2) a BIM-centered computational workflow linking geometric, material, and environmental datasets with advanced analytics; and

(3) a decision-support architecture enabling scenario-adaptive optimization across competing priorities [8].

Collectively, these contributions provide a structured pathway for embedding resilience and sustainability into construction engineering practice, addressing gaps identified in contemporary multi-hazard assessment methodologies [2].

2. LITERATURE REVIEW

2.1 Multi-hazard resilience concepts in construction engineering

Multi-hazard resilience has become a central analytical focus in construction engineering as climate-related threats intensify and interact in ways that exceed traditional single-hazard design assumptions [7]. Resilience encompasses the capacity of a built asset to anticipate, withstand, adapt to, and recover from disruptive events, but contemporary climate scenarios introduce complex stressors such as cascading failures, concurrent hazards, and nonlinear damage progressions. Construction systems exposed to extreme winds may simultaneously experience thermal stress or precipitation-related degradation, requiring holistic analytical frameworks rather than isolated hazard models [8]. A resilient system must therefore account not only for structural robustness but also for functionality preservation, recoverability, and lifecycle adaptability. Recent research emphasizes integrating material behavior, structural dynamics, energy performance, and external hazard forces into cohesive assessment models capable of reflecting how hazards accumulate or compound over time [9]. In practice, this means moving beyond static capacity checks toward dynamic simulation environments that capture evolving vulnerability pathways. Multi-hazard resilience further involves quantifying performance degradation under different intensities, durations, and sequences of events, enabling decision-makers to prioritize interventions based on a broader understanding of risk interaction. As construction environments become more complex and sustainability pressures rise, multi-hazard resilience has emerged as a comprehensive performance indicator reflecting both immediate hazard preparedness and long-term system longevity [10].

2.2 BIM as a digital backbone for hazard-informed decision-making

Building Information Modeling (BIM) has evolved into a central integrative platform for hazard-informed decision-making due to its ability to consolidate geometric, material, operational, and environmental data within a unified digital environment [11]. Traditional hazard models often rely on fragmented datasets and disparate simulation tools, making consistency and traceability challenging. BIM addresses these limitations by offering a structured information ecosystem where hazard parameters, structural attributes, and sustainability indicators can be linked seamlessly [12]. This integration allows hazard simulations such as dynamic wind modeling, thermal

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stress propagation, or water infiltration analysis to be anchored directly to asset-specific BIM objects rather than generic assumptions. As a result, BIM enables fine-grained vulnerability assessments sensitive to design variations, construction phasing, and material selections.

Moreover, BIM facilitates scenario-based analysis by allowing users to embed climate projections, maintenance schedules, and operational constraints into the model, generating multidimensional insights into hazard exposure and performance degradation across the asset lifecycle [13]. Through interoperability with simulation engines, BIM can also produce parametric hazard models that react dynamically to updated environmental conditions or design changes. Importantly, BIM supports visualization capabilities that make hazard pathways and resilience deficits interpretable for both engineering specialists and project stakeholders [14]. As decision-making becomes increasingly dependent on cross-disciplinary inputs, BIM functions as the digital backbone that unifies structural engineering analytics, climate modeling, sustainability metrics, and economic evaluations. This consolidation enables construction teams to develop more coherent, evidence-based strategies for resilience enhancement. Ultimately, BIM's ability to serve as a living, data-rich representation of the built environment positions it as an indispensable tool for developing multi-hazard resilience indices grounded in real asset properties rather than abstract assumptions [15].

2.3 Sustainability-weighted optimization approaches: limitations in current practice

Although sustainability is widely recognized as essential to modern construction practice, current optimization approaches often fail to integrate sustainability within hazard resilience frameworks in a meaningful or computationally consistent way [16]. Many sustainability evaluation tools operate independently of structural or hazard simulations, focusing instead on isolated metrics such as embodied carbon, waste reduction, or operational energy performance. While valuable, these tools rarely account for how sustainability interventions influence hazard vulnerability or, conversely, how resilience measures affect lifecycle environmental outcomes. For instance, strengthening a structure may improve resilience but increase embodied emissions, whereas material substitutions may lower carbon footprints while reducing hazard resistance. Existing optimization algorithms generally lack mechanisms to balance these competing priorities within a unified mathematical or computational space. Furthermore, sustainability weighting is typically static, failing to adjust to changing hazard intensities, evolving climate forecasts, or project-specific constraints. Without dynamic integration, sustainability assessments remain peripheral rather than central to resilience decision-making. This gap underscores the need for optimization approaches capable of assigning scenario-sensitive sustainability weights and embedding them directly into multi-hazard resilience indices, ensuring that decisions reflect holistic lifecycle impacts rather than partial evaluations [17].

2.4 Research gap and motivation for integrated indices

Despite progress in resilience engineering, BIM adoption, and sustainability modeling, a cohesive framework that integrates multi-hazard resilience with dynamic sustainability weighting remains absent. Existing methodologies excel at hazard prediction or sustainability evaluation individually, yet none systematically merge these dimensions within a unified computational workflow grounded in BIM data structures [12]. This lack of integration limits interpretability, undermines decision-making transparency, and increases the risk of selecting measures that improve resilience while worsening environmental performance or vice versa [8]. A more comprehensive model must therefore compute resilience and sustainability jointly, dynamically adjusting weights based on hazard severity, lifecycle considerations, and project priorities. Integrated indices offer the ability to quantify these relationships in a single numeric measure, bridging theoretical models with practical construction workflows. The present research is motivated by this precise gap: the need for a multidimensional, BIM-driven resilience index that captures hazard interactions and sustainability impacts simultaneously, producing actionable insights for construction engineering management [10].

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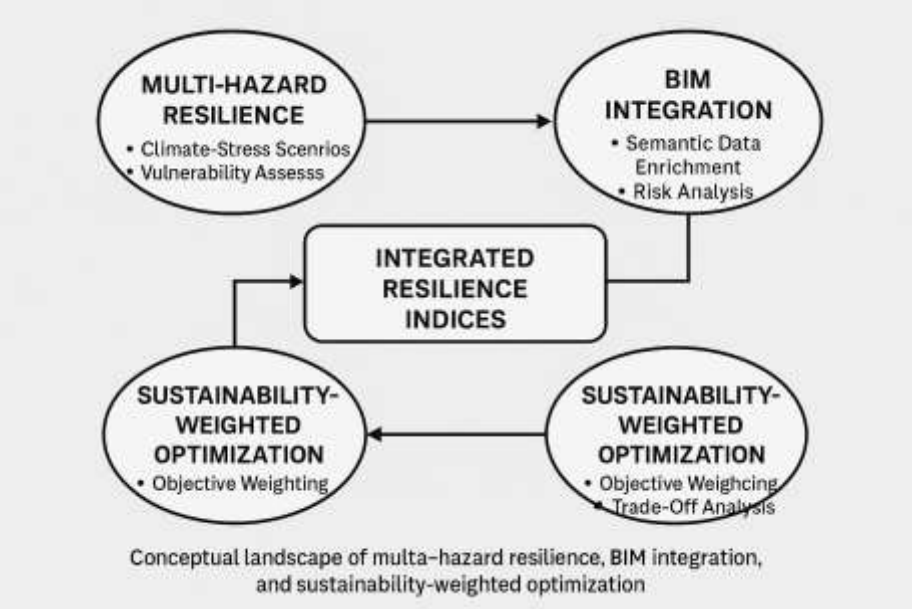

Figure 1: Conceptual landscape of multi-hazard resilience, BIM integration, and sustainability-weighted optimization.

3. METHODOLOGICAL FRAMEWORK

3.1 BIM-driven data extraction and semantic enrichment

3.1.1 Structural, thermodynamic, and environmental attribute modeling

BIM-driven data extraction begins by capturing structural, thermodynamic, and environmental parameters that define the built asset's response to external stressors across its lifecycle [14]. Structural attributes include material properties, geometry, section capacities, joint configurations, and load-path continuity. Thermodynamic attributes focus on heat transfer coefficients, thermal mass, and temperature-dependent degradation patterns. Environmental attributes encompass exposure categories, microclimatic conditions, and local hazard intensities. Through semantic enrichment, these attributes are embedded within BIM elements using standardized schemas to enhance machine interpretability and computational consistency [15]. This structured enrichment ensures that downstream hazard simulations, sustainability analyses, and optimization modules operate on harmonized, granular, and asset-specific datasets. Ultimately, BIM becomes both a geometric repository and a semantically intelligent data source capable of supporting integrated resilience computations [16].

3.1.2 Climate-stress scenario modeling and hazard parameterization

Climate-stress scenario modeling involves projecting hazard intensities such as extreme heat, wind gusts, precipitation surges, and compound climate events across probabilistic time horizons [17]. Hazard parameterization translates these projected stressors into input variables for resilience evaluation, using environmental datasets, climate models, and site-specific exposure profiles. BIM serves as the anchor point by linking hazard parameters directly to corresponding asset components, enabling localized simulation of hazard propagation across structural and thermodynamic systems [18]. Scenario modeling further incorporates frequency–severity relationships, cascading hazard sequences, and seasonal variability, ensuring realistic characterization of hazard dynamics. By embedding these scenarios within BIM, parameterized hazards become computational drivers that systematically inform resilience indices and sustainability-weighted decisions across diverse project conditions [19].

3.2 Mathematical formulation of multi-hazard resilience indices

3.2.1 Hazard load functions and vulnerability curves

Hazard load functions define the intensity and directionality of external forces acting on structural and environmental systems during climate-stress events [20]. These functions describe wind pressure distributions, thermal gradients, accumulated rainfall loads, or hydrodynamic forces, as appropriate for each hazard type.

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Vulnerability curves translate these loads into expected performance degradation, typically depicting nonlinear relationships between hazard magnitude and damage probabilities. They incorporate thresholds for elastic behavior, onset of yielding, progressive damage, and system failure [21]. Within a BIM-integrated workflow, each curve is mapped to specific asset components, enabling granular vulnerability assessment across the entire digital model. Multi-hazard conditions require combining several vulnerability curves through interaction models that account for concurrent or sequential loading effects. This coupling allows the resilience formulation to capture compounding hazard impacts on operational and structural performance [22].

3.2.2 Construction of composite resilience scoring functions

Composite resilience scoring functions synthesize hazard load functions, vulnerability curves, and system performance criteria into unified quantitative indices capable of comparing alternative design or intervention strategies [23]. Each scoring function aggregates multiple hazard contributions through weighted or normalized terms that represent relative hazard significance, exposure duration, or probability of occurrence. Component-level resilience scores derive from expected performance drops under hazard-induced stress, while system-level scores reflect aggregated behavior across interconnected subsystems. The scoring function may include performance objectives such as structural robustness, energy continuity, envelope integrity, and recovery time [22]. Through BIM integration, each term draws directly from model-linked data attributes, ensuring asset-specific precision. Multi-hazard scoring requires reconciling simultaneous contributions from thermodynamic, hydrologic, and aerodynamic stresses, requiring harmonization of units, scales, and probabilistic assumptions. The result is a comprehensive resilience index that quantifies how a construction asset withstands projected hazards while maintaining acceptable operational levels. Such indices serve as foundational metrics for sustainability-weighted decision-making and optimization routines [24].

3.3 Sustainability-weighted decision optimization engine

3.3.1 Weight modelling using multi-objective optimization theory

Weight modeling establishes dynamic sustainability weighting factors that respond to hazard intensity, project priorities, and lifecycle objectives [16]. Multi-objective optimization theory provides the mathematical foundation, enabling simultaneous balancing of performance metrics such as embodied carbon, resource efficiency, operational energy, resilience score, and cost. Pareto-front analysis identifies non-dominated solutions, defining trade-off boundaries where improved resilience may conflict with sustainability objectives. Weight functions adjust as hazard scenarios shift, ensuring that sustainability remains meaningful even under extreme or evolving climate conditions [18]. By embedding these adaptive weights into the decision engine, BIM-driven simulations can rank intervention strategies based on their ability to optimize competing objectives holistically. This ensures that sustainability metrics are integrated as active, rather than peripheral, decision drivers.

3.3.2 Trade-off quantification and scenario-adaptive prioritization

Trade-off quantification calculates how resilience-improving interventions influence sustainability outcomes and vice versa, ensuring holistic evaluation across multi-hazard conditions [19]. This includes assessing how modifications such as structural reinforcement, envelope upgrades, or material substitutions affect embodied impacts, operational efficiencies, and long-term resource consumption. Scenario-adaptive prioritization ranks alternatives differently depending on hazard probability, exposure severity, or sustainability constraints. For instance, under extreme heat scenarios, thermodynamic resilience may receive higher weighting, while under flood-risk conditions, hydrologic resistance becomes dominant. BIM supports this process by generating scenario-specific datasets for each intervention, allowing the optimization engine to compute alternative outcomes efficiently. The result is a decision-support mechanism that selects strategies consistent with both resilience objectives and sustainability priorities, producing adaptable recommendations matched to project-specific and climate-specific contexts [21].

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Table 1. Summary of variables, parameters, and computational elements used in index formulation

Symbol / Element	Description	Category	Role in Resilience Index Computation
H_i	Hazard intensity for scenario i (heatwave, wind, flood)	Hazard Parameter	Inputs to load functions and scenario modeling; drives stress profiles.
$L_i(x)$	Hazard load function applied to component x	Load Function	Converts hazard intensity into applied forces or thermodynamic gradients.
$V_i(x)$	Vulnerability curve for component x under hazard i	Vulnerability Element	Maps load magnitudes to expected performance degradation.
$D_i(x)$	Damage ratio for component x under hazard i	Damage Metric	Captures degradation severity; computed using vulnerability curves.
R_k	Resilience sub-component (robustness, adaptability, redundancy, recovery)	Resilience Component	Forms the basis for composite resilience scoring functions.
W_i	Weight assigned to hazard i	Aggregation Parameter	Reflects scenario likelihood, severity, and strategic importance.
S_j	Sustainability indicator for strategy j (embodied carbon, energy, water, circularity)	Sustainability Metric	Inputs to multi-objective optimization and trade-off modeling.
α_j	Sustainability weighting coefficient for indicator j	Optimization Weight	Governs influence of sustainability metrics on final resilience index.
$C(x)$	Composite resilience score for component x	Resilience Index Term	Aggregates hazard-specific resilience components into unified output.
Φ	Multi-hazard interaction factor	Interaction Parameter	Adjusts resilience score for compounding or cascading hazard effects.
T_s	Time-dependent scenario parameter	Scenario Variable	Models temporal variation in hazard exposure and degradation.
BIM-Attribute Set	Geometry, material properties, thermodynamic attributes, environmental metadata	Data Source	Provides all computational inputs; ensures model-to-reality alignment.
Simulation Engine $\mathcal{E}$	Hazard and performance simulation module	Computational Component	Generates load responses, stress paths, thermal fields, and hydrologic impacts.
Optimization Engine $\mathcal{O}$	Sustainability-weighted decision model	Computational Component	Computes scenario-adaptive weighting and selects optimal intervention strategies.
Normalization Operator $\mathcal{N}$	Unit and scale harmonization	Mathematical Operation	Ensures cross-hazard comparability among metrics.
Aggregation Operator Σ	Multi-criteria synthesis of resilience components	Mathematical Operation	Produces final resilience index at component and system levels.

4. BIM-INTEGRATED COMPUTATIONAL WORKFLOW

4.1 Workflow architecture linking BIM, hazard simulation, and sustainability metrics

The workflow architecture integrates BIM, hazard simulation engines, and sustainability assessment modules into a unified computational environment capable of supporting real-time, multi-hazard resilience evaluation [21]. At its core, BIM functions as the data backbone, housing geometric, material, thermodynamic, and environmental attributes enriched through semantic classification. These attributes serve as the initial inputs for hazard simulation

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modules, which compute climate-stress responses such as thermal gradients, wind pressures, hydrological loads, and their propagation through structural and envelope systems [22]. The workflow ensures bidirectional connectivity: hazard modules retrieve BIM-linked parameters while updated hazard outcomes are written back to BIM objects for iterative evaluation. Parallel to hazard modeling, sustainability metrics embodied carbon, lifecycle energy demand, water footprint, and circularity contributions are computed using data streams connected to BIM datasets [23]. Integrating these dimensions into a shared architecture allows hazard and sustainability components to interact during decision analysis, preventing contradictory recommendations. Middleware interfaces facilitate synchronization across simulation tools, ensuring that scenario variations or design updates propagate automatically through all computational layers [25]. This fusion of data streams establishes a cohesive resilience–sustainability ecosystem capable of generating both component-level and systemwide performance insights. Ultimately, the architecture provides the structural foundation for robust, BIM-centered resilience index generation [27].

4.2 Algorithmic pipeline for multi-hazard resilience index generation

The algorithmic pipeline transforms BIM-enriched datasets into quantitative resilience indices through a staged computational sequence designed to evaluate hazard interactions and sustainability influences with high precision [24]. The first stage extracts hazard-relevant attributes from BIM and standardizes them through normalization processes that align units, scales, and probabilistic assumptions. These data feed into hazard simulation engines, which compute scenario-specific load functions reflecting wind, heat, flood, and compound hazard intensities. Simulation outputs then activate vulnerability assessment modules, where component-level damage states and performance degradation rates are computed using calibrated vulnerability curves linked to BIM elements [26].

The second stage synthesizes hazard-specific degradation outputs into multi-hazard response profiles. These profiles incorporate temporal dynamics, hazard concurrency, and cascading failure likelihoods to construct a combined response model reflective of realistic climate stress behavior [28]. This multi-hazard response is translated into resilience components such as robustness, rapidity, redundancy, and adaptability. Each component is measured numerically and aggregated through weighted scoring functions grounded in system performance objectives.

The third stage incorporates sustainability-weighted adaptations by adjusting weighting parameters based on embodied carbon limits, energy performance thresholds, or environmental constraints embedded within BIM datasets. A multi-objective evaluation compares candidate interventions by examining their influence on resilience scores and sustainability indicators simultaneously, producing a final resilience index for each scenario [29].

The pipeline culminates with automated index reporting, where results are parameterized based on hazard intensity, asset configuration, and sustainability priorities. This end-to-end algorithmic flow ensures transparency, reproducibility, and computational rigor essentials for integrating resilience analytics into construction engineering management practices [30].

4.3 Integration with decision-support interfaces and visualization dashboards

Decision-support interfaces and visualization dashboards transform resilience indices into actionable insights that guide engineering, design, and project management decisions [23]. These interfaces connect directly to BIM databases and analysis engines, allowing users to interact with real-time scenario outputs. High-resolution dashboards visualize hazard propagation patterns, vulnerability hotspots, and component-level resilience scores using heat maps, structural overlays, and time-based performance trajectories [21]. Sustainability metrics appear alongside resilience results, enabling comparison across alternative interventions and highlighting trade-offs that must be negotiated to meet project-specific objectives.

Interactive modules allow stakeholders to adjust hazard intensities, sustainability weightings, or design parameters and instantly observe resulting index changes. This adaptive capability enhances decision transparency by linking each user adjustment to explicit computational outcomes derived from the underlying algorithmic pipeline [24]. Automated reporting tools generate scenario summaries, resilience–sustainability balance sheets, and recommended intervention sequences tailored to specific priorities such as carbon reduction, lifecycle extension, or enhanced robustness [27].

The interface architecture supports multi-user collaboration, enabling engineers, sustainability consultants, and project managers to explore resilience strategies concurrently through synchronized views. Integrated alerts highlight conditions where resilience improvements compromise sustainability goals, or where sustainability gains significantly reduce hazard resistance. These warnings ensure that decisions remain aligned with broader project values and regulatory contexts [25].

Finally, the dashboards integrate predictive analytics modules capable of forecasting future resilience performance under evolving climate projections, allowing long-term planning within uncertain hazard environments. Through

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seamless connectivity with BIM and computational engines, the visualization system becomes a strategic tool for guiding climate-adaptive construction practices that are both resilient and sustainable.

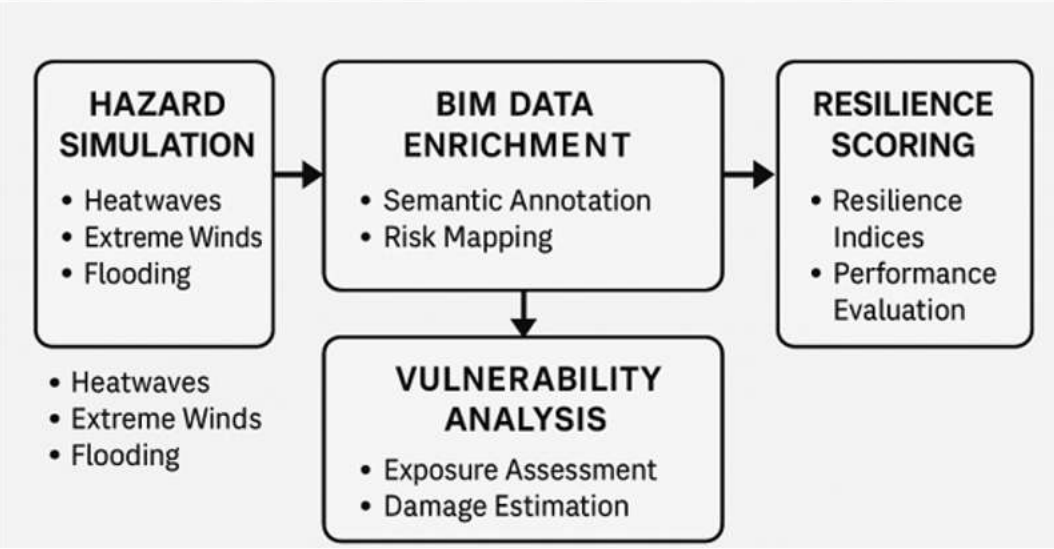

Figure 2: BIM-integrated workflow diagram, showing data flows from hazard simulation to resilience scoring.

Table 2. Mapping of BIM-Based Data Sources to Hazard–Sustainability Evaluation Modules

BIM Data Category	Specific Data Elements Extracted	Hazard Evaluation Module Utilized	Sustainability Evaluation Module Utilized	Function in Integrated Workflow
Geometric Data	Component dimensions, spatial coordinates, façade geometry, roof profiles	Wind-pressure simulation, rainfall accumulation □odelling, flood pathway mapping	Material quantity estimation for embodied carbon	Determines exposure surfaces and hazard interaction zones; drives carbon and material calculations.
Structural Attributes	Material strengths, stiffness matrices, load paths, connection details	Structural load propagation, nonlinear stress assessment, failure mode prediction	Longevity evaluation, maintenance frequency modeling	Defines hazard-induced damage progression and lifecycle durability.
Thermodynamic Properties	Thermal conductivity, heat capacity, insulation layers	Heatwave response simulation, thermal stress modeling	Building energy demand calculations, HVAC sustainability metrics	Couples thermal resilience with operational energy performance.
Environmental Metadata	Elevation, microclimate data, surrounding topography	Flood depth estimation, wind-channeling effects, microclimate-driven heat intensification	Local environmental impact assessment	Aligns hazard intensity with site conditions and sustainability baselines.
Material Specifications	Embodied carbon factors, recyclability, lifecycle degradation coefficients	Material deterioration under hydrological and thermal stress	Carbon footprint □odelling, circularity index computation	Evaluates trade-offs between reinforcement strategies and sustainability impacts.

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BIM Data Category	Specific Data Elements Extracted	Hazard Evaluation Module Utilized	Sustainability Evaluation Module Utilized	Function in Integrated Workflow
Operational Profiles	Occupancy schedules, internal heat generation, equipment loads	Thermal load amplification analysis during heatwaves	Operational energy consumption and peak demand impacts	Integrates dynamic usage conditions into hazard and sustainability □odelling.
Drainage & Utility Systems	Catchment areas, pipe diameters, pump capacities	Flood routing analysis, overflow risk assessment	Water efficiency projections, long-term utility performance	Supports flood resilience evaluation and water-related sustainability metrics.
Maintenance & Lifecycle Records	Historical repair patterns, degradation logs	Prediction of failure frequency and hazard-sensitive deterioration	Lifecycle cost and carbon estimation	Enables predictive resilience performance and sustainability benchmarking.
Semantic Classifications	Vulnerability tags, exposure categories, sustainability labels	Hazard-prioritized component ranking	Sustainability-weighted decision rules	Provides automation-ready metadata for integrated scoring and optimization.

5. CASE STUDY DEMONSTRATION

5.1 Project description and BIM dataset characteristics

The case study evaluates a mid-rise healthcare facility situated within a rapidly urbanizing, climate-sensitive region exhibiting increasing exposure to compound environmental hazards [27]. The project's BIM model includes comprehensive structural, architectural, thermodynamic, and operational datasets developed to Level of Development (LOD) 350, enabling fine-grained attribute extraction. Structural components columns, slabs, shear walls, and façade systems are parameterized with material strengths, stiffness profiles, and degradation curves. Thermodynamic elements, such as insulation layers and thermal masses, are represented using embedded conductivity and heat-capacity values [28]. Environmental metadata integrates site elevation, historical hazard frequencies, projected climate intensities, and proximity to critical infrastructure.

The BIM model is semantically enriched through classification schemas that tag components with vulnerability categories, hazard exposure coefficients, and sustainability attributes such as embodied carbon factors and predicted operational energy consumption [29]. This enriched BIM dataset serves as the analytical foundation for hazard propagation simulations and sustainability-weighted decision modeling. Its completeness ensures that resilience indices reflect the true asset configuration rather than abstract or generalized conditions. The case study thus demonstrates how BIM-centric data structuring enables precise, scenario-adaptive resilience and sustainability assessments aligned with contemporary construction engineering demands [30].

5.2 Climate-stress scenarios applied: heatwaves, extreme winds, flooding

Three primary climate-stress scenarios were applied to evaluate the facility's resilience under plausible future environmental conditions: sustained heatwaves, extreme wind events, and localized flooding. These scenarios align with regional climate projections indicating rising temperatures, intensifying wind patterns, and more frequent extreme rainfall occurrences [31].

Heatwave simulations computed thermal gradients across envelope systems, capturing the interaction between solar gains, occupancy loads, and heat island amplification. Prolonged high-temperature exposure was modeled to assess thermal fatigue, material expansion, and HVAC overload risks, all of which affect resilience and operational continuity.

Extreme wind simulations incorporated aerodynamic profiles derived from local topographic conditions and building orientation. Pressure coefficients were applied to façade systems and roof assemblies using BIM-linked geometries, enabling realistic modeling of suction forces, vortex shedding, and potential envelope breaches [27].

Flooding simulations evaluated surface runoff dynamics, infiltration pathways, drainage network performance, and subgrade impacts. Hazard depth-duration curves were mapped to BIM-embedded elevations and foundation components, identifying zones most susceptible to water-related damage.

Scenario interactions were also considered, accounting for cascading effects such as wind-induced debris damage aggravated by heat-weakened materials or flooding intensified by storm-driven drainage failures [32]. Together,

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these scenarios provide a robust representation of the multi-hazard conditions the project may encounter, ensuring that resilience indices capture realistic stress behaviors and potential compound vulnerabilities rather than isolated hazard responses [33].

5.3 Calculation of multi-hazard resilience indices

The calculation of multi-hazard resilience indices followed a structured sequence beginning with BIM-based extraction of hazard-relevant parameters. Each scenario produced component-level stress profiles that were processed through vulnerability curves calibrated to the building's materials, geometry, and thermodynamic behaviors [34]. Performance degradation values from each hazard were normalized and aggregated to form scenario-specific resilience components: robustness, adaptability, redundancy, and recovery potential.

Robustness measured the capacity of structural and envelope systems to maintain functionality under peak stress. Adaptability evaluated thermal, hydrological, and aerodynamic flexibility through system responsiveness to fluctuating hazard intensities. Redundancy captured alternative load paths, system backup availability, and envelope performance variability. Recovery potential incorporated estimated downtime and maintenance restoration periods [31].

To construct multi-hazard resilience indices, contributions from heatwave, wind, and flooding scenarios were integrated using weighted aggregation that reflected hazard probability distributions and exposure severities extracted from climate models [30]. Scenario interactions were quantified by applying penalty factors for concurrent hazard effects, ensuring that resilience indices accurately represented compounding vulnerabilities.

The final index for each BIM object, subsystem, and the entire facility was computed as a bounded numerical score, allowing cross-scenario comparison and design optimization. These indices form the quantitative core of multi-hazard decision analysis, supporting evidence-based evaluations of resilience performance aligned with project-specific priorities and climate-adaptive requirements [35].

5.4 Sustainability-weighted decision impacts under alternative design strategies

To evaluate the influence of sustainability weighting on resilience decisions, multiple design alternatives were simulated under identical hazard scenarios. Options included enhanced façade insulation, low-embodied-carbon structural materials, reinforced wind bracing, elevated service equipment, and improved drainage systems [29]. Each intervention was assessed for its effect on resilience indices and its sustainability impact, measured across embodied carbon, lifecycle energy demand, material circularity, and long-term maintenance requirements.

Results showed that sustainability-optimized options sometimes reduced resilience for example, low-carbon materials exhibited lower stiffness under extreme wind loads. Conversely, resilience-focused strategies such as heavy reinforcement increased embodied emissions [25]. The sustainability-weighted optimization engine balanced these competing outcomes by dynamically assigning weights according to hazard severity, environmental constraints, and project priorities [31].

Scenario-adaptive prioritization revealed that heatwave-dominant conditions favored thermodynamic improvements, while wind-dominant scenarios emphasized structural reinforcement. Flood-prone scenarios prioritized drainage redesign and equipment elevation [28]. This integrated evaluation demonstrated that no single strategy universally outperforms others; instead, optimal solutions emerge through holistic balancing of resilience gains and sustainability impacts informed by BIM-linked analytics [32].

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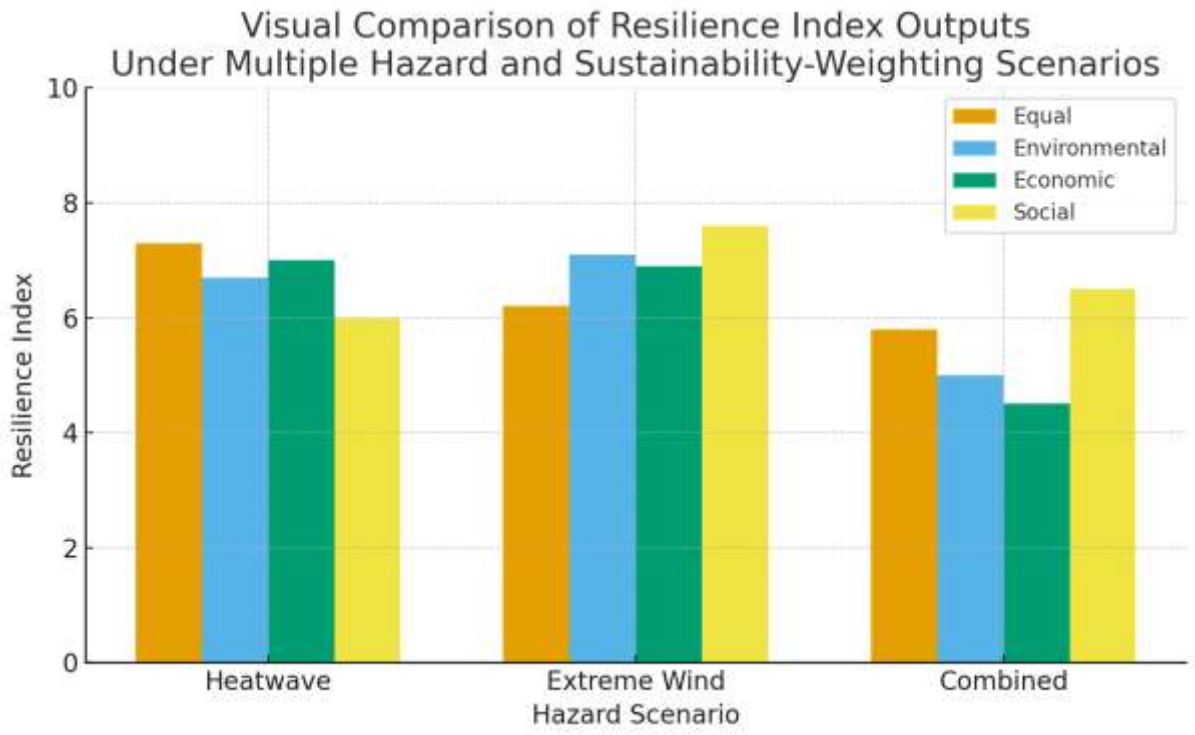

Figure 3: Visual comparison of resilience index outputs under multiple hazard and sustainability-weighting scenarios.

6. DISCUSSION

6.1 Interpretation of resilience-sustainability interactions and decision trade-offs

The case study reveals that resilience and sustainability operate as interdependent yet sometimes competing performance dimensions within construction engineering systems [32]. Resilience-enhancing interventions, such as structural reinforcement or façade hardening, often elevate embodied carbon or reduce material circularity, thereby diminishing sustainability performance. Conversely, sustainability-oriented strategies, including low-carbon material substitution or lightweight envelope design, may reduce stiffness or thermal buffering capacity, weakening the building's ability to withstand multi-hazard stressors. This two-way tension emphasizes that resilience cannot be interpreted solely as structural capacity, nor sustainability solely as environmental optimization. Instead, decision-making must navigate a continuum where both parameters influence long-term asset viability [33].

The integrated BIM-driven model demonstrates that trade-offs vary by hazard type, exposure duration, and degradation mode. For example, heatwave dominance elevates the importance of thermodynamic sustainability, while wind-driven scenarios shift attention toward robustness and redundancy. Flood scenarios intensify drainage-related vulnerabilities, disproportionately affecting sustainability attributes linked to material longevity and maintenance impacts [34].

These findings show that resilience–sustainability interactions are neither linear nor intuitive; they require computational systems capable of mapping how interventions modify performance across multiple metrics. The study illustrates that multi-objective weighting, combined with BIM-linked hazard simulation, enables a more rational negotiation of trade-offs that were previously addressed through isolated or qualitative judgement. In this sense, resilience and sustainability become mutually contextualized dimensions guiding adaptive construction strategies tailored to climate realities [35].

6.2 Implications for construction engineering management, policy, and project governance

Integrating resilience and sustainability within a unified computational workflow reshapes several dimensions of construction engineering management. First, it supports evidence-based decision-making by quantifying impacts that were traditionally assessed through intuition or narrowly scoped tools. This facilitates transparent justification of interventions across project lifecycles, reinforcing accountability in design and procurement processes [36].

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Second, BIM-based resilience indices offer structured pathways for regulatory compliance, particularly as jurisdictions increasingly require climate risk disclosures and sustainability performance verification. Policymakers can use such indices to guide standards for adaptive design, resilience certification, and carbon-sensitive construction practices [37].

For project governance, the unified model enhances coordination between structural engineers, sustainability specialists, and asset managers. Shared access to hazard simulations and sustainability-weighted outcomes creates a more informed dialogue around budget allocation, design alternatives, and lifecycle maintenance planning. Moreover, integrating resilience metrics into early-stage BIM workflows encourages proactive hazard-informed design rather than reactive risk mitigation. Collectively, these implications highlight how digital resilience–sustainability frameworks can advance climate-adaptive governance across the construction sector [38].

6.3 Critical evaluation of limitations and data dependencies

Although the integrated framework demonstrates strong analytical capability, several limitations must be acknowledged. BIM datasets may lack the granularity required for precise hazard □odelling, especially in older projects without comprehensive digital records [39]. Moreover, hazard projections depend heavily on climate model accuracy and may exhibit uncertainty that propagates into resilience indices. Sustainability metrics are similarly influenced by data availability, particularly regarding supply-chain emissions and operational performance baselines. Computational load also poses challenges, as multi-hazard simulations and sustainability-weighted optimization can be resource-intensive, limiting real-time applicability for large-scale assets [40]. Despite these constraints, the framework provides a robust foundation for advancing integrated resilience–sustainability analysis, with future enhancements aimed at improving data quality, model interoperability, and computational efficiency [41].

7. CONCLUSION

7.1 Key findings and contributions to resilience theory and BIM-enabled decision analytics

This study demonstrates that resilience and sustainability are deeply interconnected dimensions that must be evaluated concurrently to support climate-adaptive construction engineering. By integrating hazard simulations, BIM-based semantic data, and multi-objective sustainability weighting, the research establishes a computationally unified framework for generating multi-hazard resilience indices that accurately reflect both structural performance and environmental impacts. The findings show that BIM functions not only as a geometric repository but as a dynamic analytical engine for linking thermodynamic, structural, and environmental attributes to hazard-response behaviors. The resilience indices developed through this framework offer a structured means of comparing alternative design strategies under diverse climate-stress conditions. Conceptually, the study advances resilience theory by embedding sustainability considerations within hazard □odelling rather than treating them as external or secondary constraints. Methodologically, it contributes a scalable, data-driven decision architecture capable of supporting transparent, scenario-adaptive engineering decisions across project lifecycles.

7.2 Recommendations for industry adoption and future research priorities

Industry adoption should prioritize embedding resilience–sustainability workflows into early-stage BIM processes, enabling designers to visualize hazard vulnerabilities and environmental trade-offs before committing to critical design paths. Organizations should develop training protocols that equip engineers and project managers to interpret multi-hazard indices and apply them within procurement, value engineering, and compliance processes. Future research should expand datasets supporting vulnerability and sustainability □odelling, refine scenario-adaptive weighting algorithms, and integrate AI-driven predictive modules for long-term hazard forecasting. Additional work is also needed to validate the framework across diverse building typologies, climatic regions, and regulatory environments to strengthen generalizability and practical relevance.

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