Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas

(H.F.R.I. Project Number 015376)

Definition of reliable damage measures and appropriate hazard-related intensity measures for holistic renovation towards VFs

Deliverable D1.5 Work package 1

Funding source

"Hellenic Foundation for Research & Innovation (H.F.R.I.)
Greece 2.0
Basic Research Financing Action"

Host Organization

Democritus University of Thrace (DUTH)

Collaborating Organizations

Aristotle University of Thessaloniki (AUTH)

January 2025

Funded by the European Union
NextGenerationEU

The research project is implemented in the framework of H.F.R.I call "Basic research Financing (Horizontal support of all Sciences)" under the National Recovery and Resilience Plan "Greece 2.0" funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 015376)

Version	Date	Comments-Modifications
1	January 2025	Final Version
2		

Suggested citation:

Rousakis T., Voutetaki M., Zapris A., Theodoridou I., Stefanidou M., Vatitsi K., Mallinis G., Macha M., Kytinou V., Chalioris C., 2024. *Definition of reliable damage measures and appropriate hazard-related intensity measures for holistic renovation towards VFs*. Greenergy-Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D1.5 Democritus University of Thrace, Xanthi.

Project Title	Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas
Acronym	GREENERGY
HFRI Project Number	015376
Call identifier	Basic Research Financing (Horizontal support for all Sciences), National Recovery and Resilience Plan (Greece 2.0) / Sub-action 2. Funding Projects in Leading-Edge Sectors – RRFQ: Basic Research Financing (Horizontal support for all Sciences)
Thematic area	ThA1. Physical Sciences, Engineering Sciences and Technology, Environment and Energy
Thematic Field	1.16 Smart Cities
Host Organization	Democritus University of Thrace
Collaborating Institutions	Aristotle University of Thessaloniki
Project starting date	13/3/2024
Project Principal Investigator	**Dr. Theodoros Rousakis**
Affiliation	**Democritus University of Thrace / Department of Civil Engineering**
Email	**trousak@civil.duth.gr**
Telephone	25410 79645, 461 / 6977421569
Deliverable number and title	*D1.5 Definition of reliable damage measures and appropriate hazard-related intensity measures for holistic renovation towards VFs.*
Related work package	**WP1** - Vertical Forest buildings typologies, benefits, hazard-dependent risks and key parameters for renovation towards high-density urban greening
Contributors	Theodoros Rousakis, Maristella Voutetaki, Adamantis Zapris (DUTh), Macha M., Kytinou V., Chalioris C. Ifigeneia Theodoridou, Maria Stefanidou, Katerina Vatitsi, Giorgos Mallinis, (AUTh)

Τίτλος Έργου	Ανθεκτική Αντισεισμική Ανακαίνιση Κατασκευών από Ωπλισμένο Σκυρόδεμα σε Κάθετο Δάσος
Ακρωνύμιο	GREENERGY
Αριθμός Έργου ΕΛΙΔΕΚ	015376
Δράση	Χρηματοδότηση Βασικής Έρευνας (Οριζόντια υποστήριξη όλων των Επιστημών), Εθνικό Σχέδιο Ανάκαμψης και Ανθεκτικότητας (Ελλάδα 2.0)
Θεματική Περιοχή	ΘΠ1. Φυσικές Επιστήμες, Επιστήμες Μηχανικού και Τεχνολογίας, Περιβάλλον και Ενέργεια
Θεματικό Πεδίο	1.16 Έξυπνες Πόλεις
Φορέας Υποδοχής	Δημοκρίτειο Πανεπιστήμιο Θράκης
Συνεργαζόμενος Φορέας	Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης
Ημερομηνία έναρξης Έργου	13/3/2024
ΕπιστημονικάΥπεύθυνος Έργου	**Δρ. Θεόδωρος Ρουσάκης**
Ίδρυμα / Τμήμα	**Δημοκρίτειο Πανεπιστήμιο Θράκης / Πολιτικών Μηχανικών**
Email	**trousak@civil.duth.gr**
Τηλέφωνα	25410 79645, 461 / 6977421569
Αριθμός και Τίτλος Παραδοτέου	*Π1.5 Ορισμός αξιόπιστων μέτρων βλάβης και κατάλληλων μέτρων έντασης σχετιζόμενων με κίνδυνους για την ολιστική ανακαίνιση με απώτερο στόχο τα Κάθετα Δάση*
Σχετική Ενότητα Εργασίας	**ΕΕ1** - Κτήρια με Κάθετα Δάση: τυπολογίες, οφέλη, διακινδύνευση εξαρτώμενη από κρίσιμους κινδύνους και βασικές παράμετροι για την ανακαίνιση προς το αστικό πράσινο υψηλής πυκνότητας
Συμμετέχοντες	Θεόδωρος Ρουσάκης, Μαριστέλλα Βουτετάκη, Αδαμάντης Ζάπρης (ΔΠΘ), Μαχά Μ., Κυτίνου Β., Χαλιορής Κ. Ιφιγένεια Θεοδωρίδου, Μαρία Στεφανίδου Κατερίνα Βατίτση, Γιώργος Μαλλίνης (ΑΠΘ)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

RC	Reinforced Concrete
VF	Vertical Forest
PBEE	Performance-Based Earthquake Engineering
IDR	Interstory Drift Ratios
IEQ	Indoor Environmental Quality
IMS	Intensity Measures
H.F.R.I.	Hellenic Foundation for Research & Innovation
DUTH	Democritus University of Thrace
AUTH	Aristotle University of Thessaloniki
PGA	Peak Ground Acceleration
Sa	Spectral Acceleration
PGV	Peak Ground Velocity
UCAs	Unsafe Control Actions
STPA	System
MIT	Massachusetts Institute of Technology
USGS	United States Geological Survey
DYFI	Did You Feel It?
SMS	Structural Management System

ΠΕΡΙΛΗΨΗ

Η ανάπτυξη κατάλληλων και αξιόπιστων μέτρων βλάβης προϋποθέτει μια ολοκληρωμένη, πολυδιάστατη, αξιολογική προσέγγιση απόδοσης που περιλαμβάνει σεισμικές, ενεργειακές, δασοκομικές και μετρήσεις προερχόμενες από τους χρήστες, οι οποίες θα συνδυαστούν για τη θέσπιση κατάλληλων μέτρων για την ακριβή αποτίμηση όλων των στοιχείων που απαρτίζουν τα VFs (Κάθετα Δάση). Η ολιστική προσέγγιση θα βοηθήσει στη διαπίστωση του κατά πόσο τα επιλεγμένα μέτρα βλάβης μπορούν, στην πραγματικότητα, να αντιπροσωπεύσουν την πολύπλοκη αλληλεπίδραση των διαφόρων στοιχείων απόδοσης και τον τελικό τους αντίκτυπο στη συνολική απόδοση της απαιτητικής εγκατάστασης VF.

Εξετάστηκαν διάφορες επιλογές έντασης των IMs (Μέτρων Έντασης) για ακραία και δυσμενή σενάρια με σκοπό την αποτελεσματική οριοθέτηση των προβλεπόμενων κινδύνων. Τέτοια IMs είναι σημαντικοί δείκτες που επιτρέπουν την ποσοτικοποίηση και αξιολόγηση της έντασης του επαγόμενου κινδύνου που μπορεί να επηρεάσει την εγκατάσταση VF. Η επιλογή κατάλληλων IMs αποτελεί την ίδια τη βάση για την ανάπτυξη μιας σωστής κατανόησης των πιθανών κινδύνων και των επιπτώσεών τους για τις δομές και τις λειτουργίες στο VF (σε οριακές καταστάσεις αστοχίας και λειτουργικότητας).

Ο συνδυασμός των προτεινόμενων μέτρων βλάβης με τα μέτρα έντασης παρέχει ένα γενικό πλαίσιο για την αξιολόγηση και ενίσχυση της ανθεκτικότητας των εγκαταστάσεων VF. Αυτή η ολιστική θεώρηση επιτρέπει στους ενδιαφερόμενους να διερευνήσουν λεπτομερώς την αλληλεπίδραση των διαφορετικών περιβαλλοντικών και λειτουργικών παραγόντων καταπόνησης με το VF και τις πιθανές επιπτώσεις τους στα εξαρτήματα του VF, υποστηρίζοντας έτσι την τεκμηριωμένη λήψη αποφάσεων για ολιστικές προσεγγίσεις ανακαίνισης. Εξετάζει την αξιολόγηση βλαβών ενσωματώνοντας και τον χαρακτηρισμό των κινδύνων ώστε να αποκτηθεί μια πλήρης εικόνα των ζητημάτων και των αναγκών που σχετίζονται με τον σχεδιασμό και τη συντήρηση και βελτίωση των εγκαταστάσεων VF σε διάφορες συνθήκες και οριακές καταστάσεις.

SUMMARY

Developing appropriate and reliable measures of damage precludes anything less than an integrated, multi-dimensional, performance evaluative approach that is seismic, energy efficiency, forestry, and occupant-derived metrics, which will all combine in establishing appropriate measures for the accurate assessment of all the components comprising the VFs (Vertical Forests). The holistic approach will be helpful in ascertaining whether any chosen metrics of damage can, in reality, represent the complex interaction of various elements of performance and their eventual impact on the overall performance of the demanding VF facility.

Different intensive selections of IMs (Intensity Measures) examined for extreme and adverse scenarios in order to delineate prospected hazards proficiently. Such IMs are important indices, enabling quantification and assessment of the intensity of the induced hazard that may affect the VF facility. Selection of appropriate IMs forms the very basis of developing a proper understanding of potential risks and their consequences for structures and operations in VF (at ultimate or serviceability limit states).

The combination of the proposed measures of damage with the measures of intensity gives a generic framework toward the assessment and enhancement of the resilience of VF facilities. This holistic consideration allows the stakeholders to explore in detail the interaction of the different environmental and operational stressors with the VF and the possible impact thereon of the VF components, thus supporting informed decision-making for holistic renovation approaches. It considers the damage assessment integrated with the hazard characterization in order to obtain a better perspective and understanding of issues and needs related to design, maintenance and improvement of VF facilities under diverse conditions and limit states.

1 INTRODUCTION

As time passes, more and more people move to big cities which provide more opportunities and career advancement chances (United Nations, 2019; Arup, 2014) But this big increase in cities' populations and the ineffective use of transportation, heating and cooling systems among others led to the overpollution of the cities. The cases of Delhi, India or Manama, Bahrain are major problems at the time of writing this text, where the air quality index indicates hazardous conditions for human existence. Monitoring the conditions of the cities, many scientists propose the increase of greenery in different areas of cities that could be beneficial for the health of people and for the mean temperature recorded for proper human comfort (Glaeser & Gottlieb, 2009; Wong & Yu, 2005). One successful case is that of Medellín (C40 Cities, 2019; Thomson, 2024), the second largest city in Colombia, where green corridors were created, reducing significantly the air pollution and temperature. The mean temperatures in the corridors are around 4.5°C cooler than the surroundings, while the temperature across the city has fallen around 2°C, with studies expecting further reduction.

Based on the successful example of Medellín and parallel elaboration of many greenery promotion programs (including GREENERGY), the enhancement of existing building stock into vertical forests represents a holistic transformation as an individual contributor to the larger greenery envelope (Tam & Wong, 2021). A study evaluates the impact of green roofs on structural responses using nonlinear dynamic analyses across three building scenarios, highlighting their role in improving structural performance, enhancing seismic resilience, and promoting sustainability while emphasizing the need for careful consideration of building function and equipment placement during implementation (Tam and Wong, 2021). Coupled with nature-based solutions, this can be a game-changing revolution in building sustainability renovation, with particular relevance to the transformation of the existing RC (Reinforced Concrete) to VF (Vertical Forest). This is certainly a complex process that requires an integrated approach toward structural durability, ecological effectiveness, and occupants' comfort (Perini et al., 2013; Olesen, 2004). The renovation of seismically vulnerable RC buildings—structures built prior to modern seismic design codes—into VFs presents unique challenges at the intersection of structural engineering, environmental design, and building physics (Moehle & Deierlein, 2004; Porter, 2003). In particular the category of reinforced concrete (is the majority of the building stock type in the Mediterranean area) needs proper holistic renovation of existing reinforced concrete buildings into Vertical Forests (VFs).

Most of the reinforced concrete buildings existing in Mediterranean regions were designed with seismic design codes quite different from those of today, which have emerged as direct derivatives of knowledge acquired from past earthquakes showing the deficiency of older design philosophy of strong beams – weak columns or of older methodologies' approach in predicting proper response for reinforced concrete buildings. Considering deficiencies identified by expert engineers in in-situ inspections and theoretical analyses, extensive research to protect these building stocks against that has been conducted over the last decades (Calvi, 2008; Fardis, 2009). These enhancements reached a new dimension with the help of computational dynamics that became permanently integrated into the working engineer's practice during the late twentieth century.

Beyond that, their transformation to VFs introduces other performance issues than what could traditionally be considered in seismic contexts. These include the stability of vegetation support systems, the integrity of the irrigation networks, and building envelope performance when subjected to seismic and combined environmental loadings (Lagomarsino & Cattari, 2015). Besides, the inclusion of green facades has altered the building thermal behavior and energy performance characteristics in ways that any comprehensive evaluation framework must capture these leading interdependencies (Pérez et al., 2011; Dahanayake & Chow, 2017).

This report represents the methodology for defining reliable damage measures and appropriate hazard-consistent intensity measures, tailor-made for vertical forest renovation projects. The proposed framework follows basic principles of Performance-Based Earthquake Engineering (PBEE) and has included new parameters related to vegetation health, energy performance, and occupant satisfaction. The adoption of a multi-criteria view can enable this work to bridge from the classical seismic retrofit design strategy over to the forthcoming needs with respect to sustainable urban transformation. This methodology will consider structural response parameters, environmental performance indicators, and human comfort metrics as a comprehensive basis for decision-making in resilience-based design approach.

2 SELECTION OF APPROPRIATE DAMAGE MEASURES

2.1 STRUCTURAL COMPONENTS (PRIMARY RC FRAME AND SHEAR WALLS) INTENSITY

2.1.1 Interstory Drift Ratios (IDR)

The IDR is an important quantitative measure in the science of structural engineering that offers crucial insight into the relations of the magnitude of lateral displacement between adjacent floor levels with the height of that story (Filippou & Fenves, 2004; FEMA 356, 2000, Haselton, 2016). This unitless quantity provides a possible way by which the total deformation property of the structural system under different load cases, but most importantly seismic events that tend to produce significant lateral forces, can be assessed.

As mathematically formulated, IDR encompasses within itself geometric and mechanical considerations of the relative horizontal displacements between the adjacent floors Δ, normalized by the corresponding height of the story h, enabling comparative analyses among different structural configurations (Mazzoni et al., 2007). The latter normalization substantially assists the rational development of performance-based design criteria, since it directly relates to elastic and inelastic structural behavior and thus allows for precise threshold definitions corresponding to different performance objectives.

The large datasets generated through advanced analytical paradigms have established correlations between Interstory Drift Ratio (IDR) values and damage patterns in structural and non-structural elements. Extensive experimental studies and numerical simulations indicate that specific IDR thresholds correspond to distinct damage states—from minor architectural deterioration at lower limits (usually around 0.5%) to significant structural deterioration at higher limits (greater than 2.5%) (Avşar et al., 2014; Robalino et al., 2020). This quantitative mapping enables practitioners to implement performance-oriented design methodologies with enhanced precision and reliability.

Implementing IDR analyses within modern structural engineering practice involves nonlinear time-history analyses and pushover procedures that trace the progression of lateral deformations from the onset of loading. These advanced analytical techniques facilitate the assessment of structural performance under various loading scenarios, allowing engineers to optimize design parameters for improved structural resilience while maintaining operational functionality within prescribed drift limitations (Skolnik & Wallace, 2010; Caterino et al., 2013; Li et al., 2023).

Quantitative strain assessment in concrete and reinforcement within critical regions of a structure is another vital aspect of performance-based seismic design. Accurate measurement and interpretation of material deformation characteristics enable the derivation of fundamental limit states. State-of-the-art instrumentation, such as vibrating wire strain gauges and fiber optic sensors, combined with computational methods, provide essential insights into the mechanical response of reinforced concrete members under complex loading conditions, particularly in areas with high stress concentrations (Micro-Measurements, n.d.; RST Instruments Ltd, n.d.).

2.1.2 Concrete and Reinforcement Strains

The strain pattern development in beam-column joints and column bases follows distinctive patterns associated with specific damage modes (Beres et al., 1996; Calvi et al., 2002). Advanced constitutive models that consider confined and unconfined concrete behaviors, combined with reinforcement plasticity models, enable analytical predictions of strain-based limit states such as concrete crushing, reinforcement yielding, and ultimate failure modes. These mathematical frameworks facilitate the determination of precise threshold values marking transitions between different performance levels (Willam & Warnke, 1975; Bažant & Oh, 1983).

Recent experimental tests, complemented by accurate numerical simulations, have identified significant correlations between recorded strain values and observed damage patterns in critical structural areas (Vecchio & Collins, 1986; Ghobarah & Said, 2002). Fiber-reinforced element formulations allow for the identification of local strain concentrations through advanced finite element analyses, particularly in regions with complex stress conditions and material interactions (Bažant & Oh, 1983; Willam & Warnke, 1975). This approach provides insights into the progression of damage mechanisms, facilitating the development of more refined performance criteria.

Incorporating strain-oriented performance indices within comprehensive structural analysis frameworks, utilizing state-of-the-art computational procedures, enables the capture of both global and localized response features (Bažant & Jirásek, 2002; Willam & Warnke, 1975). Advanced material models in such analyses account for strain rate effects, cyclic deterioration, and confinement, enhancing the accuracy of structural response predictions under severe loading conditions (Bažant & Jirásek, 2002; Willam & Warnke, 1975). The resulting strain-based assessment criteria provide quantitative thresholds for evaluating structural performance and optimizing design parameters to achieve the desired level of seismic resilience.

2.1.3 Residual Deformations

The residual deformations in structural systems represent the geometrical changes developed during seismic events and the irreversible displacement patterns remaining after dissipation of the dynamic energy (Christopoulos et al., 2004; Pampanin et al., 2003). Long-term displacements develop from the interaction of complex material nonlinear behavior, changes in geometry, and cyclic deterioration mechanisms. Because of this, appropriate quantitative assessment and prediction require sophisticated analysis models. In light of the above, the mathematical modeling of residual deformations involves multidimensional state variables suitable for capturing both the local and global aspects of permanent structural damage.

Computational modeling of residual deformation evolution has to be performed with the implementation of advanced numerical techniques capable of handling path-dependent constitutive models interacting with geometric nonlinearities. While developing such analysis frameworks, appropriate representation through comprehensive mathematical formulation of the effects brought about by cumulative damage in the forms of material softening, strength degradation, and stiffness loss needs to be present. High-fidelity finite element analyses, supported by adaptive mesh refinement approaches, have been conducted to capture realistic localized deformation behaviors and their interaction with overall structural displacements (Jiang and Liou, 2002; Jamora , 2020).

Performance-based design methodologies call for quantification of the relationship among magnitudes of residual deformations and structural serviceability criteria in the case of a modern performance-based design. The probabilistic evaluation methods included in the analytical approach address uncertainties of seismic demand factors and characteristics of structural responses, fostering appropriate performance indicators in functionality assessment after an event (Pampanin et al., 2003). Advanced material models incorporating principles of cyclic plasticity and damage mechanics are embedded within this broader capability for predicting permanent deformation patterns.

The improvement of structural systems for residual deformation reduction may be associated with new design methodologies, well grounded on mathematics and computational mechanics. These include multi-objective optimization algorithms that balance objectives in conflict. Proposed optimum design formats enable the determination of strong structural configurations characterized by controlled permanent deformation modes with enhanced serviceability after an event; hence, an advance toward performance-based seismic design methods is offered (Pampanin et al., 2003).

2.2 NON-STRUCTURAL BUILDING ENVELOPE AND VF FAÇADE SYSTEMS

2.2.1 Cladding Displacement and Connector Damage

Rigorous quantification of the cladding displacement mechanisms and degradation of the associated connectors requires sophisticated analytical frameworks representative of the complex interaction between the primary structure deformations and the response characteristic of the façade systems. These mathematical models can implement multiscale modeling techniques that range from detailed, finite element representations of local connection components to coarser, global response models (Zhu et al., 2024; Piccioni et al., 2024). This allows for efficient computation while maintaining resolution adequate for the performance evaluation of interest.

The whole development of the connector damage states reveals peculiar nonlinear characteristics due to the plastic material behavior, geometry variations, and peculiarities of cyclic deterioration. Advanced constitutive models, incorporating the effects of both monotonic and cyclic loading, allow for the prediction of incremental damage development in critical connection regions with high accuracy (Buciumeanu et al., 2010; Duque, 2022). Such analytical formulations account for a variety of possible failure modes, including loss of clamping, shear deformations, and local instability mechanisms, using also strict mathematical representations of material and geometrical nonlinearities.

Accordingly, state-of-the-art numerical approaches to the analysis of façade systems apply methodologies of adaptive mesh refinement, combined with the most advanced contact algorithms to capture the local deformation pattern and mechanisms of force transfer across the interfaces of connectors (Davis and LeVeque, 2020; Buciumeanu et al., 2010). Furthermore, advanced material models incorporating strain-rate sensitivity with temperature-dependent properties will further heighten the precision of computed behaviors of connections under intense loading. Such computational frameworks enable the assessment of system performance attributes through the conduct of extensive parametric studies and sensitivity analyses.

In this case, optimization of façade connection systems requires novel design methodologies based on probabilistic performance evaluation and multi-objective optimization algorithms, which balance competitive performance limits considering initial cost, maintenance needs, and long-term durability concerns while ensuring sufficient safety against diverse modes of failure. Such analytical approaches result in design frameworks enabling the development of resilient façade systems with improved resistance against seismic-induced displacements and better long-term functionality (Fathalia and Vaez, 2022; Pham et al., 2011).

2.2.2 Glazing Breakage and Envelope Airtightness Loss

Performance under seismic loading conditions involves complex mathematical modeling, which embeds both probabilistic and deterministic models in the evaluation of performance. The response characteristics in such a computational methodology can be forecast considering comprehensive finite element analysis that involves material brittleness, dynamic influence, and uncertainty in boundary conditions while assessing the probability distribution of breakage (Martins et al, 2012; Memari et al., 2003).

Advanced numerical simulation methods applied to the assessment of envelope airtightness deploy complex models that describe fluid-structure interaction in a way that well captures the complicated links between the patterns of structural deformation and the associated characteristics of air infiltration. Mathematical representations involve both laminar and turbulent flow conditions; therefore, comprehensive computational fluid dynamics analyses enable an accurate evaluation of energy performance consequences associated with various damage conditions (Jaiman and Joshi, 2021; Bhardwaj et al., 1998).

The enabling of comprehensive performance metrics for evaluating glazing systems, for example, requires the combination of multi-physically based phenomena: those related to thermal transport mechanisms, acoustic transmission properties, and structural response indicators. Currently, most of the analytical models utilize multi-physics simulation tools that will enable the consideration of various different performance characteristics in an integrated analysis methodology (Jaiman and Joshi, 2021; Bhardwaj et al., 1998). These types of computational methodologies enable the optimization of the system designs toward achieving much higher post-event durability and functionality.

Advanced experimental validation methodology and statistical analysis strategies may be required to quantify the relationships between the glazing damage patterns and related envelope performance characteristics. Such analytical methodologies allow for resilient performance prediction models through their integration with empirical data via theoretical frameworks, thereby offering the capability for performance-oriented design approaches considering explicit safety factors together with the needs for environmental control.

2.2.3 Planter and Vegetation Module Dislodgement

It is obvious that the analytical evaluation of stability characteristics under seismic excitation for planters involves powerful mathematical formulations, capturing the dynamic interaction involved between vegetative containers and their respective structural supports. A computational framework involving comprehensive finite-element representations of the connection mechanism and the support conditions will apply nonlinear dynamic analysis techniques for the exact determination of displacement thresholds linked to different failure modes (Tabatabaiefar et al., 2013; Baker, 2013).

Advanced numerical analyses applied to planter systems involve complicated contact algorithms with advanced material models accounting for geometrical and material nonlinearities, inclusive of forecasting key response parameters. In these, probabilistic assessment methodologies allow judgment over the reliability characteristics of the system with comprehensive uncertainty quantification in order to come up with resilient design criteria that can ensure safety margins against failure under ultimate limit state conditions (Baker, 2013; Tabatabaiefar et al., 2013).

Advanced performance-based design of the vegetation module system allows for the quantitative derivation of the correlation between the displacement demands and the variable limit states resulting from extended analytical procedures. Mathematical models, including deterministic and probabilistic techniques of evaluation, enable the exact determination of required displacement limits, balancing the safety consideration against the architectural and functional goals by multi-objective optimization strategies (Tabatabaiefar et al., 2013; FEMA, 2016).

The new computational methodologies that may be considered in view of the development of the planter attachment systems may take into account different load cases and wide parametric analyses of environmental parameters with sensitivity checks. This form of analysis allows for truly optimal design solutions characterized by improved stability features and strength against seismic displacement actions, while maintaining architectural appeal and vegetation maintenance needs through sophisticated integration approaches.

2.3 VEGETATION AND FORESTRY COMPONENTS

2.3.1 Plant Health and Vitality Post-Event

Vegetation response attributes after seismic events are complex to assess and require analytical models that integrate multiple assessment approaches, from visual inspections to advanced remote sensing. Mathematical formulations involve algorithms of multispectral image analysis, enabling the precise definition of plant health indicators by statistically processing spectral reflectance data and performing vegetation index calculations.

Current assessment protocols utilize state-of-the-art machine learning to automatically detect and classify vegetation stress patterns (Estrada et al., 2023; Virnodkar et al., 2020). This facilitates quicker assessments in the aftermath of events by leveraging image processing algorithms. Deep learning structures are tailored for multispectral data processing, allowing accurate detection of leaf loss, distribution of branch damages, and overall canopy structure integrity through advanced feature extraction and classification methods.

These developments necessitate new statistical frameworks that incorporate temporal evolution and environmental adaptation mechanisms to establish robust correlation metrics linking documented damage patterns with sustained vegetation viability. Such analyses adopt methods from time-series analysis, enhanced by probabilistic assessment methodologies, to forecast recovery trajectories based on sound mathematical modeling of plant physiological response variables (Wang et al., 2019; Chatterjee et al., 2016).

Advanced data fusion algorithms are required to combine various assessment modalities, integrating visual survey outcomes with quantitative remote sensing data within rigorous mathematical frameworks. These computational methods enable the derivation of holistic health assessment metrics that encompass immediate damage impacts and long-term potential consequences. This is achieved through enhanced statistical analysis techniques, facilitating evidence-based management strategies for vegetation recovery post-event.

2.3.2 Soil and Root Integrity Measure

The analytical characterization of soil-root systems under seismic loading conditions calls for detailed mathematical formulations representative of the coupled mechanical behaviors both for soil media and root structural systems using sophisticated numerical simulation methodologies. Computational frameworks developed using advanced constitutive relationships relevant to both soil mechanics and root biomechanics allow for reliable predictions of system response characteristics by comprehensive finite element analyses (Alkhdour & Shraa, 2024; Nazarzadeh & Sarbishe-ee, 2017).

Advanced numerical schemes for container deformation assessments intrinsically incorporate interaction involving large geometrical and material nonlinearities through various schemes that preserve stability and convergence characteristics. These allow appropriate structural integrity evaluations in terms of rigorous parameter studies for a better solution to the localized deformation modes and their attendant stress amplitudes at the critical interfaces by using adaptive mesh refinement strategies.

Such development of quantitative relationships between the observed deformation patterns and metrics of vegetation sustainability necessitates novel approaches to analyses whereby multiple physical phenomena must be integrated through coupled analysis procedures. Included among these are: mathematical frameworks incorporating mechanical and biological response characteristics, hence enabling derivation of long-term vegetation viability by sophisticated modeling of root-soil interaction mechanisms and nutrient transport.

Some modern performance evaluation methodologies make use of the probabilistic analysis technique for uncertainties of material properties, loading conditions, and environmental factors by extensive reliability analysis processes (Kaczmarek & Popielski, 2019; Liu & Wang, 2021). For these computational methods, resilient design criteria are established with ample safety margins against the effects of both soil displacement and container deformations, while sophisticated optimization algorithms compromise between different performance objectives to maintain vegetation growth conditions at their optimum.

2.4 OCCUPANT SATISFACTION AND COMFORT MEASURE

2.4.1 IEQ (Indoor Environmental Quality) and OEQ (Outdoor as well) Degradation

Different analytical frameworks have been developed that allow the simulation of a wide range of physical phenomena, encompassing deterioration of indoor environmental quality related to seismic activities (Ma et al., 2008). In this respect, mathematical models adopt advanced methodologies of computational fluid dynamics, enriched by algorithms of heat transfer and acoustic propagation, able to allow a detailed characterization of environmental variables by means of comprehensive numerical analysis procedures, considering complex relationships of the patterns of structural damage and subsequent indoor conditions. Li et al. (2023) conducted an experimental study using multiple piezoelectric sensors to monitor damage in a reinforced concrete planting balcony within a high-rise vertical greenery building.

State-of-the-art performance evaluation methodologies of today employ high-fidelity sensor networks with data acquisition systems that allow one to monitor in real time the key environmental parameters through widespread measurement methodologies (Lim et al., 2005; Pogfay et al., 2010). Active statistical processing algorithms apply sophisticated pattern recognition methods, which may include temporal and spatial correlation frameworks in measured data, in order to locate irregular fluctuations in temperature distributions, humidity gradients, and acoustic field properties.

It may require innovative mathematical frameworks that establish strong correlation metrics, associating the identified patterns of environmental degradation with criteria for occupant comfort. The mathematical frameworks may integrate different assessment modalities through comprehensive statistical analysis procedures. There are incorporated sophisticated uncertainty quantification methods, computational strategies dealing with measurement noise, sensor placement influences, and environmental variability, based on extensive probabilistic assessment methodologies, so accurate performance thresholds can be defined.

It calls for advance computational systems that may appropriately integrate multi-performance objectives using multi-criteria decision analyses methodologies. Such analytic techniques might be used to realize adaptive control algorithms that might be set to maintain optimal indoor environmental conditions by taking the impacts of structural damage through novel mathematical formulations that guarantee stability and convergence characteristics of such a system.

2.4.2 Accessibility and Exit Blockage, Injuries or Fatalities

The analytics that underpin the determination of the dynamics of evacuee flow at an event require highly developed mathematical modeling capable of capturing human motion through powerful simulation models of crowd movement (Nishida et al., 2023). Computational models will implement advanced agent-based modeling in concert with probabilistic assessment methodologies using advanced distributions that quantify evacuation times by comprehensive numerical analyses of occupant movement trajectories.

Current performance metrics for the evaluation of egress systems include comprehensive protocols to quantify the effects of structural damage patterns on accessibility and the delivery of means of egress (Göttlich and Knapp, 2020; Xiang et al., 2010). These methodologies, using advanced mathematical models, allow for the production of realistic estimates of evacuation times by sophisticated simulation techniques that take into account the impact of physical blockages and psychological influences on occupant response in emergency situations.

It implies the integration of advanced multimodal assessment methodologies, which merge spatial analysis techniques with attributes of temporal evolution by complex mathematical expressions. The approach allows one to find the main blockage patterns with high precision and their impact on the performance of the whole system since it allows deep parametric analyses that help in enhancing emergency response strategies.

The quantification of the relationships, both physical accessibility measures, and the occupant safety parameters require the introduction of novel statistical frameworks able to capture uncertainties of both structural damage behaviors and human behavioral attributes. These will, in turn, set the ground to derive comprehensive performance metrics in terms of short-term safety and consequences on people's psychological status through state-of-the-art simulation methods in mathematics.

2.4.3 Post-Event Habitat Functionality, Repairability or Obligation to Remove

Establishing rigorous assessment methodologies for determining habitat functionality after an event involves applying sophisticated statistical frameworks that effectively integrate quantitative measures with qualitative survey data through comprehensive analytical techniques. Such mathematical models enable precise mapping of occupant satisfaction metrics by using advanced data-processing algorithms that account for response variability and potential biases inherent in survey methodologies.

Validated questionnaire formats undergo systematic statistical testing through multiple validation methods in order to ensure the reliable measurement of intended constructs (Aithal and Aithal (2020) and Díaz-Oreiro et al. 2019). For assessing the relationships among the airport servicescape factors, satisfaction metrics, and behavioral intentions, statistical analyses such as multiple regression and hierarchical modeling are considered, with particular attention given to perceived safety both as a moderator and as a direct factor affecting customer experience (Moon et al. 2017), This necessitates integrating various measurement modalities, requiring new data integration algorithms that couple survey responses with physical measurements through comprehensive statistical analysis methods. These computational methods are employed to build predictive models of objective building performance features and subjective occupant assessments by leveraging advanced machine learning techniques fine-tuned for heterogeneous data analysis (Jayathissa et al., 2020).

Developing quantitative relationships between patterns of physical damages and measures of occupant satisfaction relies on complex mathematical modeling that accommodates direct and indirect influences through advanced causal analysis techniques. Such analytical approaches provide exhaustive performance measures, enabling evidence-based decisions on post-event building management based on valid and reliable measurement attributes and appropriate statistical methods.

3 SELECTION OF APPROPRIATE HAZARD-RELATED INTENSITY MEASURES (IMS)

3.1 SEISMIC INTENSITY MEASURES

3.1.1 Different Structural IMs

Traditional seismic demand assessment using intensity measures relies on strong mathematical models representing probabilistic correlations between characteristics of ground motion and parameters of structural response (Baker and Cornell, 2006; Vargas-Alzate et al., 2022, Kavvadias et al. 2017, Lazaridis et al. 2022). While Peak Ground Acceleration (PGA) enjoys ease of computation and wide applicability, it has some fundamental shortcomings that make it insufficient to effectively represent complex dynamic behavior, especially for multi-degree-of-freedom systems and substantial contribution of higher modes into overall response patterns.

The calculation of Spectral Acceleration (Sa) at the fundamental period enforces strong correlation features due to the direct inclusion of the system-specific dynamic properties in the evaluation, enabling better response predictions when incorporated into more advanced probabilistic formats. Frequency-dependent amplification of different modes along with corresponding modal participation factors form the mathematical development; thus, it characterizes structural demand parameters with higher precision in more advanced statistical analysis methodologies, accounting for record-to-record variability and propagating uncertainty mechanisms (Cantagallo et al., 2024).

Peak Ground Velocity (PGV) metrics supplement the seismic demand characteristics, particularly related to the response of nonstructural components and façade systems known to be sensitive to velocity (Wang et al., 2021). The analytical framework uses a sophisticated signal-processing technique for velocity time-history analysis and enables robust correlation assessment by involving comprehensive statistical methodologies representing amplitude-frequency content effects on the performance evaluation of systems.

3.1.1.1 Approach 1: Correlation of sites with state-accredited seismic accelerometer recording and microzoning elaborated values in micro (building level) and macro-scale (region level)

Basic research into seismic microzoning and site amplification is important for understanding earthquake hazards on both micro and/or macro scales. The Swiss Seismological Service has presented detailed models of site amplification based on geophysical measurement and earthquake records (Bergamo et al., 2023). These models combine local site response knowledge at about 245 seismic stations and geospatial prediction methods outlining the amplification factors across diverse areas.

These include techniques for quantifying site-specific amplification based on an integration of geophysically measured data and recorded ground motions. For example, such studies demonstrate that techniques incorporating empirical spectral modeling methodologies have been found to successfully forecast the observed site amplification factors at instrumented sites Edwards et al.

(2013). Amplification is then interpolated over larger areas based on site condition proxies such as topographic slope and geological classification.

Such site response analysis at the building level helps in understanding how the local soil conditions affect the ground shaking intensity. According to Böse et al. 2010, decades of research in correlating recorded motions with site conditions to develop microzonation studies and site-specific elastic response spectra have been implemented in the Swiss building code. This multi-scale approach has provided valuable insight thanks to instrumentation data combined with site characterization at both the regional hazard mapping scale and building-specific analyses.

3.1.1.2 Approach 2: Correlation of sites with state-accredited seismic accelerometer recording and Q-Felt maps

The "Did You Feel It?" (DYFI) system developed by the USGS constitutes an innovative method for collecting earthquake impact data via citizen science. Since it was established in the 1990s, DYFI has amassed millions of individual intensity reports through digital questionnaires, facilitating the swift production of Community Internet Intensity Maps within minutes following an earthquake (Wald et al., 2020). This system has transformed macroseismic data collection, offering significantly enhanced spatial and temporal resolution in comparison to conventional postal surveys.

Another innovative approach to mapping felt areas involves search engine query analysis. Zhu et al. 2020 showed that monitoring search queries in real time containing earthquake-related keywords can be employed to quickly estimate the geographical distribution of earthquake effects. Their Q-Felt Map uses machine learning to weight the reliability of more than 1 million queries processed within 3 minutes following an earthquake and produces isoseismal maps. This approach achieved high correlation with official intensity maps, particularly in populated areas.

Recent advancements in earthquake alert systems have concentrated on the incorporation of various data sources to enhance both precision and scope. Wald (2023) explains that the fusion of conventional seismic monitoring with crowd-sourced information and social media inputs can yield a more thorough situational awareness. The Swiss Seismological Service serves as a prime example of this integrated methodology, merging instrumental recordings, macroseismic data, and rapid impact assessment tools, such as ShakeMap, into a cohesive earthquake information system (Böse et al., 2010).

3.1.1.3 Approach 3: Correlation of sites with state-accredited seismic accelerometer recording and building collapse from satellite images

Remote sensing has become a commonly used means for fast post-earthquake damage assessment, particularly in identifying collapsed buildings. Liu et al. (2023) investigated a total of 25 different remote sensing features while identifying collapsed buildings. The result showed that Homogeneity, Energy, Local Entropy, Local Standard Deviation, and Gradient were helpful in finding the rapid damage effect. They could apply such features to large-scale imagery with a high recognition accuracy featuring F1-scores in the range of 0.71-0.94.

Deep learning approaches have achieved state-of-the-art performance regarding automated building damage assessment. For detecting collapsed buildings in post-earthquake remote sensing images, an enhanced YOLOv3 model was developed by Ma et al. (2020). By replacing a conventional Darknet53 neural network with a lightweight ShuffleNet v2 backbone and some other modifications in terms of the loss function, they attained detection speeds as high as 29.23 frames per second at 90.89% accuracy. Those were significant gains over the original YOLOv3 both in speed and accuracy.

The combination of these detection technologies with traditional damage assessment methodologies forms an immense asset in response to disasters. According to Liu et al., 2023, it is effective depending on factors such as image resolution and population density around the epicenter, but their framework can still identify the areas where structure collapses are likely within minutes after imagery was acquired post-disaster. Ma et al. (2020) additionally illustrated that their enhanced deep learning methodology preserves substantial detection accuracy, even in difficult circumstances such as fluctuating lighting and intricate backgrounds.

3.1.2 Advanced/Combined IMs

Vector-valued IMs (Sa(T1), Sa(T2), PGA) represent one important step forward in characterizing seismic demands using multidimensional probabilistic frameworks that capture complex response features over diverse spectral domains (Baker and Cornell, 2006; Baker and Cornell, 2008). The mathematical framework encompasses sophisticated statistical correlation structures among the spectral ordinates, enabling a more complete representation of ground motion attributes with advanced multivariate analysis methods tailored specifically to address the prediction of structural responses. Cumulative parameters, such as those represented through Arias Intensity measures, introduce new approaches in quantifying seismic demand, by considering explicitly mechanisms of dissipation of energy and the influence of duration. These analytical formulations enable much-improved evaluations of correlation with the performance of both vegetative and façade systems through tight mathematical frameworks considering the process of accumulation of damage under cyclic loading conditions, enabled by sophisticated numerical integration methodologies and statistical analysis methodologies (Sandıkkaya and Akkar , 2017; Bullock et al., 2017). Advanced computational algorithms need to be developed to integrate the different measures of intensity into coherent assessment frameworks balancing predictive accuracy and implementability. The proposed mathematical methodologies will allow the development of robust correlation metrics through the performance of extensive parametric investigations and sensitivity analyses, hence fostering the improvement of performance prediction models by using sophisticated statistical learning methods that preserve both accuracy and computational efficiency attributes.

3.2 HAZARD INTENSITY MEASURES FOR ENVIRONMENTAL AND CLIMATE ASPECTS

3.2.1 Wind Intensity Considerations

The analysis of wind effects on integrated façade-vegetation systems embodies complex mathematical formulations able to realistically model multiple interactions between the dynamics of the atmospheric boundary layer and the nature of the structural response. Computational methods involve advanced turbulence modeling strategies along with statistical post-processing analysis techniques able to provide an accurate quantification of the gust effect through full probabilistic formulations (Wächter et al., 2012; Kareem, 2020).

The latter requires the development of powerful correlation metrics between wind intensity variables and system performance attributes, employing innovative numerical techniques that can integrate both deterministic and stochastic elements of atmospheric influences. Such a mathematical construct will allow for the correct determination of the aerodynamic loading patterns, enabling advanced computational fluid dynamics simulations for comprehensive parametric investigations into façade stability traits and vegetation response dynamics.

Fully integrated state-of-the-art performance evaluation schemes embody intricate wind engineering concepts through extensive analytical procedures, making consideration for spatial and temporal variabilities in atmospheric boundary conditions (Gameiro Lopes et al., 2021; Kareem, 2020). Advanced statistical processing techniques allow for the highly resolved characterization of extreme wind events by comprehensive studies of probability distribution functions, contributing to the derivation of reliable performance forecasting models using systematic uncertainty quantification methodologies.

This aeroresistance design methodology involves an ever-increasingly complicated mathematical model that weighs all the competitive performance objectives using cutting-edge multi-criteria decision-making systems. Under such a framework, a designer could be allowed to come up with an effective system configuration through comprehensive assessment processes, including but not limited to the features related to aerodynamic stability, structural integrity specifications, and vegetation sustainability indices.

3.2.2 Rainfall Intensity Analysis

Quantitative assessment of dynamic effects of rain-induced loads on integrated building systems requires advanced mathematical formulations to represent the strongly coupled behavior of hydraulic and structural components through numerical simulation techniques. Computational methodologies typically incorporate sophisticated hydrological modeling methodologies augmented by structural analysis procedures, providing effective means to describe response characteristics of such systems under combined loading conditions (Hu et al., 2023; Ghosh Dastider et al., 2024).

Modern analytical frameworks developed for analyzing rainfall intensities have incorporated detailed time-distribution pattern analysis along with spatial variability using a wide range of statistical methods (Cristiano et al., 2017; Monjo, 2016). Advanced probabilistic theories facilitate the development of robust metrics correlating rainfall parameters and system performance characteristics through intricate mathematical formulations that consider both direct and indirect impacts on structural integrity.

The integration of multimodal assessment methodologies necessitates the formulation of sophisticated computational techniques that merge hydraulic analysis approaches with structural response assessments within coherent mathematical frameworks. These analytical methods enable accurate quantification of drainage system performance characteristics and infiltration phenomena through extensive numerical simulations, accounting for potential changes in system efficiency induced by seismic events.

This includes comprehensive performance metrics utilizing advanced statistical methodologies to encapsulate the complex relationships between rainfall intensity parameters and system responses post-earthquake. Such mathematical constructs allow for the assessment of long-term sustainability consequences through sophisticated probabilistic analytical techniques, accounting for uncertainties related to environmental loading conditions and the state of system damages.

3.3 INTEGRATION OF MULTIPLE INTENSITY MEASURES IN PERFORMANCE EVALUATION

Optimal combinations of the intensity measures that can be used in integrated performance evaluation have quite complicated analytical frameworks in order to embed multiple response characteristics through comprehensive mathematical formulations. Assessment of spectral acceleration at the fundamental period, Sa(T1), yields a fundamental association with overall structural response patterns, facilitated by stringent modal analysis techniques enhanced through sophisticated statistical processing approaches.

The integration of PGA metrics into comprehensive frameworks greatly enhances predictive capability regarding the response of non-structural components, through rigorous consideration of high-frequency content. These quantitative methodologies make use of fairly sophisticated signal processing techniques to describe the behaviors of acceleration-sensitive systems by extended correlation analyses.

Complementary information on the characteristics of system response provided by the PGV parameters assumes particular importance in view of the evaluation of the façade components and the assessment of vegetation stability. These analytical methodologies further allow an improvement in predictive capabilities due to advanced statistical frameworks accounting for the velocity-sensitive damage mechanisms and cumulative response effects.

These various measures of intensity naturally require more sophisticated algorithms computationally for extensive evaluation methodologies so that the attributes of precision and efficiency are not lost through optimized implementation techniques. Such mathematical structures enable the construction of robust performance forecasting models through detailed parametric investigations and sensitivity analyses, thereby supporting the enhancement of design parameters in multiobjective decision-making situations.

3.4 LINKING DAMAGE MEASURES TO INTENSITY MEASURES

With the development of architectural design, not only typical reinforced concrete buildings but also the emergence of green buildings brings new challenges in the assessment of structural performance (Spyridis & Proske, 2021). Therefore, the current research proposes a detailed classification system for risk assessment about the possibility of damage according to various expert opinions, hence valuable for practical applications in the construction field.

Central to this approach to assessment is a detailed investigation into the performance of conventional reinforced concrete structures where experts may consider three main modes of potential failure, namely material-related problems, design defects, and reinforcing details. The rating is given in each category for the three-level scale of severity: Level 1 corresponds to allowable deteriorations-not needing immediate actions; Level 2 describes conditions that require further investigation and possibly intervention; while Level 3 describes dangerous/life-threatening conditions, thus needing urgent response. On the whole, such an orderly procedure finds its support in, among other things, the unanimous verdict by different expert or end-user evaluators.

It widens the scope towards vegetated buildings, based on a tripartite model of analysis including structural performance, greenery efficacy, and human welfare implications. This holistic approach recognizes the complex interaction that exists between building integrity and vegetative elements with regard to root invasion, moisture management, and environmental stress. Human welfare denotes aspects related to occupant safety, maintenance in demand, among several other aspects of quality of life; it, therefore, denotes extensive impacts of environmentally sustainable building design on architecture integrity and welfare of society. The scoring system used, concerns being categorized either as of low importance-5-8, medium importance-9-12, or high importance-13 or over, works as an effective tool for determining priority in terms of the maintenance action and informs future design decisions.

It gives values to this framework in that it can balance the traditional structural engineering problems and modern ones resulting from the implementation of the sustainable construction. This is because it provides a structured approach to risk assessment that can be able to give application to all kinds of building by documenting all the potential damage with its assumed severity level. The multi-expert evaluation approach assures reliability and consensus on the estimation of the risk, while the broad consideration of both technical and human aspects makes it a very usable tool in both modern building management and design optimization.

This far-reaching assessment framework represents an important advance in construction science, recognizing that modern building practices must balance structural strength with ecological sustainability and occupant comfort. This structured approach to risk evaluation is of growing relevance for the design professional community of architects, engineers, and facility managers as urban centers continue to use sustainable building technologies. In what follows two main categories of buildings are identified: Common Reinforced Concrete Buildings (not including vertical forests, Table 1) and Greenery Covered Buildings (including vertical forests, Table 2), integrating mainly the work already done in WP 1 (D11-D14) and WP 3 (D31). It should be noted that in most of the parameters the levels of severity are similar and high discrepancies are absent.

Table 1 Expert Assessment (EO=Expert Opinion) of Damage Causes and Severity in Common Reinforced Concrete Buildings

CLASSIFICATION								
COMMON REINFORCED CONCRETE BUILDINGS			LEVELS					TOTAL
Structural performance								
CAUSES OF DAMAGES		DAMAGES	EO1	EO2	EO3	EO4	EO5	
Material	**Poor concrete quality**	Cracking	2	2	2	3	3	12
		Reduced load-bearing capacity	2	2	2	3	3	12
		Surface spalling	2	2	2	3	3	12
		Permeability issues	2	2	2	3	3	12
	Corrosion	Reinforcement deterioration	2	2	2	3	3	12
		Loss of structural integrity	2	2	2	3	3	12
		Water leakage	2	2	2	3	3	12
Design	**Non- compliance with the earthquake regulations**	Structural cracking	2	2	2	3	2	11
	Short column	High risk of Failure of structural elements (columns, beams and joints), Loss of structural integrity during design EQ	2	2	2	3	2	11
	Strong beam-weak column	High risk of Partial or full collapse during design EQ	2	2	2	2	2	10
	Insufficient shear capacity	High risk of Reduced load-bearing capacity during design EQ	2	2	2	2	2	10
	Soft and weak story	High risk of Soft story failure, Joint failures during design EQ	2	2	2	2	2	10
	Weak attachment to the frames	High risk of Falling of elements like infill walls, ceilings and facades during design EQ	2	2	2	2	2	10

Reinforcement details	Insufficient reinforcement ratio	Reinforcement slippage	3	3	3	3	3	15
	Insufficient transverse reinforcement	Shear cracking	3	3	3	3	3	15
	Smooth stirrups	Loss of structural integrity	3	3	3	2	3	14
	Lack of crossties	Buckling of longitudinal reinforcement	3	3	3	3	3	15
	Lack of transverse reinforcement in connection region	Reduced load-bearing capacity	3	3	3	3	3	15
	90° hooks instead of 135°	Joint and connection failure	3	3	3	3	3	15
Others	Adjacent buildings effect	Collision damage, Structural instability, Cracking	2	3	2	2	2	11
	Insufficient determination of soil properties	Structural tilting,Cracks in walls and floors, Foundation failure	2	3	3	2	2	12
	Infill wall damages	Loss of lateral stability, Loss of lateral stability	3	3	2	3	2	13

Table 2 Expert Assessment of Damage Causes and Severity in Greenery-Covered Buildings

GREENERY-COVERED BUILDINGS		**LEVELS**					**TOTAL**
Structural performance							
CAUSES OF DAMAGES	**DAMAGES**	EO1	EO2	EO3	EO4	EO5	
Root penetration (growth/action)	Wall and foundation integrity	2	2	2	2	3	11
	Potential instability issues	2	2	2	2	3	11
	Cracks	2	2	2	2	3	11
	Potential damage to technical features (e.g. pipelines)	2	2	2	2	3	11
Plants direct attachment/green layer removal	Wall and foundation integrity	2	2	2	2	2	10
	Lifted blocks	2	2	2	2	2	10
	Cracks	2	2	2	2	2	10

	Scarring	2	2	2	2	2	10
	Plaster removal	2	3	2	2	2	11
	Local wetness	2	3	2	2	2	11
High level of moisture (due to evapotranspiration)	Mould development	3	3	3	3	3	15
	Indoor & outdoor dampness	2	3	2	3	3	13
	Material covers damages	3	3	3	3	3	15
	Slow drying	3	3	3	3	3	15
High level of moisture (due to watering/ irrigation systems)	Water leaks	3	3	3	3	3	15
	Water pooling	3	3	3	3	3	15
	Dripping water	3	3	3	3	3	15
	Indoor & outdoor dampness	3	3	3	3	3	15
	Mould development	3	3	3	3	3	15
	Corrosion	3	3	3	3	3	15
	Streaking	3	3	3	3	3	15
	Material covers damages	3	2	3	3	3	14
Soil moisture changes	Wall and foundation integrity	2	2	2	1	2	9
	Potential instability issues	2	2	2	1	2	9
	Subsidence	2	2	2	1	2	9
Soil microbial flora & organic acids	Concrete erosion	2	3	2	2	2	11
Overgrown vegetation	Overtaking space	2	2	2	2	2	10
	Blocking windows	2	2	2	2	2	10
	Cascading branches	2	2	2	2	2	10
	Technical features obstruction (e.g. drip grooves, pipes)	2	2	3	3	2	12

H.F.R.I. Hellenic Foundation for Research & Innovation
Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
Funded by the European Union NextGenerationEU
GREENERGY

Additional weight and stresses (plants/planting media)	Potential instability issues (e.g. reinforced concrete planting balcony)	1	2	3	2	2	10
Fire	Structural integrity	3	3	3	3	3	15
	Burned materials	3	3	3	3	3	15
	Collapse	3	3	3	3	3	15
Wind	Structural integrity	2	3	2	3	3	13
	Cracks		1	2	3	3	11
	Collapse	3	3	2	3	3	14
	Blown out	2	2	2	3	3	12
	Debris	3	2	2	3	3	13
Earthquake	Structural integrity	3	3	3	3	3	15
	Cracks	3	3	3	3	3	15
	Collapse	3	3	3	3	3	15
	Spalling	3	3	3	3	3	15
	Instability	3	3	3	3	3	15

Greenery performance		**LEVELS**					**TOTAL**
CAUSES OF DAMAGES	**DAMAGES**	EO1	EO2	EO3	EO4	EO5	
High level of moisture (due to evapotranspiration)	Pests	3	3	3	3	3	15
	Degradation of planting media	3	3	3	3	3	15
Low level of moisture (due to watering/ irrigation systems)	Plant stress	3	3	3	3	3	15
	Dry vegetation	3	3	3	3	3	15
	Dead plants	3	3	3	3	3	15
	Wilting	3	3	3	3	3	15
	Gaps	3	3	3	3	3	15
	Degradation of planting media	3	3	3	3	3	15

Improper maintenance	Overgrown vegetation	3	3	3	3	3	15
	Dead biomass	3	3	3	3	3	15
	Bio-debris	2	3	3	3	3	14
	Gaps		3	3	3	3	14
	Degradation of planting media	3	3	3	3	3	15
	Loss	3	3	3	3	3	15
	Compaction	3	3	3	3	3	15
Inadequate space	Distorted vegetation growth	2	2	3	2	2	11
Environmental stressors (harsh sunlight, strong wind)	Plant stress	3	3	3	3	3	15
	Dehydration	2	3	3	3	3	14
Fire	Burnt vegetation	3	3	3	3	3	15
Wind	Uprooting	3	3	3	3	3	15
	Mechanical stress	3	3	3	3	3	15
	Dehydration	3	3	3	3	3	15
	Reduced plant growth rate	3	2	3	3	3	14
	Wilting	3	3	3	3	3	15
	Bended trees	3	3	3	3	3	15
	Falling bio-debris	3	2	3	2	2	12
Earthquake	Planter anchorage and instability	3	3	3	3	3	15
	Tree pot anchorage and instability	3	3	3	3	3	15
Human welfare		**LEVELS**					**TOTAL**
CAUSES OF DAMAGES	**DAMAGES**	EO1	EO2	EO3	EO4	EO5	
Dead plants	Aesthetics	3	3	3	3	3	15
	Utility	3	3	2	3	3	14
	Energy needs (increased during summer)	3	3	2	3	3	14

Overgrown vegetation	Insects	3	3	3	3	3	15
	Aesthetics	2	2	3	3	3	13
	Energy needs (increased during winter)	2	2	3	3	3	13
	Utility	2	2	3	3	3	13
	Reduced sunlight/view	2	2	3	3	3	13
	Living space occupation	2	2	3	3	3	13
High moisture level	Health issues	3	3	3	3	3	15
	Pests	3	3	3	3	3	15
	Insects	3	3	3	3	3	15
	Mould development	3	3	3	3	3	15
Maintenance	Cost	2	2	3	2	3	12
	Time	2	2	3	2	3	12
	Potential falls	3	3	3	3	3	15
	Work at height	2	3	3	2	3	13
Non-native species	Ecological imbalances	2	2	3	2	3	12
Fire	Safety	3	3	3	3	3	15
	Evacuation obstruction	3	3	3	3	3	15
	Fire vertical propagation	3	3	3	3	3	15
	Chimney effect	3	3	3	3	3	15
Wind	Safety	3	3	3	3	3	15
	Fallen objects/bio-debris	3	3	3	3	3	15
	Turbulence	3	3	3	3	3	15
Earthquake	High repairing cost	3	3	3	3	3	15

Levels	Color	Description
Low	1	Acceptable damage, no need of repair
Moderate	2	Under investigation, component replacement/reinforcement may happen
High	3	Urgent action, life threating conditions

Low Importance: Total score between **5-8**.
Medium Importance: Total score between **8-12**.
High Importance: Total score **12 or more**.

3.4.1 Monte Carlo Simulation

Monte Carlo analysis, popularly known as Monte Carlo simulation (IBM, 2023; Wikipedia, 2023), is one of the statistical techniques in modeling and analyzing uncertainties and variability within systems and processes. It is developed on random sampling with the purpose of approximating the outcome probabilities of a decision, process, or model whose inputs are uncertain.

Steps of a Monte Carlo Analysis (Wikipedia, 2023; Minitab, 2023):

- Problem Definition: Define the system, process, or decision analyzed in this case, and its objectives.
- Model the System: One must develop a mathematical or computational model of the system.
- Define Input Variables: Identify which inputs are random, assign a probability distribution to the random variables or sample from a defined range of numbers.
- Monte Carlo Simulation: Run many iterations, sampling randomly each time from the input distributions; then calculate the output.
- Analyze results: Integrate data to identify trends, probabilities, or expected risks to different outcome scenarios.

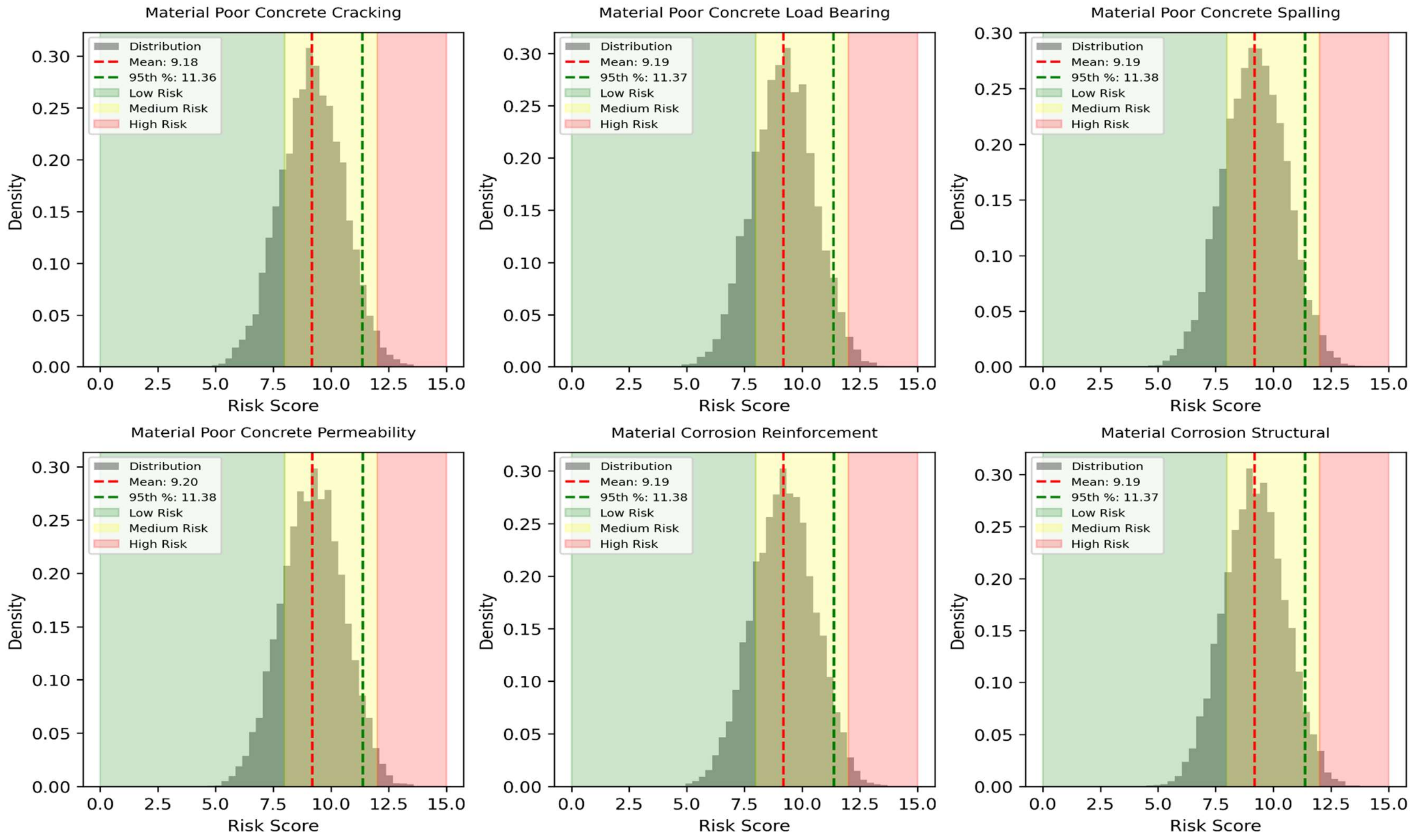
In the given project application, a Monte Carlo analysis is used to assess the evaluations that different experts give in order to ascertain the type of probability distribution of the risk levels in different system subcomponents. Such analytical methodology allows the identification of the probabilities of each subcomponent falling in three predefined risk levels and hence results in computing the average risk value for the whole system. The idea here is to convert discrete ratings of damage into continuous intervals with partial overlapping: rating 1 corresponds to [0.0, 1.3], rating 2 corresponds to [0.7, 2.3], and rating 3 corresponds to [1.7, 3.0]. This will enable more detailed modeling of expert assessments and take into account some uncertainty in the boundary regions.

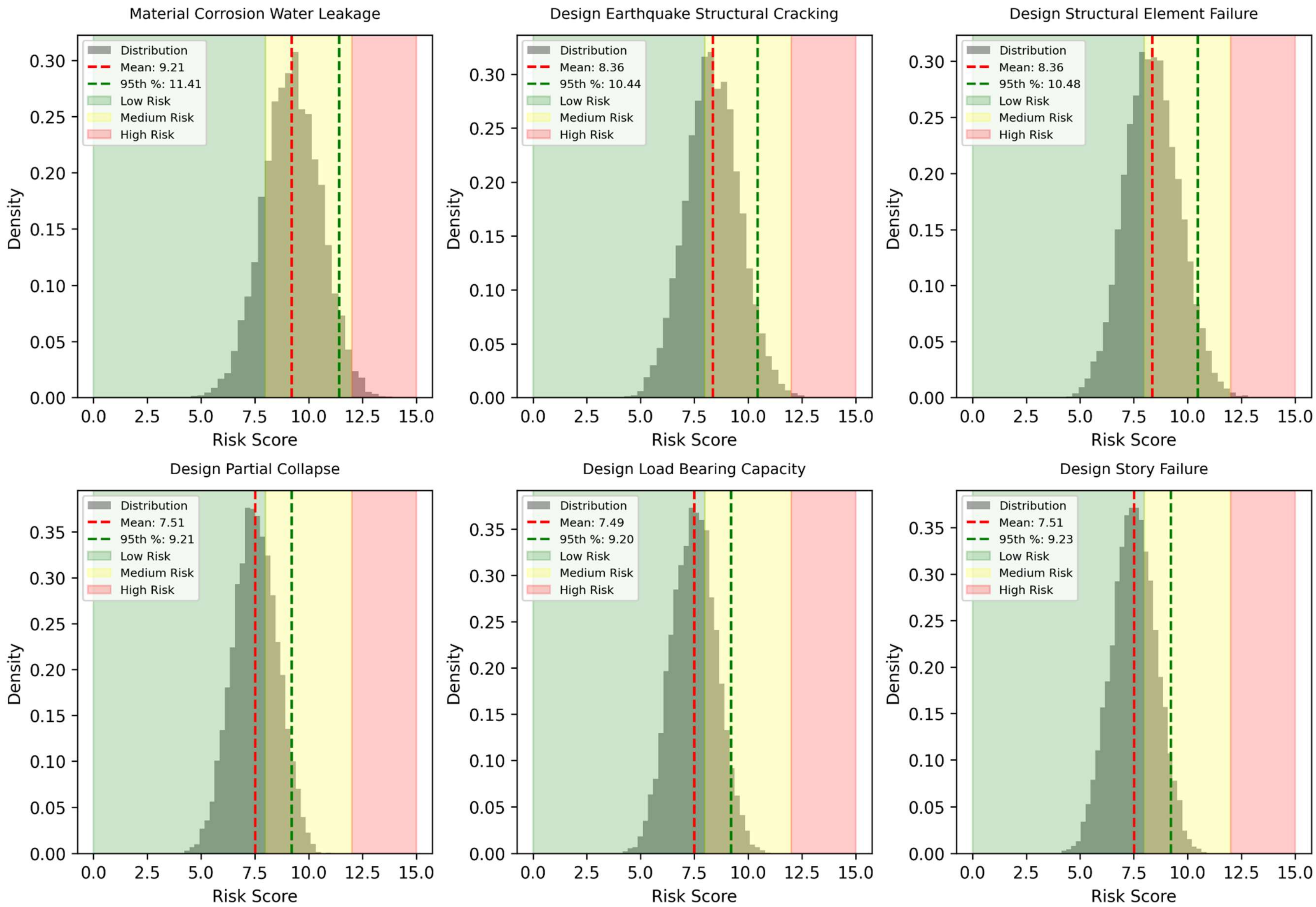
This Monte Carlo simulation is run 10000 times in order to reach statistical reliability (error <1%). During each run, the process samples randomly from the pool of ratings by every expert in each category for the various types of damages. These discrete ratings, having thus been sampled, are then converted into continuous values based on overlapping ranges and summed to develop a total score pertaining to damage. The approach develops a sound distribution of outcomes possible while retaining the variability due to the opinions of the experts.

It follows that the test proceeds with deterministic calculations in which the level of risk falls into three categories: low risk, between 5 and 8 points; medium risk, between 8 and 12 points; and high risk, between 12 and 15 points. For every kind of damage, the simulation calculates all the useful statistical indicators, including average scores, standard deviations, and 95th percentile values. These measures provide complete information about the central tendency and dispersion of the risk assessments, enabling the identification of both regular and extreme situations.

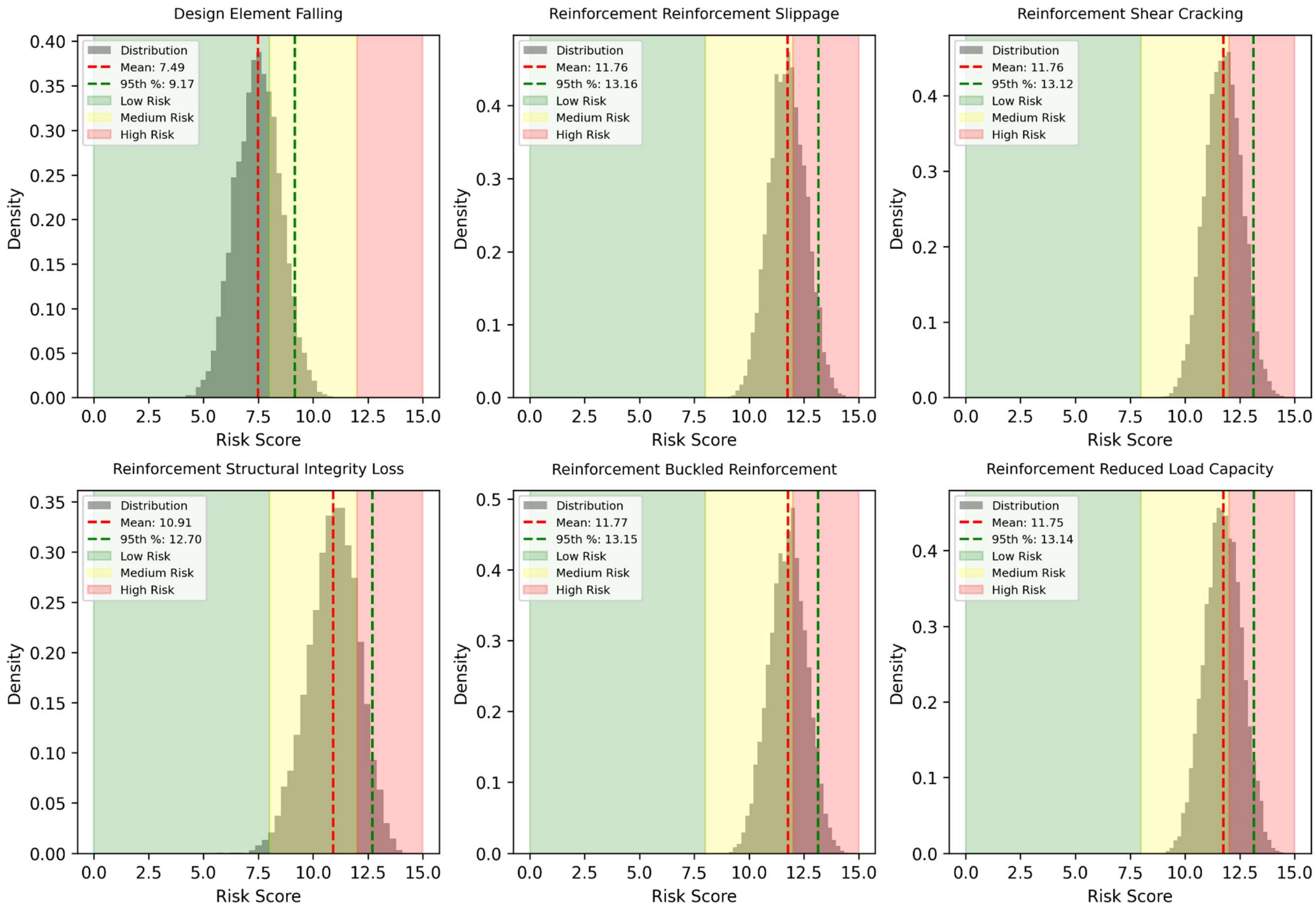
The last step represents the consolidation of results for an indication of the overall risk profile of the system. In this, several risk assessments are combined in order to arrive at overall probabilities of risk, while showing results through a set of graphs, including distribution of risk score, clear demarcation of zones of risk, and some important statistical measures like average and 95th percentile. It allows stakeholders to understand the setting of risk much faster through this broad-ranging visualization methodology and make fact-based decisions, both based on probabilistic results and specific thresholds of risk.

3.4.1.1 Common Buildings




Material Corrosion Water Leakage
Distribution
Mean: 9.21
95th %: 11.41
Low Risk
Medium Risk
High Risk
Density
Risk Score
Design Earthquake Structural Cracking
Distribution
Mean: 8.36
95th %: 10.44
Low Risk
Medium Risk
High Risk
Density
Risk Score
Design Structural Element Failure
Distribution
Mean: 8.36
95th %: 10.48
Low Risk
Medium Risk
High Risk
Density
Risk Score
Design Partial Collapse
Distribution
Mean: 7.51
95th %: 9.21
Low Risk
Medium Risk
High Risk
Density
Risk Score
Design Load Bearing Capacity
Distribution
Mean: 7.49
95th %: 9.20
Low Risk
Medium Risk
High Risk
Density
Risk Score
Design Story Failure
Distribution
Mean: 7.51
95th %: 9.23
Low Risk
Medium Risk
High Risk
Density
Risk Score

H.F.R.I. Hellenic Foundation for Research & Innovation
Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
Funded by the European Union NextGenerationEU
GREENERGY



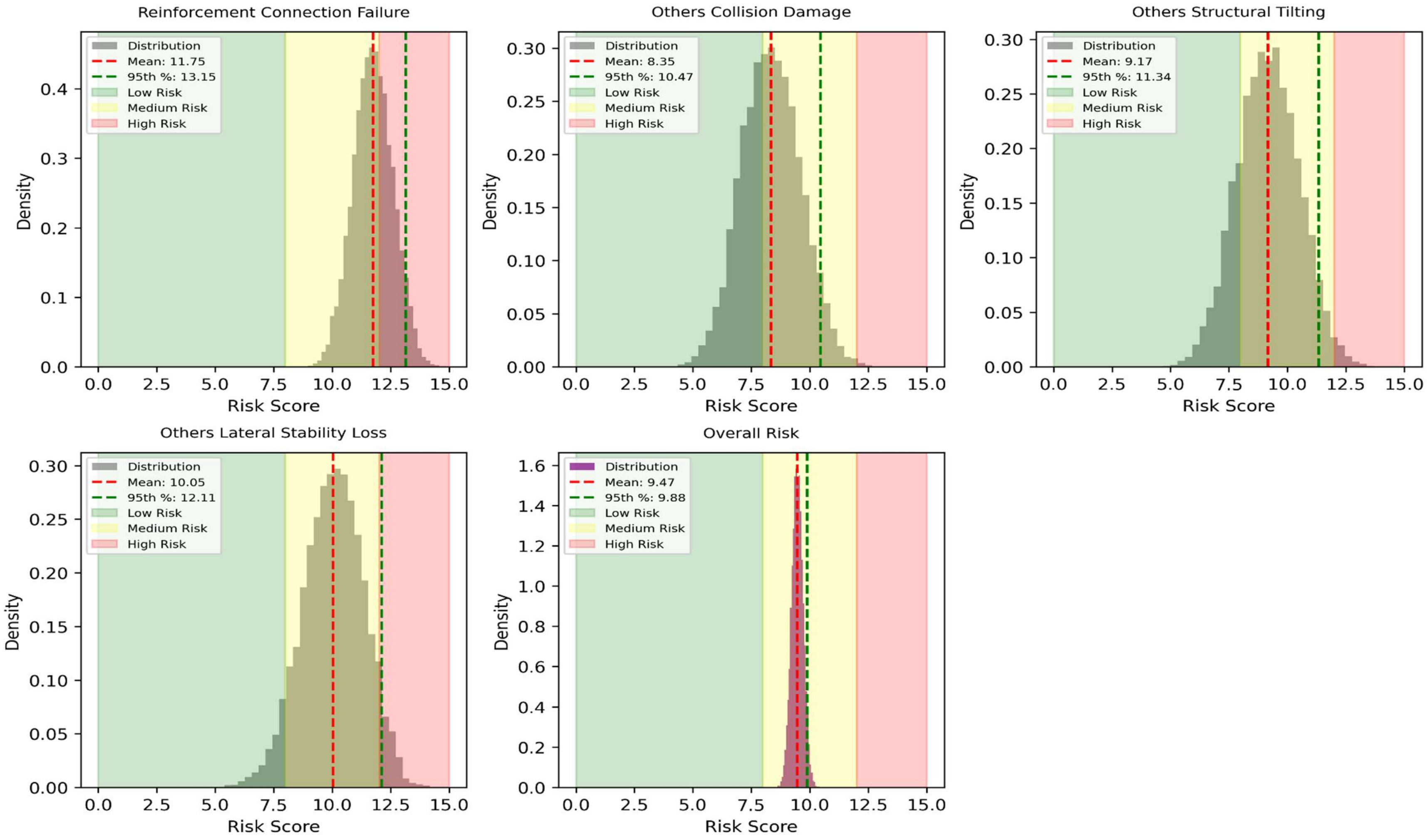


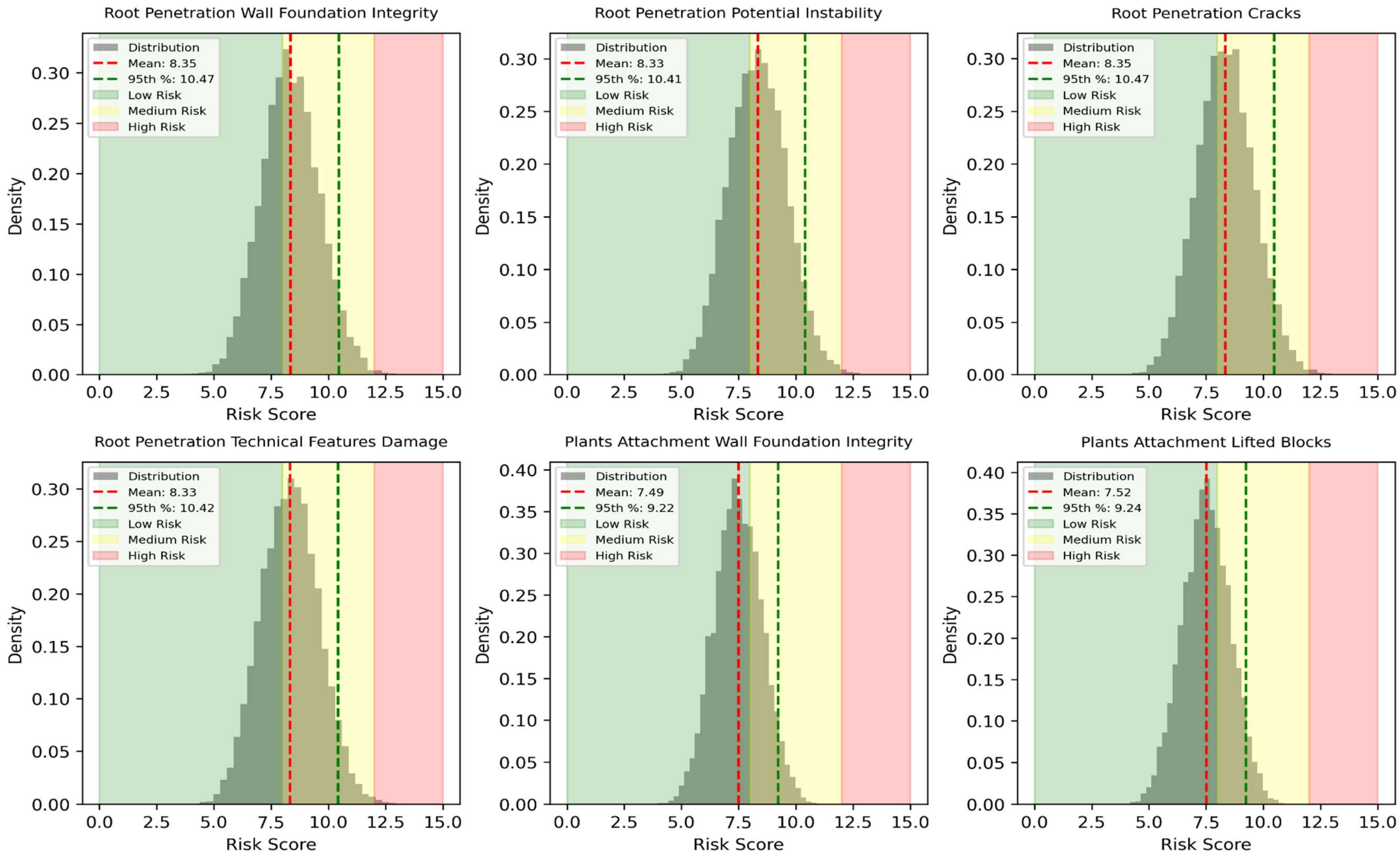
Figure 1 Monte Carlo Analysis Results for Common RC Buildings

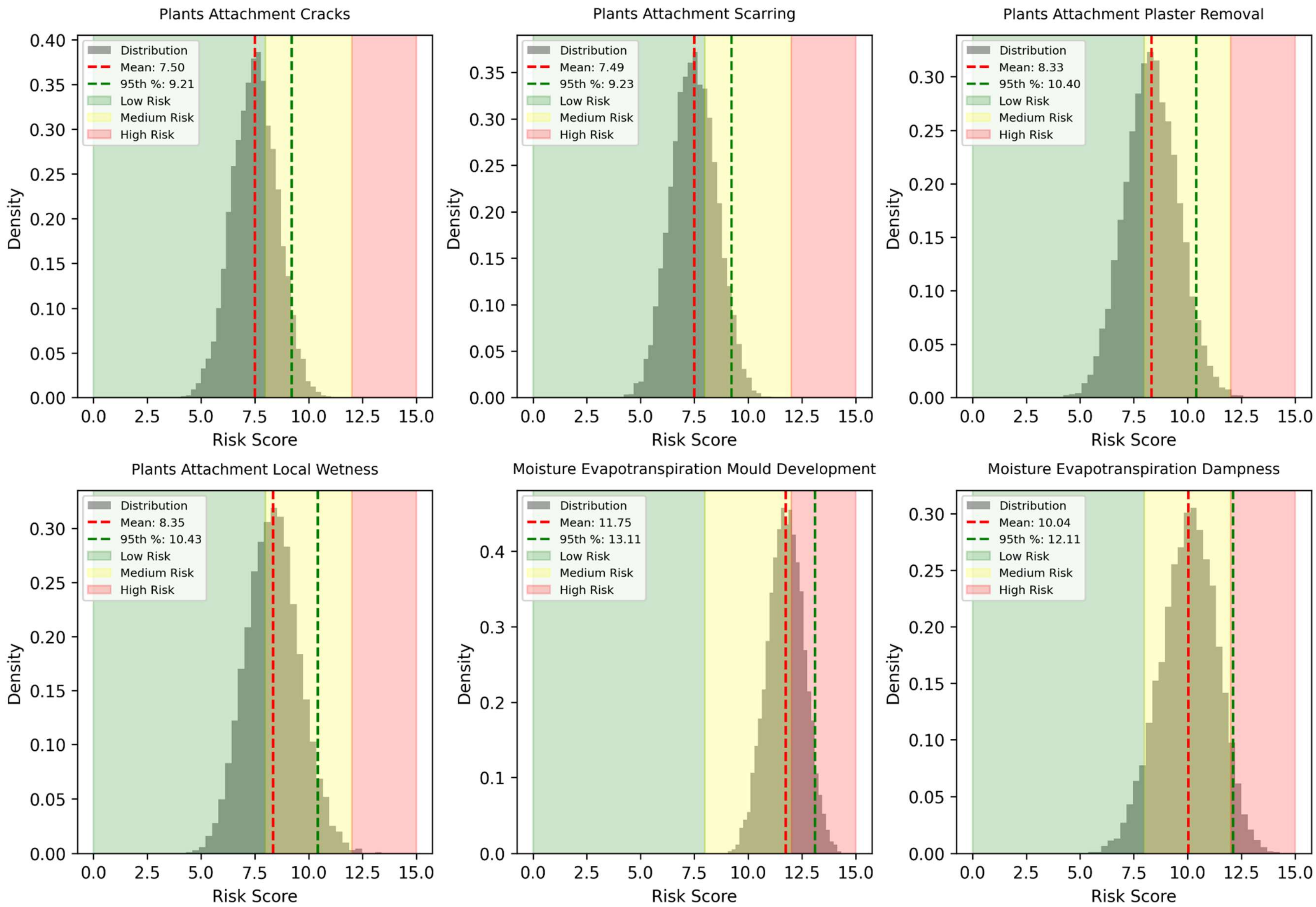
Table 3 Monte Carlo Analysis Results for Common RC Buildings

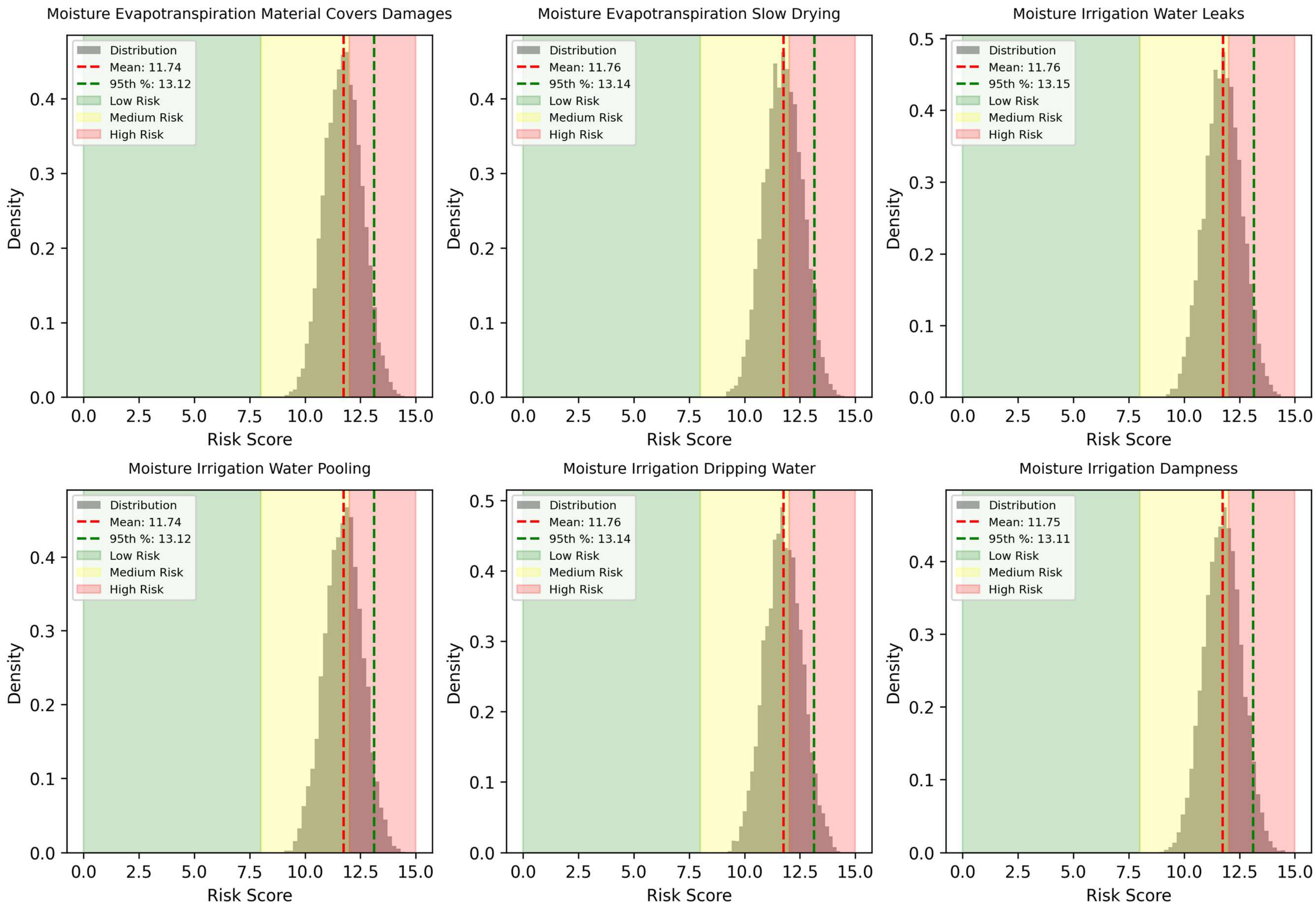
Group	Damage Type	Mean Score	Standard Deviation	95th Percentile	Low Risk (%)	Medium Risk (%)	High Risk (%)
Material	poor_concrete_cracking	9.18	1.34	11.36	19.73	78.69	1.58
	poor_concrete_load_bearing	9.19	1.32	11.37	19.12	79.47	1.41
	poor_concrete_spalling	9.19	1.34	11.38	19.29	79.00	1.71
	poor_concrete_permeability	9.20	1.33	11.38	18.89	79.74	1.37
	corrosion_reinforcement	9.19	1.34	11.38	19.21	79.35	1.44
	corrosion_structural	9.19	1.31	11.37	18.56	80.05	1.39
	corrosion_water_leakage	9.21	1.33	11.41	18.16	80.24	1.60
Design	earthquake_structural_cracking	8.36	1.25	10.44	39.04	60.77	0.19
	structural_element_failure	8.36	1.25	10.48	39.78	60.01	0.21
	partial_collapse	7.51	1.03	9.21	67.56	32.44	0.00
	load_bearing_capacity	7.49	1.03	9.20	68.32	31.68	0.00
	story_failure	7.51	1.04	9.23	67.70	32.30	0.00
	element_falling	7.49	1.02	9.17	68.19	31.81	0.00

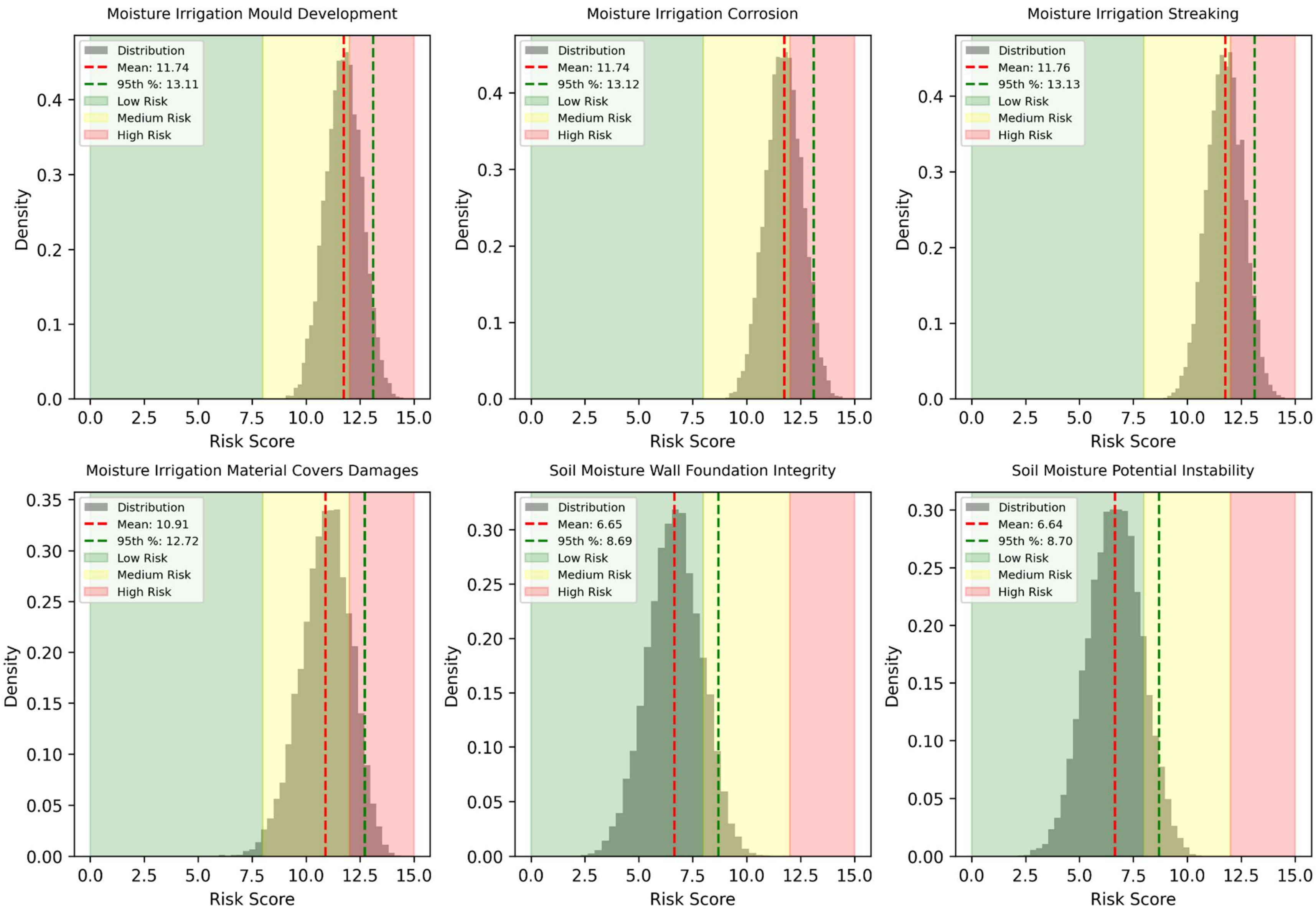
Reinforcement	slippage	11.76	0.83	13.16	0.00	61.58	38.42
	shear_cracking	11.76	0.83	13.12	0.00	61.04	38.96
	structural_integrity_loss	10.91	1.15	12.70	0.88	81.84	17.28
	buckled_reinforcement	11.77	0.85	13.15	0.00	59.93	40.07
	reduced_load_capacity	11.75	0.84	13.14	0.00	61.48	38.52
	connection_failure	11.75	0.85	13.15	0.00	61.60	38.40
Others	collision_damage	8.35	1.27	10.47	40.20	59.63	0.17
	structural_tilting	9.17	1.32	11.34	19.22	79.27	1.51
	lateral_stability_loss	10.05	1.30	12.11	6.26	87.45	6.29
Overall Score		9.47	0.25	9.88	0.00	100.00	0.00

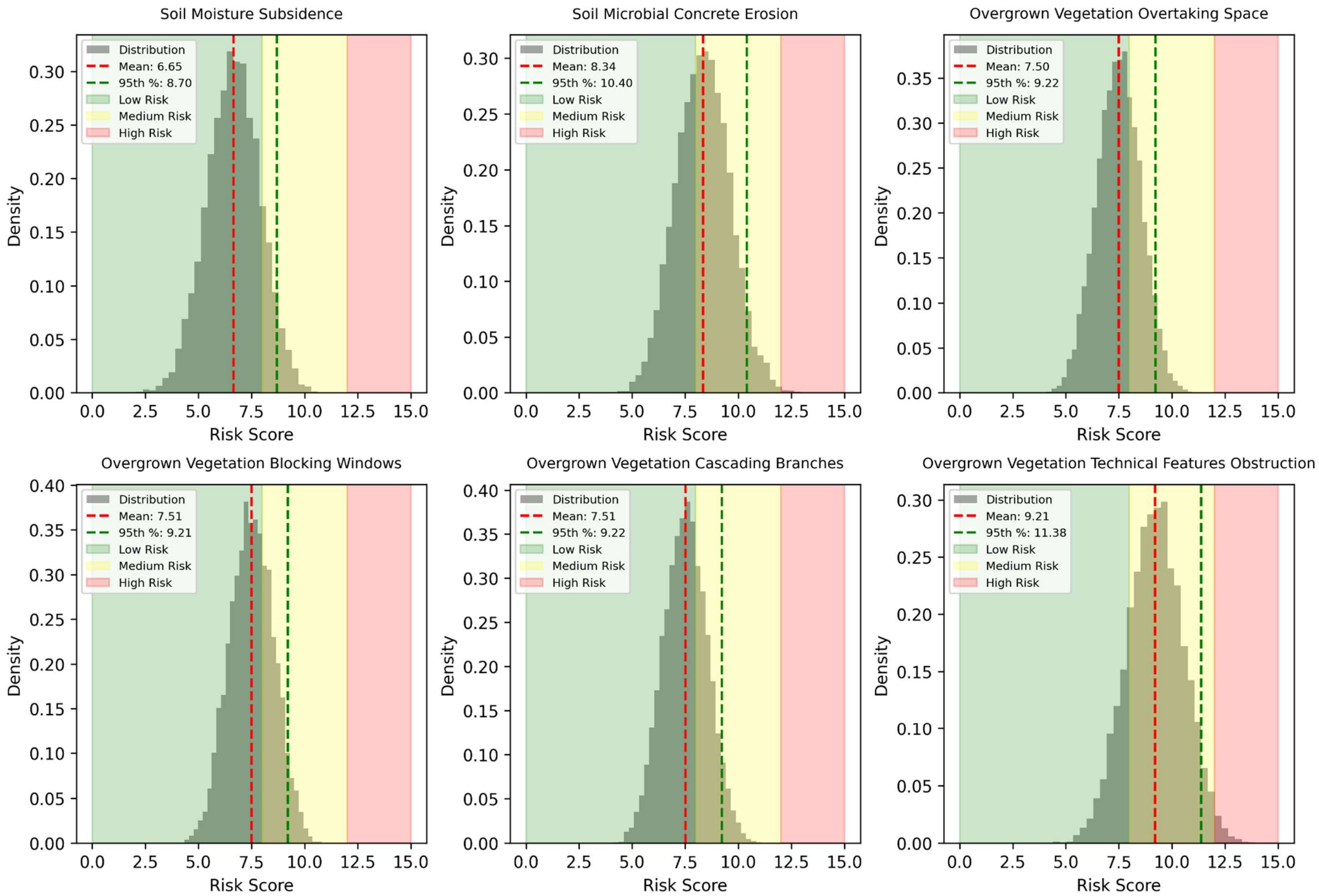
3.4.1.2 Green Buildings - Structural performance



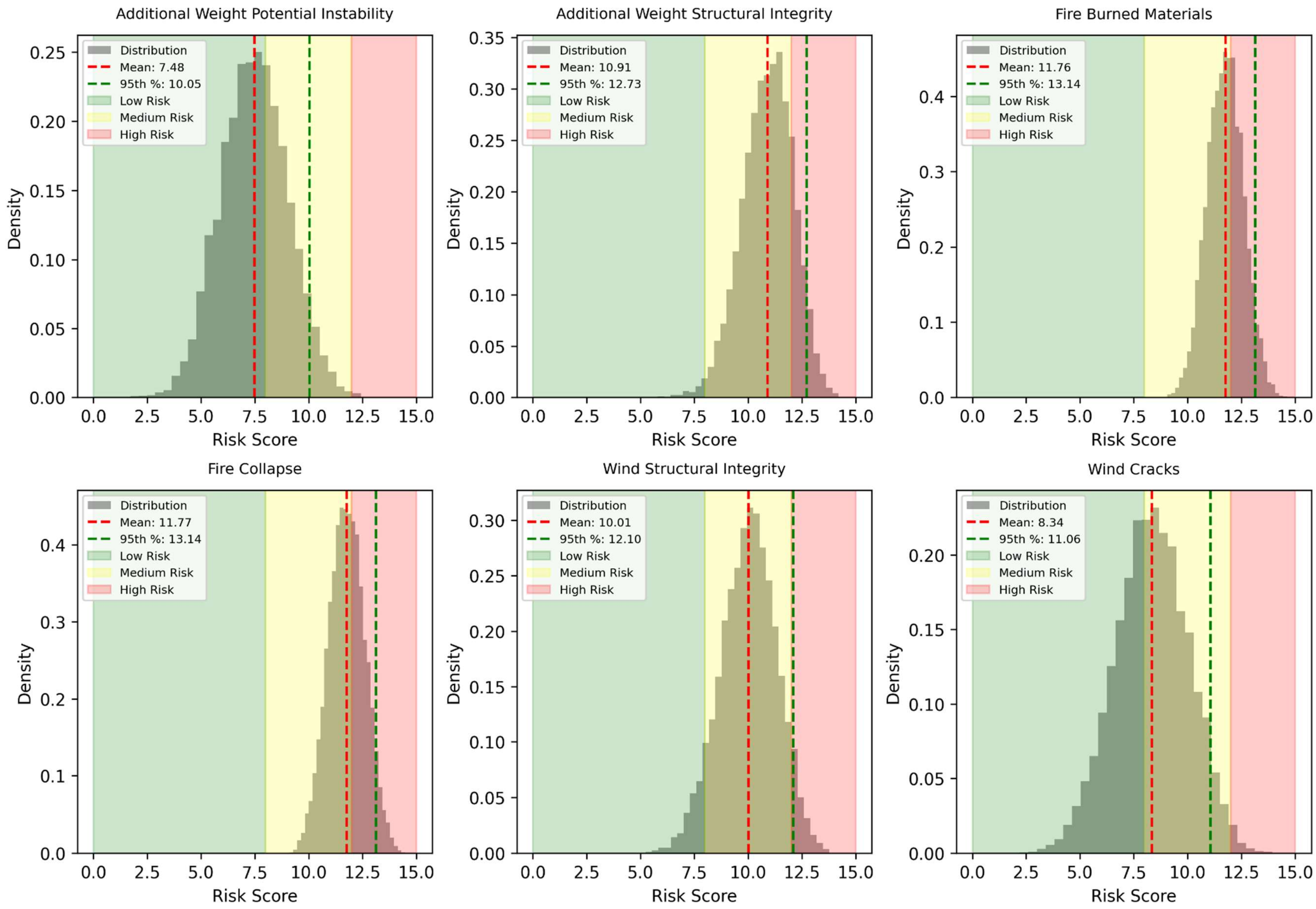

Plants Attachment Cracks
Distribution
Mean: 7.50
95th %: 9.21
Low Risk
Medium Risk
High Risk
Density
Risk Score
Plants Attachment Scarring
Distribution
Mean: 7.49
95th %: 9.23
Low Risk
Medium Risk
High Risk
Density
Risk Score
Plants Attachment Plaster Removal
Distribution
Mean: 8.33
95th %: 10.40
Low Risk
Medium Risk
High Risk
Density
Risk Score
Plants Attachment Local Wetness
Distribution
Mean: 8.35
95th %: 10.43
Low Risk
Medium Risk
High Risk
Density
Risk Score
Moisture Evapotranspiration Mould Development
Distribution
Mean: 11.75
95th %: 13.11
Low Risk
Medium Risk
High Risk
Density
Risk Score
Moisture Evapotranspiration Dampness
Distribution
Mean: 10.04
95th %: 12.11
Low Risk
Medium Risk
High Risk
Density
Risk Score

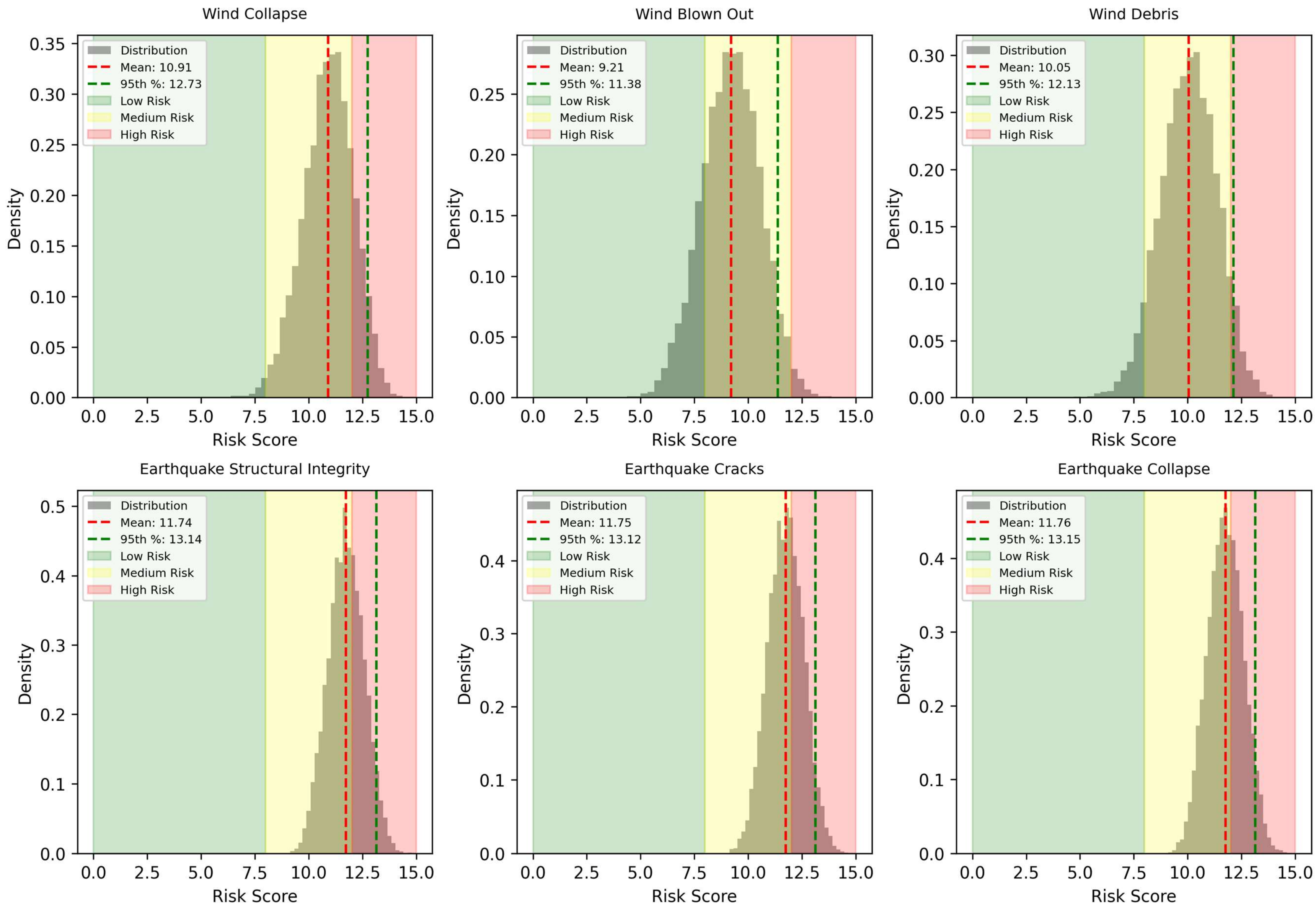

Moisture Evapotranspiration Material Covers Damages
Distribution
Mean: 11.74
95th %: 13.12
Low Risk
Medium Risk
High Risk
Moisture Evapotranspiration Slow Drying
Distribution
Mean: 11.76
95th %: 13.14
Low Risk
Medium Risk
High Risk
Moisture Irrigation Water Leaks
Distribution
Mean: 11.76
95th %: 13.15
Low Risk
Medium Risk
High Risk
Moisture Irrigation Water Pooling
Distribution
Mean: 11.74
95th %: 13.12
Low Risk
Medium Risk
High Risk
Moisture Irrigation Dripping Water
Distribution
Mean: 11.76
95th %: 13.14
Low Risk
Medium Risk
High Risk
Moisture Irrigation Dampness
Distribution
Mean: 11.75
95th %: 13.11
Low Risk
Medium Risk
High Risk
Density
Risk Score


Moisture Irrigation Mould Development
Distribution
Mean: 11.74
95th %: 13.11
Low Risk
Medium Risk
High Risk
Density
Risk Score
Moisture Irrigation Corrosion
Distribution
Mean: 11.74
95th %: 13.12
Low Risk
Medium Risk
High Risk
Density
Risk Score
Moisture Irrigation Streaking
Distribution
Mean: 11.76
95th %: 13.13
Low Risk
Medium Risk
High Risk
Density
Risk Score
Moisture Irrigation Material Covers Damages
Distribution
Mean: 10.91
95th %: 12.72
Low Risk
Medium Risk
High Risk
Density
Risk Score
Soil Moisture Wall Foundation Integrity
Distribution
Mean: 6.65
95th %: 8.69
Low Risk
Medium Risk
High Risk
Density
Risk Score
Soil Moisture Potential Instability
Distribution
Mean: 6.64
95th %: 8.70
Low Risk
Medium Risk
High Risk
Density
Risk Score


Soil Moisture Subsidence
Distribution
Mean: 6.65
95th %: 8.70
Low Risk
Medium Risk
High Risk
Soil Microbial Concrete Erosion
Distribution
Mean: 8.34
95th %: 10.40
Low Risk
Medium Risk
High Risk
Overgrown Vegetation Overtaking Space
Distribution
Mean: 7.50
95th %: 9.22
Low Risk
Medium Risk
High Risk
Overgrown Vegetation Blocking Windows
Distribution
Mean: 7.51
95th %: 9.21
Low Risk
Medium Risk
High Risk
Overgrown Vegetation Cascading Branches
Distribution
Mean: 7.51
95th %: 9.22
Low Risk
Medium Risk
High Risk
Overgrown Vegetation Technical Features Obstruction
Distribution
Mean: 9.21
95th %: 11.38
Low Risk
Medium Risk
High Risk
Density
Risk Score
0.0
2.5
5.0
7.5
10.0
12.5
15.0

H.F.R.I. Hellenic Foundation for Research & Innovation
Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
Funded by the European Union NextGenerationEU
GREENERGY




Wind Collapse
Distribution
Mean: 10.91
95th %: 12.73
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Blown Out
Distribution
Mean: 9.21
95th %: 11.38
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Debris
Distribution
Mean: 10.05
95th %: 12.13
Low Risk
Medium Risk
High Risk
Density
Risk Score
Earthquake Structural Integrity
Distribution
Mean: 11.74
95th %: 13.14
Low Risk
Medium Risk
High Risk
Density
Risk Score
Earthquake Cracks
Distribution
Mean: 11.75
95th %: 13.12
Low Risk
Medium Risk
High Risk
Density
Risk Score
Earthquake Collapse
Distribution
Mean: 11.76
95th %: 13.15
Low Risk
Medium Risk
High Risk
Density
Risk Score

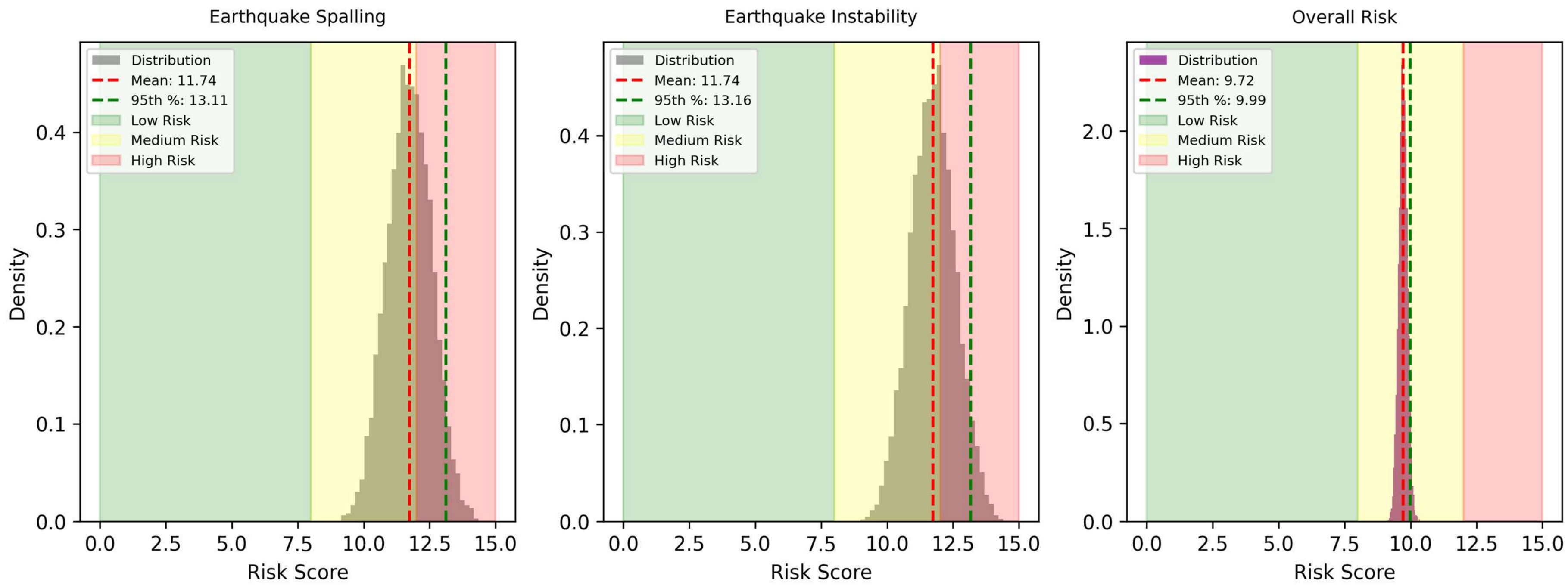


Figure 2 Monte Carlo Analysis Results for Green Buildings - Structural Performance

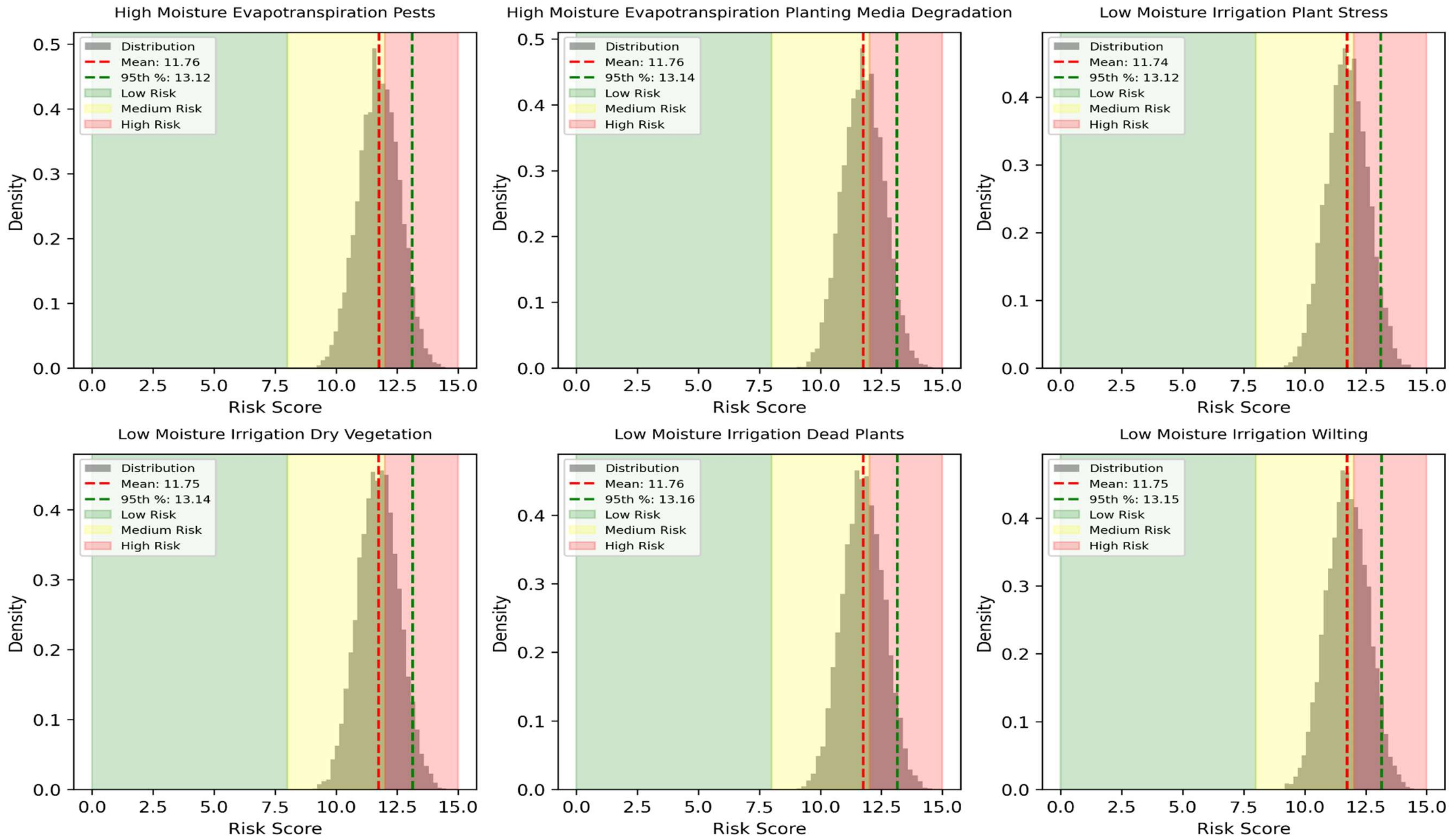
Table 4 Monte Carlo Analysis Results for Green Buildings - Structural Performance

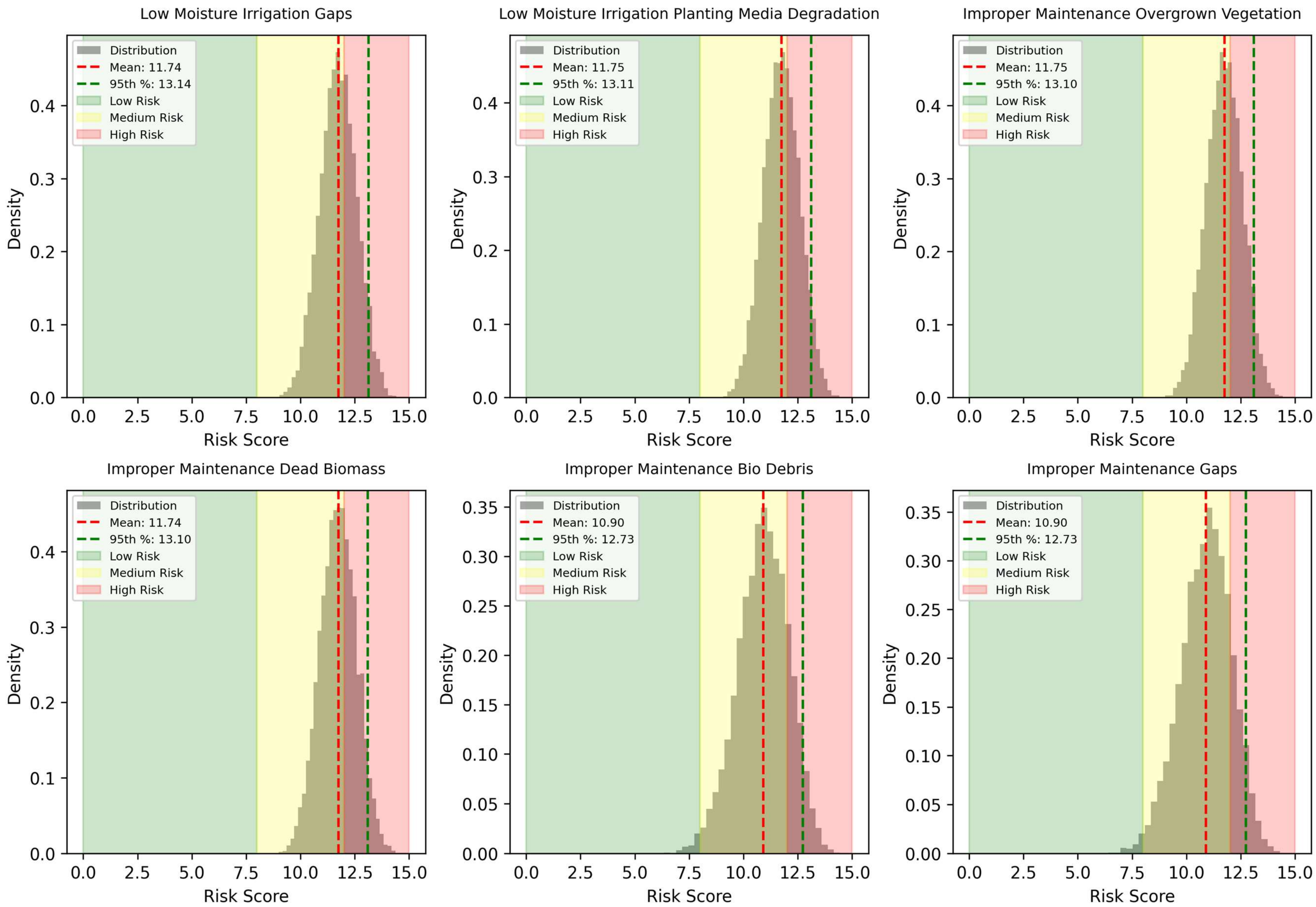
Group	Damage Type	Mean Score	Standard Deviation	95th Percentile	Low Risk (%)	Medium Risk (%)	High Risk (%)
Root	Penetration_wall_foundation_integrity	8.35	1.26	10.47	39.81	59.96	0.23
	Penetration_potential_instability	8.33	1.26	10.41	40.61	59.18	0.21
	Penetration_cracks	8.35	1.26	10.47	39.71	60.05	0.24
	Penetration_technical_features_damage	8.33	1.26	10.42	40.12	59.63	0.25
Plants	Attachment_wall_foundation_integrity	7.49	1.03	9.22	68.45	31.55	0.00
	Attachment_lifted_blocks	7.52	1.05	9.24	67.35	32.65	0.00
	Attachment_cracks	7.50	1.03	9.21	68.17	31.83	0.00
	Attachment_scarring	7.49	1.04	9.23	67.90	32.10	0.00
	Attachment_plaster_removal	8.33	1.24	10.40	39.85	60.03	0.12
	Attachment_local_wetness	8.35	1.24	10.43	39.63	60.14	0.23
	mould_development	11.75	0.84	13.11	0.00	61.15	38.85

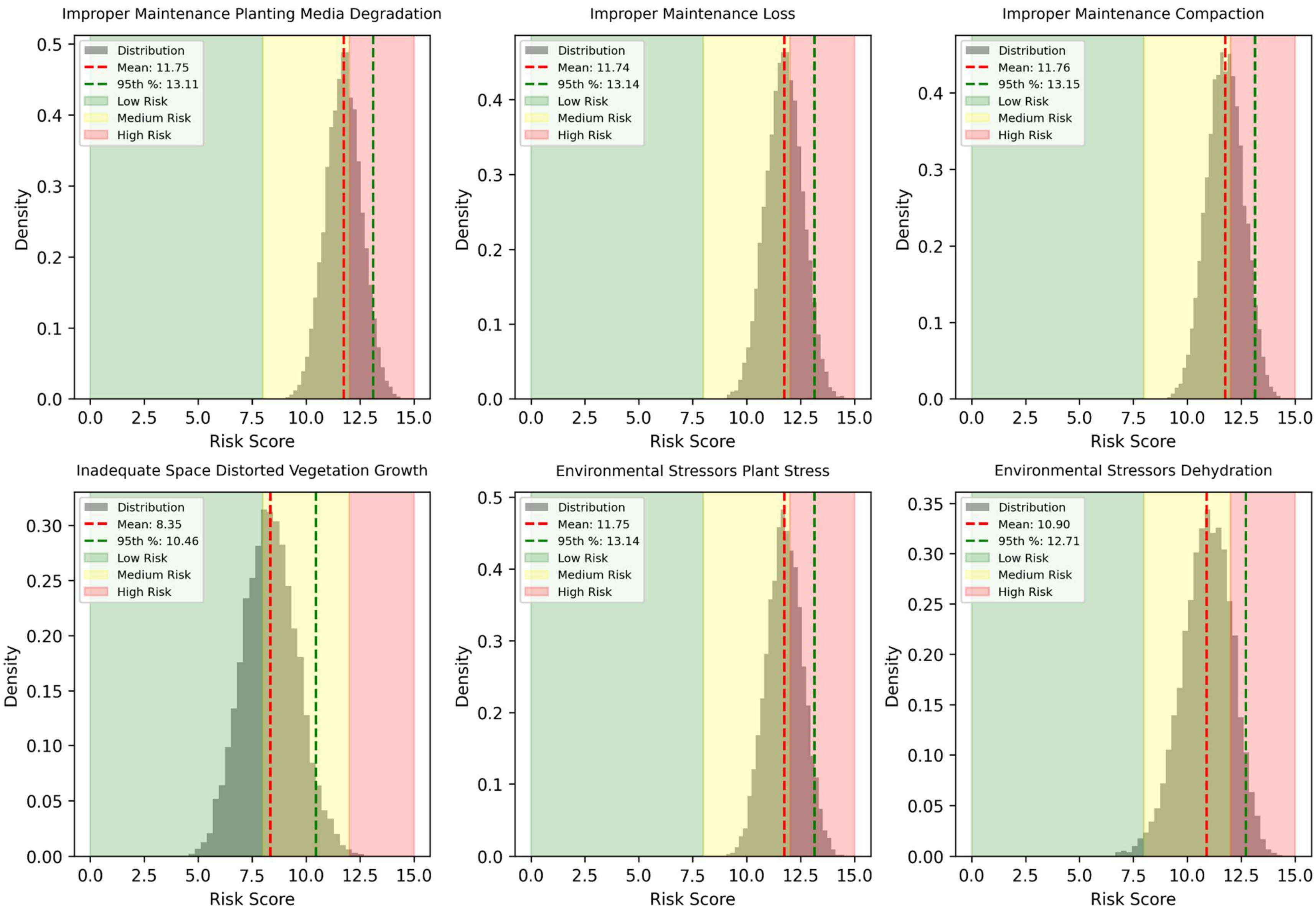
Moisture Evapotranspiration	dampness	10.04	1.31	12.11	6.80	87.21	5.99
	material_covers_damages	11.74	0.84	13.12	0.00	62.15	37.85
	slow_drying	11.76	0.85	13.14	0.00	60.77	39.23
Moisture Irrigation	water_leaks	11.76	0.84	13.15	0.00	61.32	38.68
	water_pooling	11.74	0.84	13.12	0.00	61.21	38.79
	dripping_water	11.76	0.83	13.14	0.00	61.29	38.71
	dampness	11.75	0.84	13.11	0.00	61.59	38.41
	mould_development	11.74	0.84	13.11	0.00	61.60	38.40
	corrosion	11.74	0.84	13.12	0.00	61.83	38.17
	streaking	11.76	0.84	13.13	0.00	60.83	39.17
	material_covers_damages	10.91	1.16	12.72	1.00	81.02	17.98
Soil Moisture	wall_foundation_integrity	6.65	1.25	8.69	85.35	14.65	0.00
	potential_instability	6.64	1.25	8.70	85.92	14.08	0.00
	subsidence	6.65	1.25	8.70	85.89	14.11	0.00
	Soil_Microbial_concrete_erosion	8.34	1.26	10.40	39.72	60.14	0.14
Overgrown Vegetation_	overtaking_space	7.50	1.04	9.22	68.30	31.70	0.00
	blocking_windows	7.51	1.03	9.21	67.52	32.48	0.00

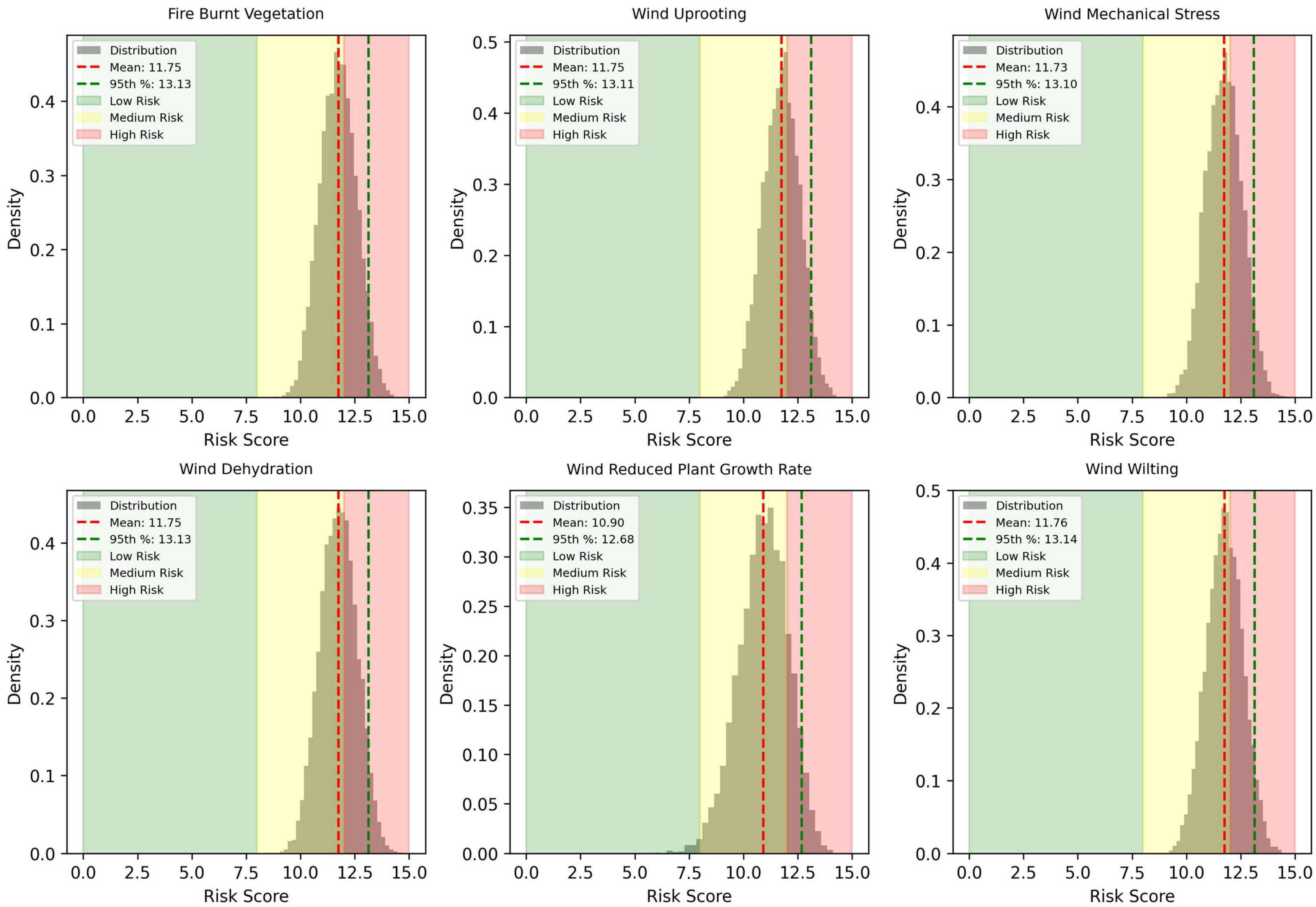
	cascading_branches	7.51	1.03	9.22	68.18	31.82	0.00
	technical_features_obstruction	9.21	1.33	11.38	18.21	80.24	1.55
Additional Weight	potential_instability	7.48	1.55	10.05	62.94	36.92	0.14
	structural_integrity	10.91	1.18	12.73	1.04	80.80	18.16
Fire	burned_materials	11.76	0.84	13.14	0.00	60.69	39.31
	collapse	11.77	0.84	13.14	0.00	60.47	39.53
Wind	structural_integrity	10.01	1.31	12.10	6.82	87.12	6.06
	cracks	8.34	1.69	11.06	41.97	57.06	0.97
	collapse	10.91	1.16	12.73	0.84	81.60	17.56
	blown_out	9.21	1.35	11.38	18.91	79.57	1.52
	debris	10.05	1.30	12.13	5.95	87.77	6.28
Earthquake	structural_integrity	11.74	0.84	13.14	0.00	61.92	38.08
	cracks	11.75	0.83	13.12	0.00	61.37	38.63
	collapse	11.76	0.84	13.15	0.00	61.32	38.68
	spalling	11.74	0.84	13.11	0.00	61.90	38.10
	instability	11.74	0.85	13.16	0.00	61.79	38.21
Overall Score		9.72	0.17	9.99	0.00	100	0.00

3.4.1.3 Green Buildings - Greenery performance




Low Moisture Irrigation Gaps
Distribution
Mean: 11.74
95th %: 13.14
Low Risk
Medium Risk
High Risk
Density
Risk Score
Low Moisture Irrigation Planting Media Degradation
Distribution
Mean: 11.75
95th %: 13.11
Low Risk
Medium Risk
High Risk
Density
Risk Score
Improper Maintenance Overgrown Vegetation
Distribution
Mean: 11.75
95th %: 13.10
Low Risk
Medium Risk
High Risk
Density
Risk Score
Improper Maintenance Dead Biomass
Distribution
Mean: 11.74
95th %: 13.10
Low Risk
Medium Risk
High Risk
Density
Risk Score
Improper Maintenance Bio Debris
Distribution
Mean: 10.90
95th %: 12.73
Low Risk
Medium Risk
High Risk
Density
Risk Score
Improper Maintenance Gaps
Distribution
Mean: 10.90
95th %: 12.73
Low Risk
Medium Risk
High Risk
Density
Risk Score


Improper Maintenance Planting Media Degradation
Distribution
Mean: 11.75
95th %: 13.11
Low Risk
Medium Risk
High Risk
Improper Maintenance Loss
Distribution
Mean: 11.74
95th %: 13.14
Low Risk
Medium Risk
High Risk
Improper Maintenance Compaction
Distribution
Mean: 11.76
95th %: 13.15
Low Risk
Medium Risk
High Risk
Inadequate Space Distorted Vegetation Growth
Distribution
Mean: 8.35
95th %: 10.46
Low Risk
Medium Risk
High Risk
Environmental Stressors Plant Stress
Distribution
Mean: 11.75
95th %: 13.14
Low Risk
Medium Risk
High Risk
Environmental Stressors Dehydration
Distribution
Mean: 10.90
95th %: 12.71
Low Risk
Medium Risk
High Risk
Density
Risk Score


Fire Burnt Vegetation
Distribution
Mean: 11.75
95th %: 13.13
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Uprooting
Distribution
Mean: 11.75
95th %: 13.11
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Mechanical Stress
Distribution
Mean: 11.73
95th %: 13.10
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Dehydration
Distribution
Mean: 11.75
95th %: 13.13
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Reduced Plant Growth Rate
Distribution
Mean: 10.90
95th %: 12.68
Low Risk
Medium Risk
High Risk
Density
Risk Score
Wind Wilting
Distribution
Mean: 11.76
95th %: 13.14
Low Risk
Medium Risk
High Risk
Density
Risk Score

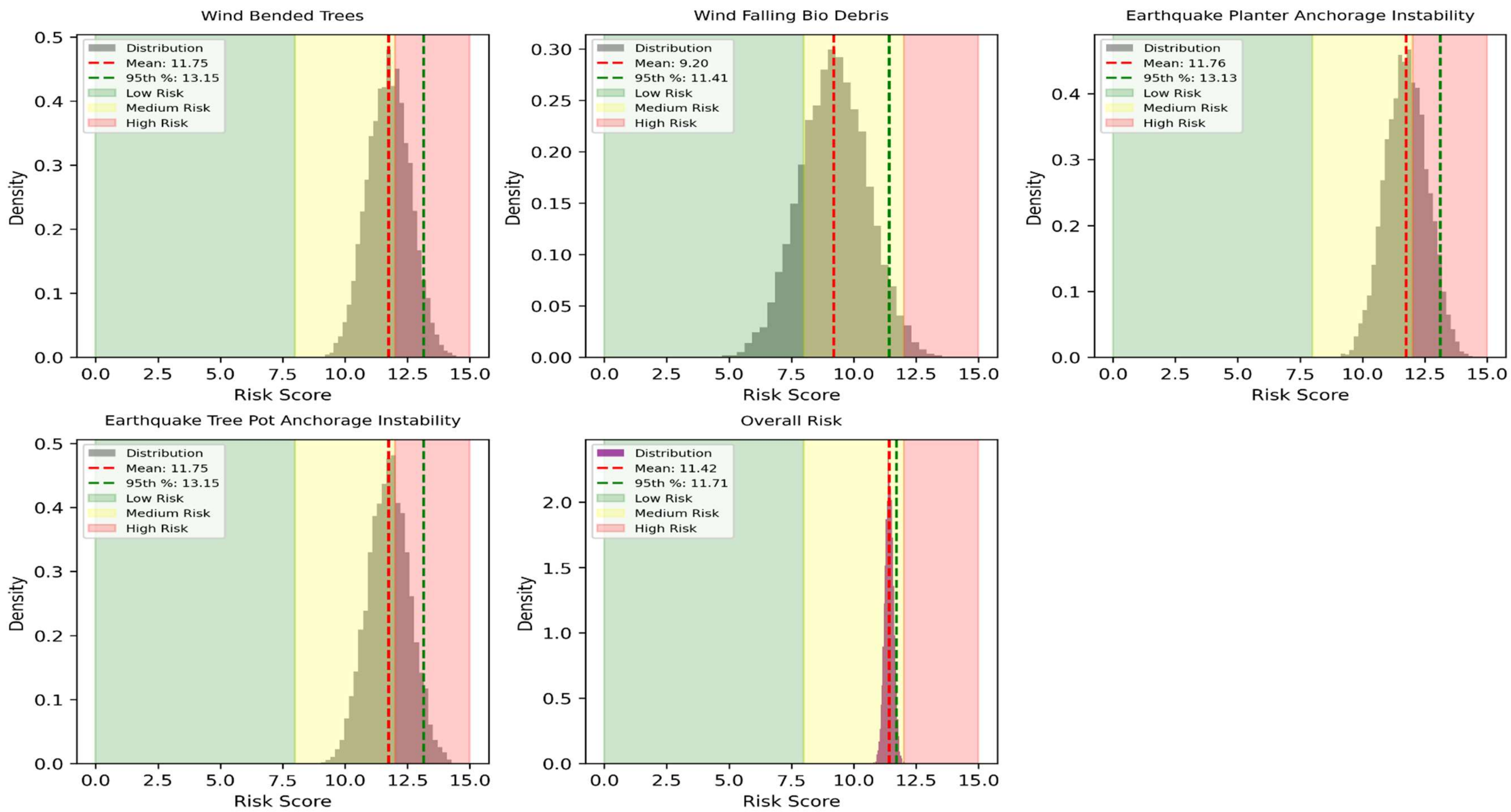


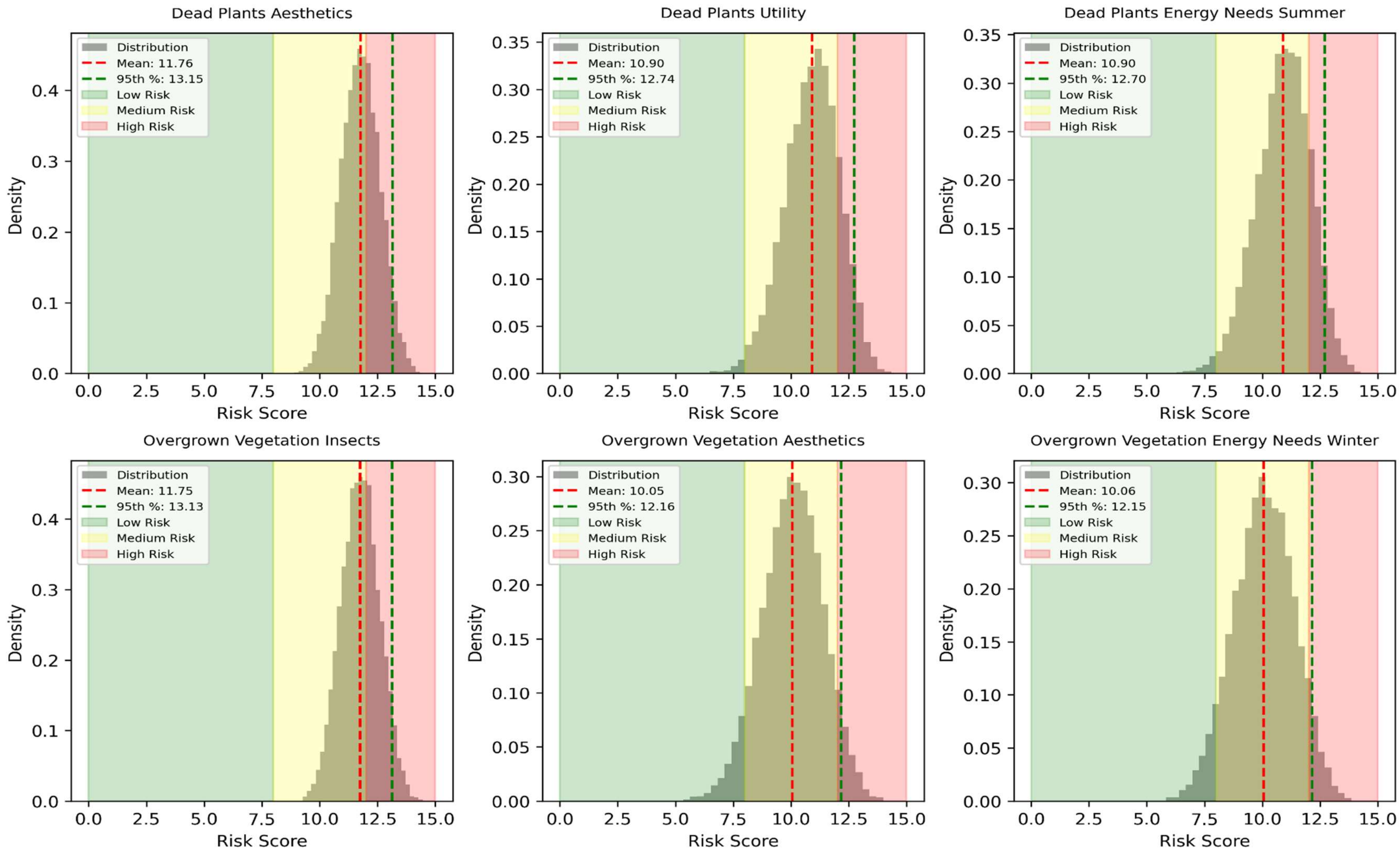
Figure 3 Monte Carlo Analysis Results for Green Buildings - Greenery Performance

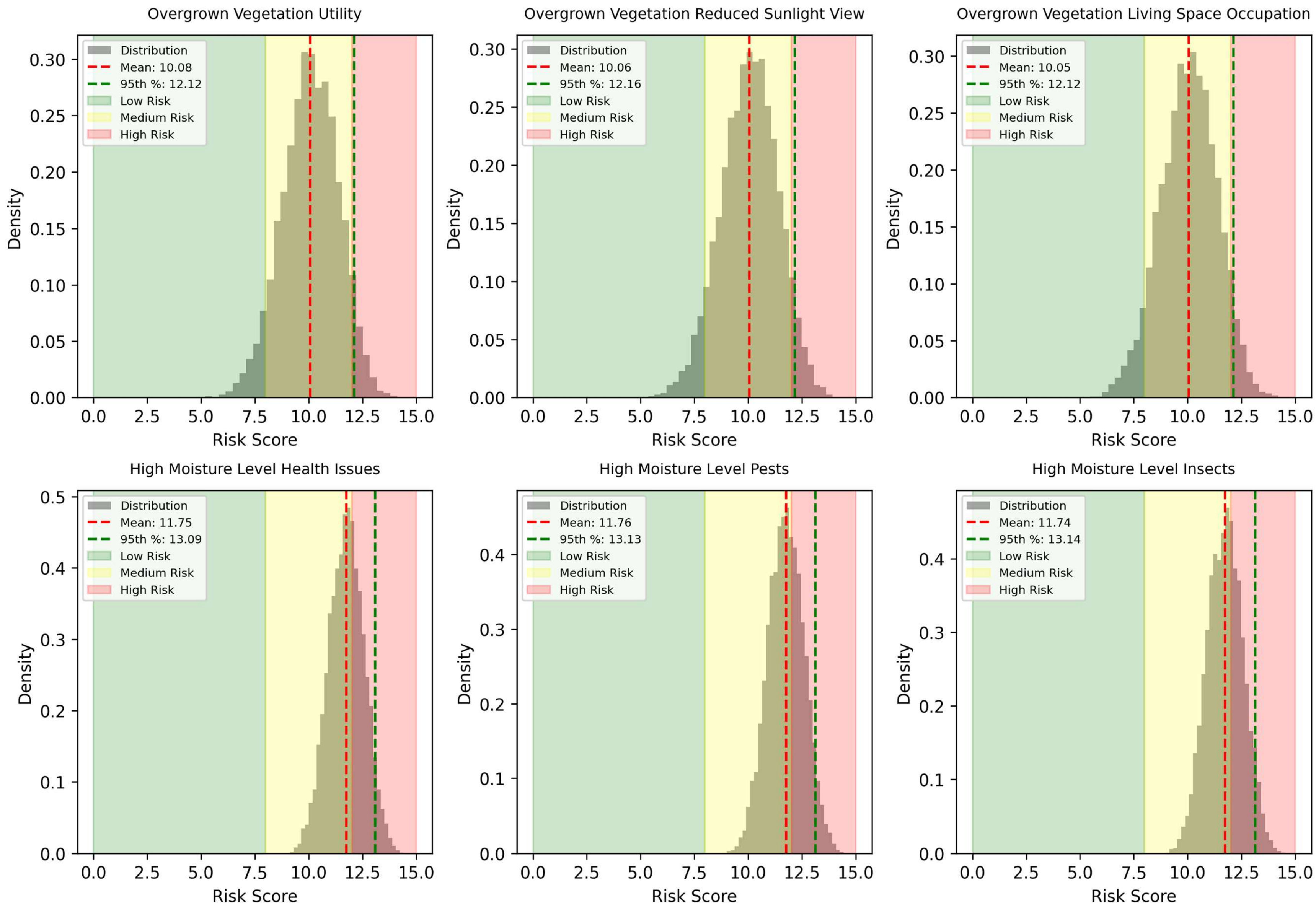
Table 5 Monte Carlo Analysis Results for Green Buildings - Greenery Performance

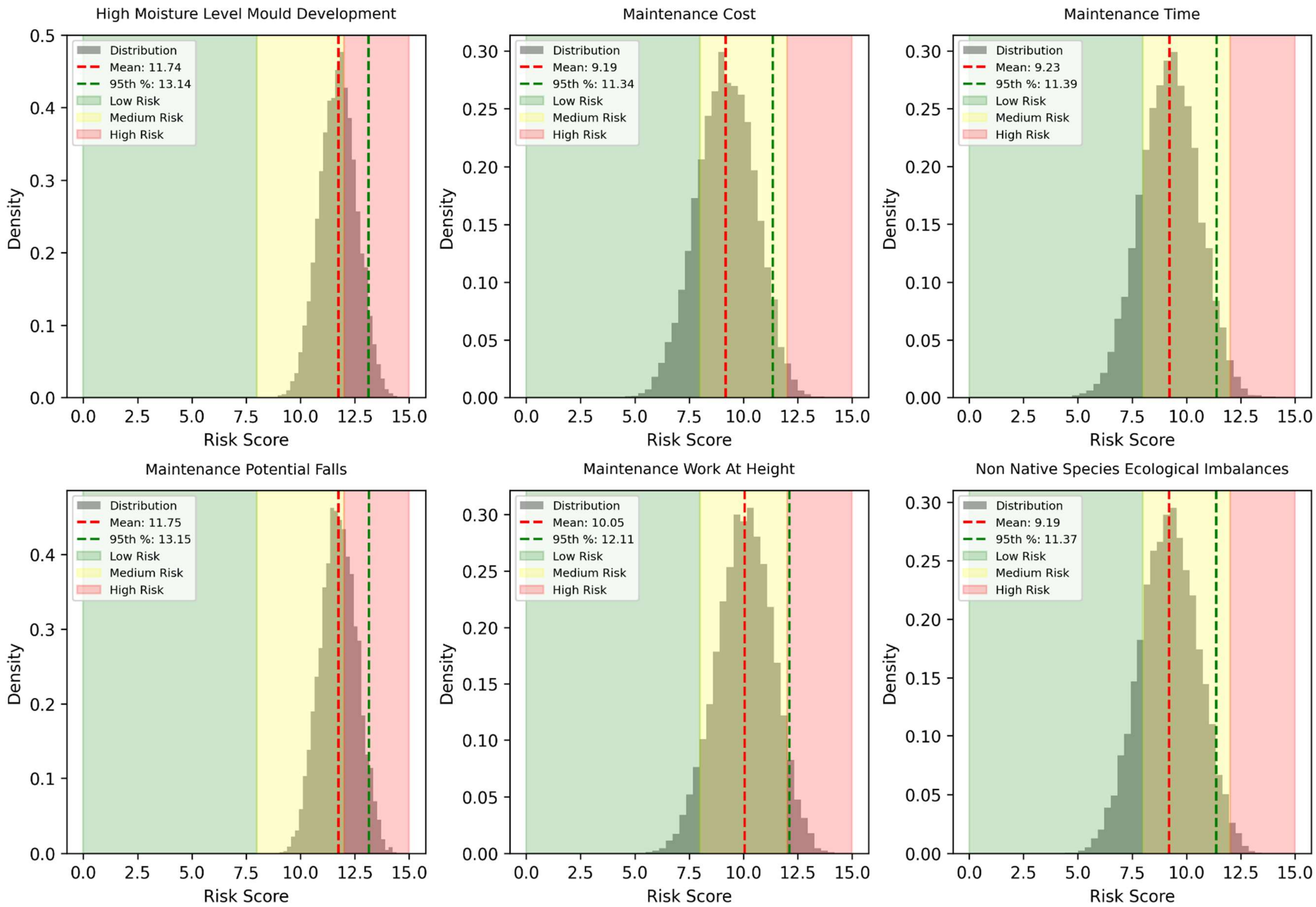
Group	Damage Type	Mean Score	Standard Deviation	95th Percentile	Low Risk (%)	Medium Risk (%)	High Risk (%)
High Moisture Evapotranspiration	pests	11.76	0.84	13.12	0.00	60.84	39.16
	planting_media_degradation	11.76	0.84	13.14	0.00	60.65	39.35
Low Moisture	Irrigation_plant_stress	11.74	0.83	13.12	0.00	61.94	38.06
	Irrigation_dry_vegetation	11.75	0.84	13.14	0.00	61.64	38.36
	Irrigation_dead_plants	11.76	0.84	13.16	0.00	61.30	38.70
	Irrigation_wilting	11.75	0.84	13.15	0.00	61.41	38.59
	Irrigation_gaps	11.74	0.84	13.14	0.00	61.49	38.51
	Irrigation_planting_media_degradation	11.75	0.83	13.11	0.00	61.55	38.45
Improper Maintenance	overgrown_vegetation	11.75	0.83	13.10	0.00	61.46	38.54
	dead_biomass	11.74	0.83	13.10	0.00	61.87	38.13
	bio_debris	10.90	1.16	12.73	1.08	81.23	17.69
	gaps	10.90	1.17	12.73	0.99	81.54	17.47
	planting_media_degradation	11.75	0.82	13.11	0.00	62.03	37.97
	loss	11.74	0.85	13.14	0.00	61.57	38.43
	compaction	11.76	0.84	13.15	0.00	60.90	39.10

Inadequate	Space_distorted_vegetation_growth	8.35	1.25	10.46	39.64	60.17	0.19
Environmental Stressors	plant_stress	11.75	0.83	13.14	0.00	61.29	38.71
	dehydration	10.90	1.16	12.71	1.16	81.23	17.61
Fire	burnt_vegetation	11.75	0.83	13.13	0.00	61.57	38.43
Wind	uprooting	11.75	0.84	13.11	0.00	61.25	38.75
	mechanical_stress	11.73	0.83	13.10	0.00	62.22	37.78
	dehydration	11.75	0.84	13.13	0.00	60.89	39.11
	reduced_plant_growth_rate	10.90	1.14	12.68	0.91	81.86	17.23
	wilting	11.76	0.84	13.14	0.00	60.93	39.07
	bended_trees	11.75	0.84	13.15	0.00	60.65	39.35
	falling_bio_debris	9.20	1.34	11.41	18.93	79.24	1.83
Earthquake	planter_anchorage_instability	11.76	0.84	13.13	0.00	60.90	39.10
	tree_pot_anchorage_instability	11.75	0.84	13.15	0.00	61.68	38.32
Overall Score		11.42	0.18	11.71	0.00	99.97	0.03

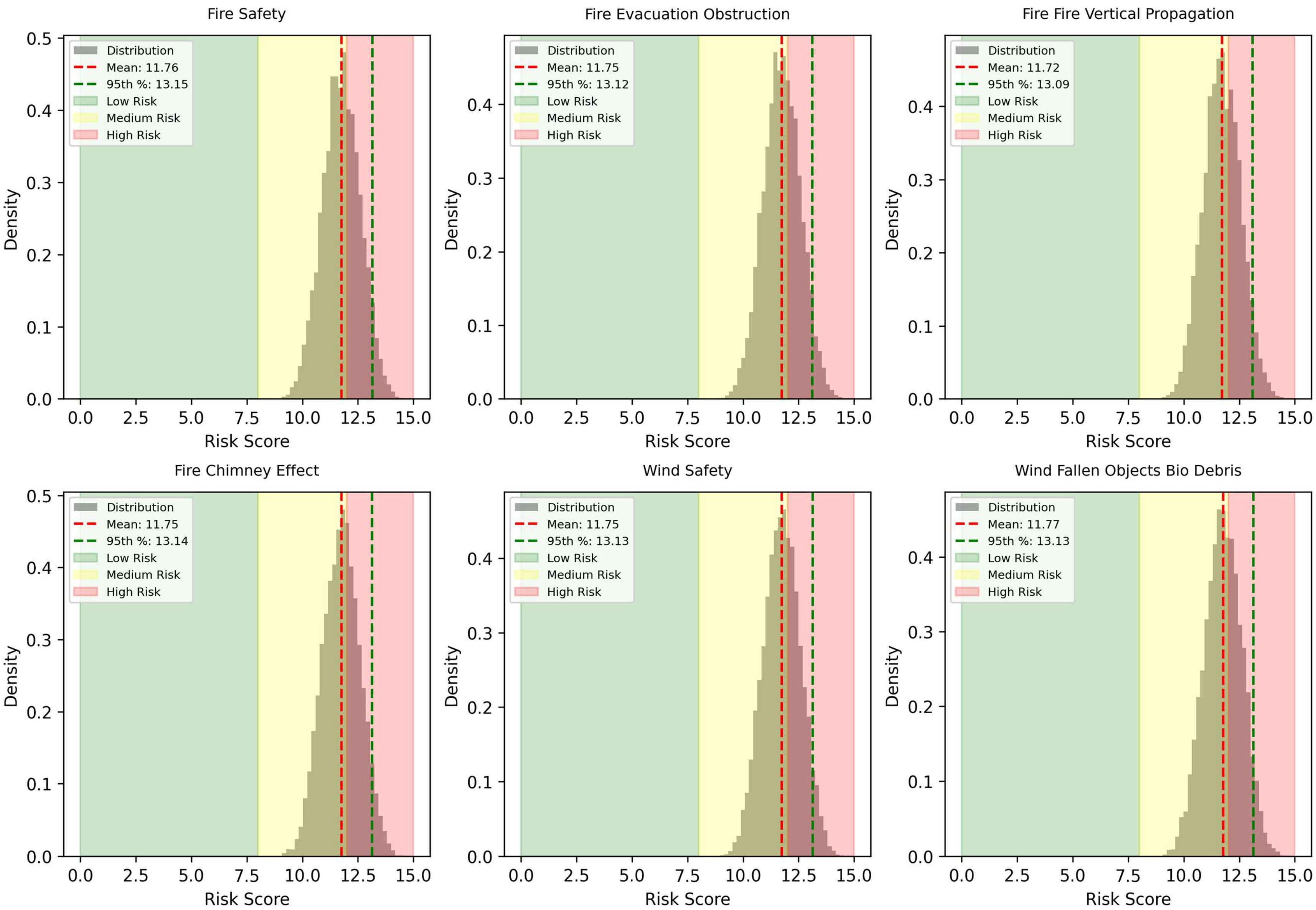
3.4.1.4 Green Buildings - Human welfare




Overgrown Vegetation Utility
Distribution
Mean: 10.08
95th %: 12.12
Low Risk
Medium Risk
High Risk
Density
Risk Score
Overgrown Vegetation Reduced Sunlight View
Distribution
Mean: 10.06
95th %: 12.16
Low Risk
Medium Risk
High Risk
Density
Risk Score
Overgrown Vegetation Living Space Occupation
Distribution
Mean: 10.05
95th %: 12.12
Low Risk
Medium Risk
High Risk
Density
Risk Score
High Moisture Level Health Issues
Distribution
Mean: 11.75
95th %: 13.09
Low Risk
Medium Risk
High Risk
Density
Risk Score
High Moisture Level Pests
Distribution
Mean: 11.76
95th %: 13.13
Low Risk
Medium Risk
High Risk
Density
Risk Score
High Moisture Level Insects
Distribution
Mean: 11.74
95th %: 13.14
Low Risk
Medium Risk
High Risk
Density
Risk Score


High Moisture Level Mould Development
Distribution
Mean: 11.74
95th %: 13.14
Low Risk
Medium Risk
High Risk
Maintenance Cost
Distribution
Mean: 9.19
95th %: 11.34
Low Risk
Medium Risk
High Risk
Maintenance Time
Distribution
Mean: 9.23
95th %: 11.39
Low Risk
Medium Risk
High Risk
Maintenance Potential Falls
Distribution
Mean: 11.75
95th %: 13.15
Low Risk
Medium Risk
High Risk
Maintenance Work At Height
Distribution
Mean: 10.05
95th %: 12.11
Low Risk
Medium Risk
High Risk
Non Native Species Ecological Imbalances
Distribution
Mean: 9.19
95th %: 11.37
Low Risk
Medium Risk
High Risk
Density
Risk Score
0.0
2.5
5.0
7.5
10.0
12.5
15.0

H.F.R.I. Hellenic Foundation for Research & Innovation
Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
Funded by the European Union NextGenerationEU
GREENERGY



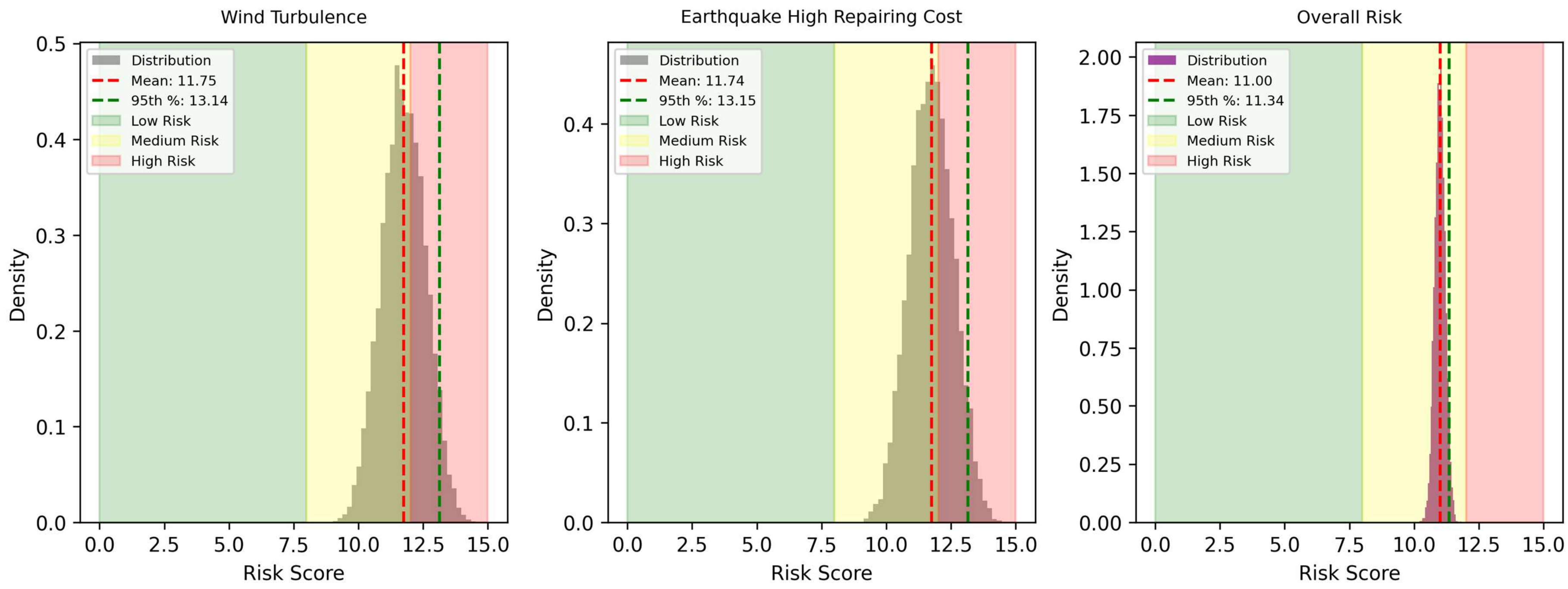


Figure 4 Monte Carlo Analysis Results for Green Buildings - Human welfare

Table 6 Monte Carlo Analysis Results for Green Buildings - Human welfare

Group	Damage Type	Mean Score	Standard Deviation	95th Percentile	Low Risk (%)	Medium Risk (%)	High Risk (%)
Dead Plants	aesthetics	11.76	0.84	13.15	0.00	60.55	39.45
	utility	10.90	1.16	12.74	0.90	81.66	17.44
	energy_needs_summer	10.90	1.17	12.70	1.16	80.90	17.94
Overgrown Vegetation	insects	11.75	0.83	13.13	0.00	61.16	38.84
	aesthetics	10.05	1.31	12.16	6.32	87.00	6.68
	energy_needs_winter	10.06	1.30	12.15	6.21	87.20	6.59
	utility	10.08	1.29	12.12	5.94	87.94	6.12
	reduced_sunlight_view	10.06	1.32	12.16	6.56	86.77	6.67
	living_space_occupation	10.05	1.30	12.12	6.25	87.43	6.32
High Moisture Level	health_issues	11.75	0.82	13.09	0.00	61.40	38.60
	pests	11.76	0.84	13.13	0.00	60.74	39.26
	insects	11.74	0.84	13.14	0.00	61.18	38.82
	mould_development	11.74	0.85	13.14	0.00	61.62	38.38
Maintenance	cost	9.19	1.33	11.34	19.03	79.65	1.32
	time	9.23	1.32	11.39	18.18	80.33	1.49
	potential_falls	11.75	0.84	13.15	0.00	61.09	38.91
	work_at_height	10.05	1.29	12.11	6.39	87.59	6.02

Non Native Species	ecological_imbalances	9.19	1.34	11.37	18.92	79.56	1.52
Fire	safety	11.76	0.85	13.15	0.00	61.14	38.86
	evacuation_obstruction	11.75	0.84	13.12	0.00	61.37	38.63
	vertical_propagation	11.72	0.84	13.09	0.00	62.61	37.39
	chimney_effect	11.75	0.84	13.14	0.00	61.27	38.73
Wind	safety	11.75	0.84	13.13	0.00	61.44	38.56
	fallen_objects_bio_debris	11.77	0.84	13.13	0.00	60.13	39.87
	turbulence	11.75	0.84	13.14	0.00	61.14	38.86
	Earthquake_high_repairing_cost	11.74	0.85	13.15	0.00	61.62	38.38
Overall Score		11.00	0.21	11.34	0.00	100	0.00

3.4.2 Additional hazard analyses

In the context of vertical forest applications to an existing reinforced concrete (RC) building, a domain-specific application of STPA (System-Theoretic Process Analysis) is conducted to identify specific and more detailed hazards. STPA represents a modern hazard analysis technique based on systems theory, not traditional reliability theory. Developed at MIT by Nancy Leveson (Leveson, 2012; Leveson & Thomas, 2018), this approach regards safety as a control problem rather than a component failure issue. STPA systematically identifies potential hazards and safety constraints in complex systems (Leveson, 2012; Charalampidou et al., 2024; Zeleskidis et al., 2023). Two main system components are analyzed: a balcony with vertical forest and a living wall system.

3.4.2.1.1 Vertical Forest (Vf) Balcony System

3.4.2.1.1.1 System Description

System Summary

The RC Balcony Vertical Forest Integration System represents a higher step in integrating structural engineering methods with horticultural technologies specifically developed to enable the growth of plants vertically on residential balconies. It makes sure that vegetation will be integrated into the built environment, ensures structural stability, and assures optimum plant health through automated maintenance systems.

Structural Elements

The system is based on a reinforced concrete balcony: a load-carrying concrete slab resting on structural beams. The balcony will carry superimposed loads such as dead loads, permanent weight of planters, soil, and mature plants, and the live loads related to the activities of maintenance, environmental forces. A parapet/railing system robust enough to provide safety for the residents and additional structural support to the plant integration system.

Supportive Plant Structure

Self-designed planter boxes line the balcony for containment of growth medium and fastening of plant systems. Careful design is involved in providing adequate soil volume for plant growth while minimizing the overall structural load that such a container could present. Anchoring systems make plants stable during bad weather conditions and at the same time allow natural growth and displacement.

Plant Care Systems Integration

At the heart of the Coherent Plant Care Network are, for all practical purposes, two major subsystems:

Irrigation Infrastructure

The proposed vertical garden is allowed to distribute water through a precision irrigation delivery system. Distribution pipes with pressure-regulated drippers and in-ground moisture sensors monitoring soil conditions can occur in real-time to ensure that optimal levels are met without allowing for overwatering, which would affect the structural loading.

Nutrient Management FrameworkA sophisticated fertigation system manages plant nutrition through:

- Centralized nutrient storage containers
- Precision dosing equipment to track and adjust nutrient concentration
- Inbuilt distribution network within the irrigation network
- Smart controls: Selectively regulating nutrient delivery in respect to plant needs and growth cycles.

Oversight and Regulatory Framework

The system leverages an enterprise-wide surveillance network with the following coverage:

- Load monitoring sensors that provide constant weight distribution tracking
- Structural Health Monitoring Systems that would identify any significant deflection or fissuring.
- Soil moisture, nutrient level, and growing condition-measuring environmental sensors
- Smart controllers with the integration of sensor information to manage irrigation and nutrient applications.

Human Interface and Management

This involves concurrent monitoring by different stakeholders:

- Residents participate in basic system monitoring and report any problems to the appropriate staff.
- Periodical testing and low-level maintenance by system maintenance personnel.
- Horticulturists manage plant health and adjust care parameters
- Structural engineers sometimes reassess the system integrity and loading conditions

Drainage and Resource Management

A well-engineered drainage system prevents any building-up of water that might be harmful to the structural integrity. The drainage system includes:

- Collection channels integrated into the planter designs Filtered drainage pathways to reduce soil erosion
- Potential recovery systems for reusing water
- Surveillance to avoid overFlow or blockage

Safety and Emergency Protocol

A comprehensive monitoring system is equipped with fail-safes and emergency protocols:

- Automatic shut-off of liquid distribution systems when a leak event occurs.
- Loading warning systems, indicating potential structural problems to the stakeholders.
- Emergency drainage capability after an extreme event
- Standby power supply for basic monitoring and control functions.

Combination on a larger scale of structural, horticultural, and control systems develops a sustainable and safe environment for the growth of vertical forests while protecting the basic structure of the building and its occupants.

3.4.2.1.1.2 Hazards and Accidents (Loses)

Table 7 Accidents for RC Balcony with VF

Accidents (Losses)	Description
A-1: Loss of human life or injury	People injured/killed by falling plants/containers
	People injured/killed by structural collapse
	People injured/killed by slipping on wet surfaces
A-2: Property damage	Damage to balcony structure
	Damage to apartment interior due to water/nutrient leakage
	Damage to lower floors/apartments

	Damage to personal property on balcony
A-3: Environmental damage	Plant death/ecosystem disruption
	Chemical/nutrient runoff affecting environment
	Excessive water waste
A-4: Mission losses	Failure to maintain healthy vertical forest
	System abandonment due to maintenance issues
	Loss of property value

Table 8 Hazards for RC Balcony with VF

Hazards	Description
H-1: Structural Integrity Hazards	H-1.1: Balcony load capacity exceeded
	H-1.2: Uneven load distribution creates structural stress
	H-1.3: Structural deterioration from water/chemical exposure
	H-1.4: Plant anchoring system failure
H-2: Plant System Hazards	H-2.1: Over-saturated growing medium
	H-2.2: Nutrient imbalance in delivery system
	H-2.3: Root system compromises structural elements
	H-2.4: Plants grow beyond designed size/weight limits
H-3: Control System Hazards	H-3.1: Incorrect sensor readings lead to system malfunction
	H-3.2: Failure of automated irrigation/nutrient delivery
	H-3.3: Monitoring system failure masks dangerous conditions
	H-3.4: Control system provides incorrect commands
H-4: Environmental Interaction Hazards	H-4.1: High wind conditions affect plant/container stability
	H-4.2: Extreme weather compromises system integrity
	H-4.3: Excessive heat/cold damages system components
	H-4.4: Water accumulation creates unsafe conditions

Table 9 Mapping between Hazards and Accidents for RC Balcony with VF

Hazard	Related Accidents
H-1.1 - H-1.4	A-1, A-2
H-2.1 - H-2.4	A-2, A-3, A-4
H-3.1 - H-3.4	A-1, A-2, A-3, A-4
H-4.1 - H-4.4	A-1, A-2, A-3

3.4.2.1.1.3 Control Structure

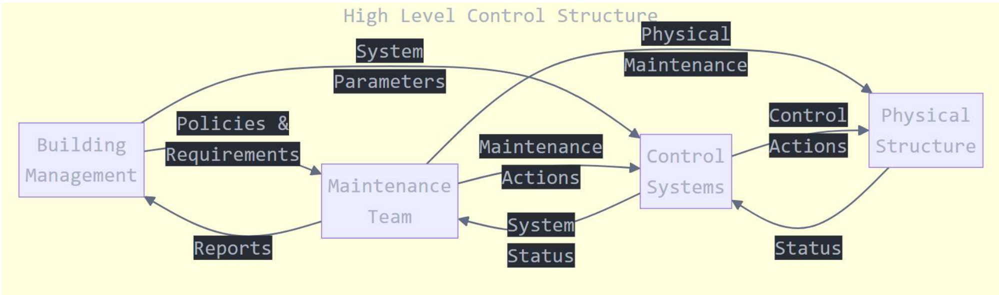


Figure 5 High level Control Structure of RC balcony with VF

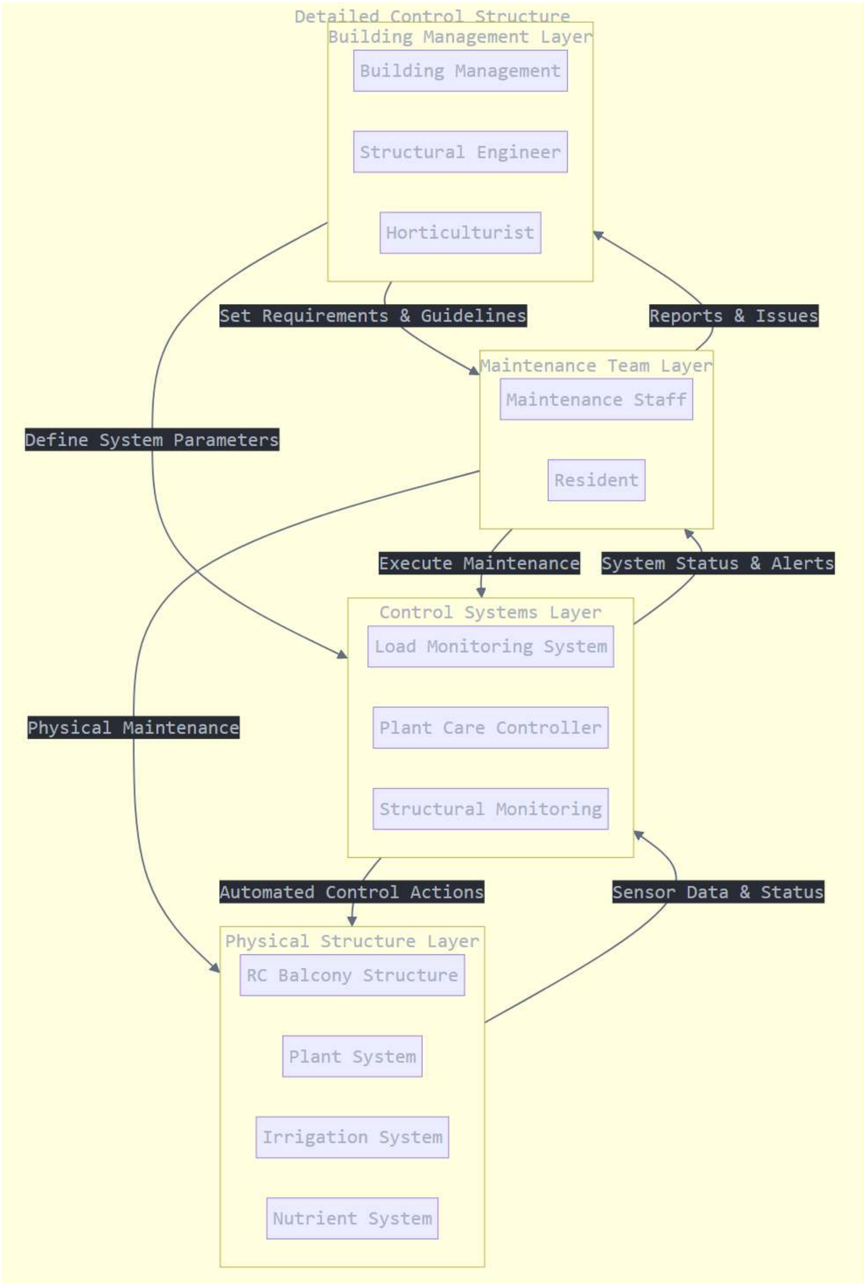


Figure 6 Expanded level Control Structure of RC balcony with VF

3.4.2.1.1.4 Unsafe Control Actions Analysis

1. Load Monitoring System UCAs

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon / Applied Too Long
Emergency System Shutdown	System continues operating under dangerous load conditions	Unnecessary shutdown when load is within safe limits	Delayed shutdown after critical load detected	Partial shutdown leaving some systems running
Load Warning Alerts	No warning of dangerous loading conditions	False alarms causing unnecessary evacuations	Delayed warnings after critical conditions	Warning stops before condition resolved
Weight Distribution Control	Uneven load distribution not corrected	Incorrect load redistribution causing stress	Adjustment during peak usage times	Redistribution process incomplete
Maximum Load Limit Enforceme nt	Overloading condition not prevented	System restricts necessary maintenance access	Limit enforcement during emergency operations	Temporary override remains active too long
Dynamic Load Response	Wind/weather load effects not managed	Excessive movement restrictions applied	Response during stabilization period	Dynamic response ends prematurely

2. Plant Care Controller UCAs

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon / Applied Too Long
Irrigation Control	Plants die from lack of water	Oversaturation causing excess weight	Watering during high wind conditions	Continuous watering leading to saturation

Nutrient Delivery	Plant health deterioration	Excess nutrients damaging structure	Delivery during rain events	Extended delivery causing accumulation
Growth Rate Monitoring	Excessive growth not detected	False growth alerts triggering pruning	Delayed growth assessment	Monitoring interruption during growth season
Root System Control	Root invasion not prevented	Excessive root restriction	Root check during critical growth	Partial root management
Environme ntal Adjustment	Climate stress not mitigated	Excessive environmental modification	Adjustment during plant dormancy	Incomplete climate adaptation

3. Maintenance Staff UCAs

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon / Applied Too Long
Plant Pruning	Excessive growth exceeding loads	Excessive pruning damaging plants	Pruning during flowering/growth	Incomplete pruning cycle
System Inspection	Component deterioration undetected	Invasive inspection damage	Inspection during peak loads	Partial system check
Equipment Maintenan ce	System failure from wear	Improper maintenance procedures	Maintenance during critical operations	Incomplete maintenance routine
Safety Check Protocol	Safety hazards unidentified	Disruptive safety procedures	Checks during emergency conditions	Abbreviated safety assessment
Drainage Cleaning	Blockage leading to water damage	Aggressive cleaning damaging pipes	Cleaning during heavy water use	Partial drainage clearance

4. Structural Monitoring UCAs

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon / Applied Too Long
Crack Monitoring	Structural damage undetected	False crack detection alerts	Delayed crack assessment	Monitoring gaps during stress
Deflection Assessment	Critical deformation missed	Incorrect deflection readings	Assessment during loading	Incomplete deflection analysis
Strain Measurement	Stress concentration undetected	False strain readings	Measurement during movement	Partial strain assessment
Vibration Monitoring	Dangerous resonance missed	False vibration alerts	Monitoring during stabilization	Interrupted vibration analysis
Material Degradation Check	Corrosion/damage undetected	Invasive material testing	Check during peak stress	Incomplete degradation assessment

5. Building Management UCAs

Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon / Applied Too Long
Maintenance Schedule	System deterioration unchecked	Excessive maintenance disruption	Schedule during peak usage	Incomplete maintenance cycle
Emergency Response	No response to critical conditions	Unnecessary system shutdown	Delayed emergency procedures	Premature procedure termination
Resource Allocation	Critical supplies not provided	Excess resource commitment	Resource delivery timing wrong	Partial resource provision

Inspection Protocol	System problems unidentified	Overly invasive inspections	Inspection during critical ops	Incomplete inspection coverage
Access Control	Unauthorized maintenance allowed	Excessive access restrictions	Access during critical operations	Temporary access left active

3.4.2.1.1.5 Safety Constraint Table

System Component	Potential Accidents	Hazards	Unsafe Control Actions	Causal Factors	Safety Requirements
Load Monitoring System	A1: Structural collapse	H1: Load capacity exceeded	UCA1: No emergency shutdown when overloaded	CF1: Sensor calibration drift	SR1: Maximum load must not exceed design capacity by implementing:
	A2: Component failure	H2: Uneven load distribution	UCA2: False load warnings	CF2: Algorithm errors	- Real-time monitoring
	A3: Property damage	H3: Dynamic load failure	UCA3: Delayed response	CF3: Communication delays	- Automatic shutdown at 85% capacity
	A4: Personal injury	H4: Sensor system failure	UCA4: Incomplete shutdown	CF4: Power failure	- Redundant sensor systems
	A5: System abandonment	H5: Control system error	UCA5: Wrong load calculation	CF5: Model inaccuracies	- Weekly calibration checks
Plant Care System	A1: Plant death	H1: Over-saturation	UCA1: No irrigation when needed	CF1: Pump failure	SR1: Plant health maintenance through:
	A2: Root damage	H2: Nutrient imbalance	UCA2: Excess water delivery	CF2: Valve malfunction	- Moisture content 40-70%
	A3: Container failure	H3: Growth limit exceeded	UCA3: Wrong nutrient mix	CF3: Sensor errors	- Daily monitoring

	A4: Water damage	H4: Root invasion	UCA4: Missed maintenance	CF4: Control logic errors	- Weekly inspections
	A5: Nutrient leakage	H5: System blockage	UCA5: Improper pruning	CF5: Maintenance gaps	- Size control protocols
Structural Monitoring	A1: Undetected damage	H1: Crack propagation	UCA1: Missed crack detection	CF1: Sensor detachment	SR1: Structural integrity via:
	A2: False alarms	H2: Excessive deflection	UCA2: False structural alerts	CF2: Data errors	- Crack monitoring ≥0.3mm
	A3: Delayed detection	H3: Material degradation	UCA3: Late warning	CF3: Power issues	- Monthly inspections
	A4: Missed threats	H4: Support failure	UCA4: Wrong assessment	CF4: Algorithm flaws	- Deflection limits L/360
	A5: System failure	H5: Connection failure	UCA5: Incomplete inspection	CF5: Model errors	- Quarterly audits
Maintenance Operations	A1: System deterioration	H1: Missed maintenance	UCA1: Skipped inspections	CF1: Staff availability	SR1: Maintenance compliance through:
	A2: Safety violations	H2: Wrong procedures	UCA2: Improper repairs	CF2: Training gaps	- Weekly checkups
	A3: Access issues	H3: Documentation gaps	UCA3: No documentation	CF3: Access limitations	- Monthly detailed inspection
	A4: Training failures	H4: Training inadequacy	UCA4: Wrong timing	CF4: Resource constraints	- Quarterly comprehensive review
	A5: Resource depletion	H5: Resource shortage	UCA5: Incomplete work	CF5: Weather constraints	- Annual system audit
	A1: Delayed response	H1: Detection failure	UCA1: No emergency action	CF1: Alert system failure	SR1: Emergency preparedness via:

Emergency Response	A2: Wrong response	H2: Wrong procedure	UCA2: Wrong procedure	CF2: Communication breakdown	- 30-second response time
	A3: System damage	H3: Communication failure	UCA3: Late response	CF3: Power loss	- Automatic shutdowns
	A4: Incomplete action	H4: Power loss	UCA4: Partial response	CF4: Training inadequacy	- Backup power systems
	A5: Recovery failure	H5: Recovery failure	UCA5: No documentation	CF5: Resource limits	- Response team training
System Component	**Potential Accidents**	**Hazards**	**Unsafe Control Actions**	**Causal Factors**	**Safety Requirements**
Load Monitoring System	A1: Structural collapse	H1: Load capacity exceeded	UCA1: No emergency shutdown when overloaded	CF1: Sensor calibration drift	SR1: Maximum load must not exceed design capacity by implementing:
	A2: Component failure	H2: Uneven load distribution	UCA2: False load warnings	CF2: Algorithm errors	- Real-time monitoring
	A3: Property damage	H3: Dynamic load failure	UCA3: Delayed response	CF3: Communication delays	- Automatic shutdown at 85% capacity
	A4: Personal injury	H4: Sensor system failure	UCA4: Incomplete shutdown	CF4: Power failure	- Redundant sensor systems
	A5: Recovery failure	H5: Recovery failure	UCA5: No documentation	CF5: Resource limits	- Response team training

Now the results from STPA analysis are linked in order form a fixed 5x5 risk matrix.

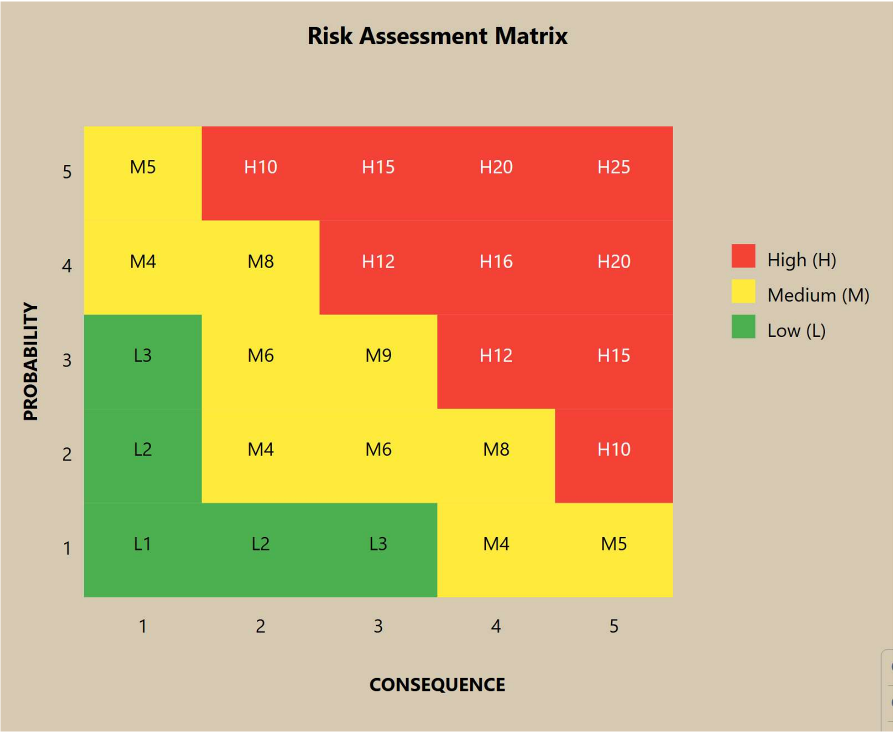


Figure 7 Risk Matrix vertical forest (VF) balcony system

RISK MATRIX NUMBERING EXPLANATION

Level	(Consequences) - Scale 1-5		(Probability) - Scale 1-5	
1	Minor	- Sensor calibration drift within acceptable range - Minor plant growth issues - Temporary irrigation interruption - Small moisture sensor misreading - Documentation delays	Very Low	- Rare maintenance oversight - Highly unlikely system failure - Almost no environmental stress - Exceptional preventive measures in place - No historical precedent
2	Moderate	- Partial nutrient system malfunction - Minor load distribution variance - Temporary monitoring system interruption - Plant pruning delays - Non-critical sensor failure	Low	- Annual maintenance issues - Uncommon sensor drift - Limited environmental exposure - Strong preventive measures - Rare occurrence in similar systems
3	Significant	- Complete irrigation system failure - Multiple sensor system failures - Significant plant die-off	Medium	- Monthly calibration needs - Occasional sensor issues - Moderate environmental exposure

		- Moderate structural stress detected - Control system malfunction		- Standard preventive measures - Known to occur in similar systems
4	Severe	- Major structural deflection - Critical monitoring system failure - Complete plant system failure - Severe water/nutrient leakage - Multiple control system failures	High	- Weekly maintenance required - Regular sensor adjustments - Frequent environmental stress - Basic preventive measures - Common in similar systems
5	Catastrophic	- Complete structural failure - Total system collapse - Life-threatening structural damage - Complete control system breakdown - Catastrophic water damage to building	Very High	- Daily system stress - Constant environmental exposure - Multiple risk factors present - Minimal preventive measures - Frequently observed issuesmeasures

Risk Level Calculations (Examples)		
Low Risk (L) Scenarios	**Medium Risk (M) Scenarios**	**High Risk (H) Scenarios**
L1 (1,1): Minor sensor calibration drift with rare occurrence	M4 (2,2): Plant care system requiring recalibration	H10 (5,2): Critical structural monitoring system failure
L2 (1,2): Temporary irrigation interruption during routine maintenance	M5 (3,1): Single control loop failure with backup systems active	H12 (4,3): Major load distribution anomaly
L2 (1,2): Temporary irrigation interruption during routine maintenance	M6 (2,3): Nutrient delivery system temporary malfunction	H15 (5,3): Complete plant support system failure
	M8 (4,1): Non-critical monitoring system interruption	H16 (4,4): Severe structural stress detection
	M9 (3,3): Multiple non-critical sensor failures	H20 (4,4): Multiple critical control system failures
	M4 (2,2): Plant care system requiring recalibration	H25 (5,5): Catastrophic structural failure with multiple contributing factors

3.4.2.1.2 Living Wall System

3.4.2.1.2.1 System Description

The examined external living wall system will be a completely integrated biological and mechanical system that will be directly attached to the reinforced concrete building façades. It will support self-climbing vegetation, ivy, or creepers able to attach directly onto concrete substrates by means of natural adhesive roots, assisted by the use of a stainless steel supporting cable mesh configuration, while being directed to tautening growth and structural stability. The well-positioned drip lines avail the automatic irrigation mechanism made available by controls from the central management system. With input derived from sensors of environmental conditions of soil moisture and temperature, along with the plants' health indicators, a central control system regulates the delivery of water.

Mechanical attachment points for cables and meshes support the direct planting into the substrate. In addition, there is a network of attachments concerning irrigation. In general, a watertight membrane is placed for protection of the building envelope between the concrete surface and the elements composing the living wall. In this regard, the irrigations system involves an eminently supply side and also, when possible, an element of recovery with recycling.

It does this with a combination of automation and human input. The automated control system operates on basic tasks like irrigation scheduling, nutrient application, and elementary environmental monitoring. This is occasionally checked physically by specialized technicians who assess plant health, structural integrity, and system performance. It needs to operate throughout the year-seasonal changes together with meteo conditions-but with maintained building envelope integrity and plant vitality.

3.4.2.1.2.2 Hazards and Accidents (Loses)

Table 10 Accidents and Hazards for Living Wall System

Accident Category & ID	Accident (Loss) Description	Hazard ID	Associated Hazards
A.1 Structural Integrity			
A.1-1	Building structural damage due to excessive load	H.1.1	Plant mass exceeds structural design limits
A.1-2	Facade material deterioration	H.1.2	Root system penetrates waterproofing membrane
A.1-3	Support system failure	H.1.3	Cable/mesh attachment points fail or deteriorate
A.2 Water-Related			
A.2-1	Internal water damage to building	H.2.1	Irrigation system leakage into building envelope
A.2-2	Foundation damage from water accumulation	H.2.2	Drainage system blockage or failure
A.2-3	Mold/moisture damage to building materials	H.2.3	Inadequate ventilation between plants and wall
A.3 Plant System			
A.3-1	Complete plant die-off requiring system replacement	H.3.1	Critical irrigation system failure
A.3-2	Uncontrolled plant growth damaging building systems	H.3.2	Plant growth monitoring system failure
A.3-3	Invasive plant spread to unintended areas	H.3.3	Containment system breach
A.4 Human Safety			
A.4-1	Injury from falling plant material or debris	H.4.1	Dead plant material accumulation
A.4-2	Injury during maintenance operations	H.4.2	Unsafe access for maintenance

A.4-3	Health issues from mold/biological agents	H.4.3	Harmful biological growth in plant system
A.5 Environmental Control			
A.5-1	Building energy efficiency loss	H.5.1	Gap formation between wall and plant coverage
A.5-2	Building envelope thermal damage	H.5.2	Excessive heat buildup between plants and wall
A.5-3	Local ecosystem disruption	H.5.3	Introduction of invasive species or pests
A.6 Operational			
A.6-1	System maintenance cost overrun	H.6.1	Control system malfunction
A.6-2	Building operation disruption	H.6.2	Integration failure with building systems
A.6-3	Aesthetic value loss	H.6.3	Uneven or patchy plant growth

3.4.2.1.2.3 Control Structure

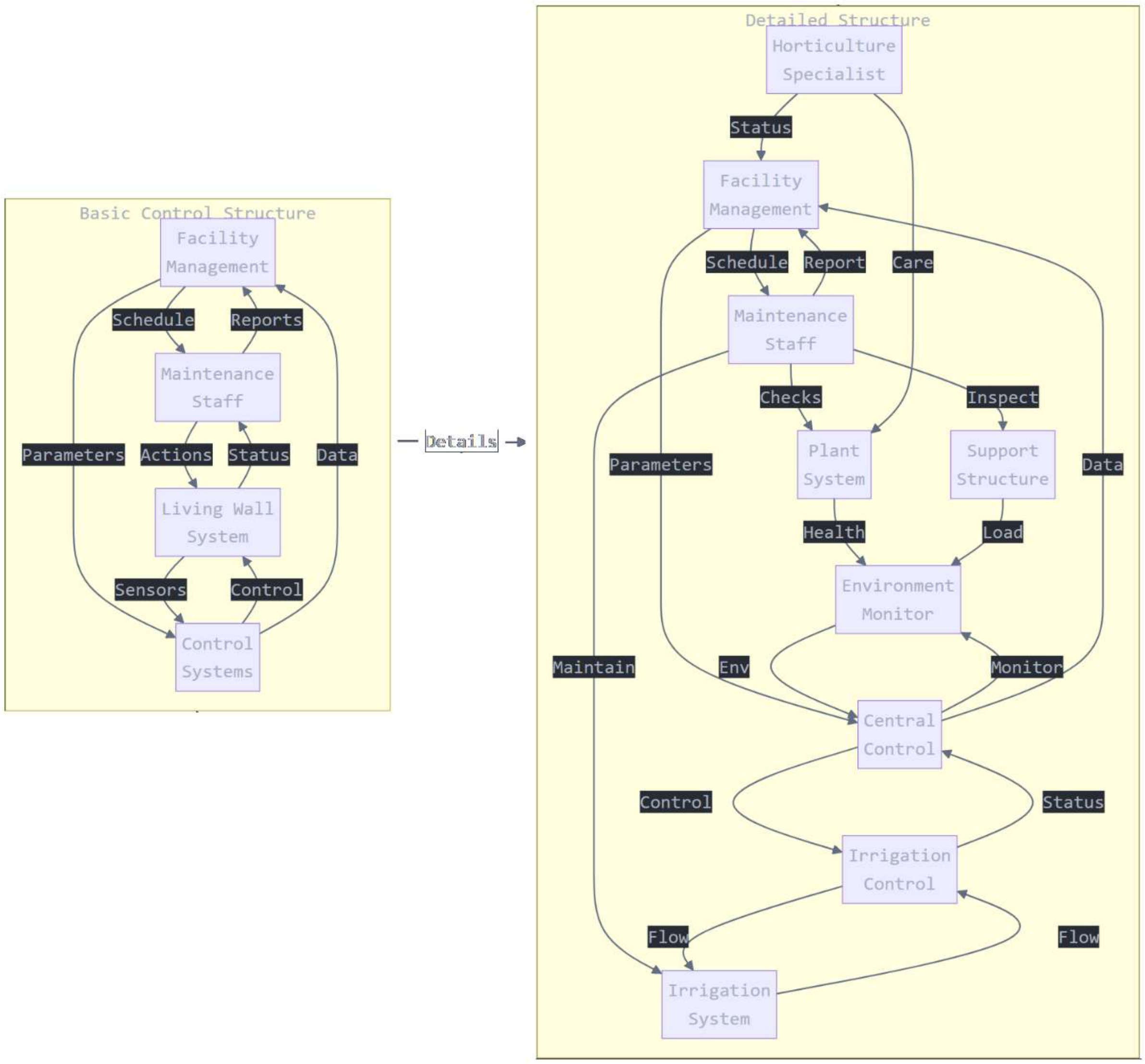


Figure 8 High level and expanded Control Structure of Living Wall System

3.4.2.1.2.4 Unsafe Control Actions Analysis

Controller	Control Action	Not Providing Causes Hazard	Providing Causes Hazard	Wrong Timing/Order	Stopped Too Soon/Applied Too Long	Related Hazards
Facility Management						
	Set Mainten ance Schedul e	No maintenance schedule established	Schedule too infrequent or intensive	Maintenance scheduled during inappropriate weather conditions	Schedule terminated before critical checks completed	H.1.2, H.2.2, H.3.1, H.4.2
	Define Operatin g Paramet ers	No system parameters defined	Parameters set outside safe limits	Parameters changed during critical operations	Parameters modified before verification complete	H.2.1, H.3.1, H.5.1, H.6.1
Maintenance Staff						
	Perform Plant Mainten ance	Required pruning not performed	Excessive/improp er pruning performed	Maintenance during extreme weather	Incomplete maintenance operation	H.3.2, H.3.3, H.4.1, H.6.3
	Check Support Structur e	Structure inspection skipped	Incorrect load assessment	Delayed inspection after storm events	Inspection stopped before completion	H.1.1, H.1.3, H.4.1
	Maintai n Irrigatio	Required cleaning skipped	Improper system modification	Maintenance during peak usage	Partial system maintenance	H.2.1, H.2.2, H.3.1

	n System					
Horticultural Specialist						
	Plant Care Actions	Required treatment not provided	Wrong treatment applied	Treatment during stress conditions	Treatment stopped mid-process	H.3.1, H.3.2, H.3.3
	Growth Management	Growth limits not enforced	Incorrect growth training	Late intervention in growth pattern	Incomplete growth management	H.1.1, H.3.2, H.6.3
Central Controller						
	Irrigation Control	No water provided	Excessive water provided	Watering at wrong time	Watering duration incorrect	H.2.1, H.2.2, H.3.1
	Environmental Monitoring	No monitoring active	Wrong parameters monitored	Delayed response to conditions	Monitoring interrupted	H.3.1, H.5.1, H.5.2
Irrigation Controller						
	Water Flow Control	No water flow when needed	Excessive water flow	Wrong timing of water delivery	Water flow duration incorrect	H.2.1, H.2.2, H.3.1
	Nutrient Dosing	No nutrients provided	Excessive nutrients provided	Wrong timing of nutrient delivery	Nutrient cycle incomplete	H.3.1, H.3.2, H.6.3
Controller	**Control Action**	**Not Providing Causes Hazard**	**Providing Causes Hazard**	**Wrong Timing/Order**	**Stopped Too Soon/Applied Too Long**	**Related Hazards**

Facility Management	Set Maintenance Schedule	No maintenance schedule established	Schedule too infrequent or intensive	Maintenance scheduled during inappropriate weather conditions	Schedule terminated before critical checks completed	H.1.2, H.2.2, H.3.1, H.4.2
	Define Operating Parameters	No system parameters defined	Parameters set outside safe limits	Parameters changed during critical operations	Parameters modified before verification complete	H.2.1, H.3.1, H.5.1, H.6.1
Maintenance Staff						
	Perform Plant Maintenance	Required pruning not performed	Excessive/improper pruning performed	Maintenance during extreme weather	Incomplete maintenance operation	H.3.2, H.3.3, H.4.1, H.6.3
	Check Support Structure	Structure inspection skipped	Incorrect load assessment	Delayed inspection after storm events	Inspection stopped before completion	H.1.1, H.1.3, H.4.1
	Maintain Irrigation System	Required cleaning skipped	Improper system modification	Maintenance during peak usage	Partial system maintenance	H.2.1, H.2.2, H.3.1
Horticultural Specialist						
	Plant Care Actions	Required treatment not provided	Wrong treatment applied	Treatment during stress conditions	Treatment stopped mid-process	H.3.1, H.3.2, H.3.3

	Growth Manage ment	Growth limits not enforced	Incorrect growth training	Late intervention in growth pattern	Incomplete growth management	H.1.1, H.3.2, H.6.3

3.4.2.1.2.5 Consolidated Analysis Table

Hazard	Control Action	Unsafe Control Action	Safety Constraint	Safety Requirements	Verification Method	Hazard
H.1.1: Plant mass exceeds structura l limits	Growth Managemen t	UCA-1: No load monitoring UCA-2: Wrong growth control UCA-3: Missed inspections	SC-1: Must prevent excessive loading	SR-1.1: Load monitoring system SR-1.2: Growth limits protocol SR-1.3: Regular inspections	'- Load cell data - Growth measurements - Inspection logs	H.1.1: Plant mass exceeds structural limits
H.1.2: Root penetrati on	Root Managemen t	UCA-4: No root barriers UCA-5: Wrong root pruning UCA-6: Missed checks	SC-2: Must contain root system	SR-2.1: Root barrier system SR-2.2: Root monitoring SR-2.3: Inspection schedule	'- Barrier integrity tests - Root imaging - Check records	H.1.2: Root penetration
H.2.1: Water leakage	Irrigation Control	UCA-7: Excess water flow UCA-8: Wrong timing UCA-9: No monitoring	SC-3: Must prevent water infiltration	SR-3.1: Leak detection SR-3.2: Flow control SR-3.3: Moisture monitoring	'- Leak sensors - Flow meters - Moisture data	H.2.1: Water leakage
H.2.2: Drainage failure	Drainage Managemen t	UCA-10: No cleaning UCA-11: Wrong maintenance UCA-12: Blocked flow	SC-4: Must maintain drainage	SR-4.1: Flow monitoring SR-4.2: Cleaning protocol SR-4.3: Blockage detection	- Flow rates - Maintenance logs - Sensor data	H.2.2: Drainage failure
H.3.1: Irrigation	System Control	UCA-13: No water supply UCA-14: Wrong	SC-5: Must maintain irrigation	SR-5.1: Backup systems SR-5.2: Alert protocols	- System status - Alert logs	H.3.1: Irrigation

system failure		settings UCA-15: System shutdown		SR-5.3: Emergency response	- Response times	system failure
H.3.2: Uncontrolled growth	Growth Control	UCA-16: No pruning UCA-17: Wrong technique UCA-18: Missed areas	SC-6: Must control growth	SR-6.1: Growth monitoring SR-6.2: Pruning schedule SR-6.3: Coverage checks	- Growth data - Maintenance records - Coverage maps	H.3.2: Uncontrolled growth
H.4.1: Falling debris	Maintenance	UCA-19: No removal UCA-20: Wrong timing UCA-21: Incomplete check	SC-7: Must prevent debris fall	SR-7.1: Debris monitoring SR-7.2: Removal protocol SR-7.3: Safety checks	- Inspection reports - Removal logs - Safety audits	H.4.1: Falling debris
H.4.2: Unsafe access	Access Control	UCA-22: No safety gear UCA-23: Wrong procedure UCA-24: Missed checks	SC-8: Must ensure safe access	SR-8.1: Safety protocols SR-8.2: Access systems SR-8.3: Safety training	- Safety records - Training logs - Audit reports	H.4.2: Unsafe access
H.5.1: Energy efficiency loss	Coverage Control	UCA-25: Coverage gaps UCA-26: Wrong density UCA-27: No monitoring	SC-9: Must maintain coverage	SR-9.1: Coverage monitoring SR-9.2: Density control SR-9.3: Gap prevention	- Coverage data - Thermal imaging - Efficiency tests	H.5.1: Energy efficiency loss
H.6.1: Control system failure	System Management	UCA-28: No monitoring UCA-29: Wrong settings UCA-30: System conflicts	SC-10: Must maintain control	SR-10.1: System redundancy SR-10.2: Fault detection SR-10.3: Backup protocols	- System logs - Error reports - Backup tests	H.6.1: Control system failure

Hazard	Control Action	Unsafe Control Action	Safety Constraint	Safety Requirements	Verification Method	Hazard
H.1.1: Plant mass exceeds structural limits	Growth Management	UCA-1: No load monitoring UCA-2: Wrong growth control UCA-3: Missed inspections	SC-1: Must prevent excessive loading	SR-1.1: Load monitoring system SR-1.2: Growth limits protocol SR-1.3: Regular inspections	'- Load cell data - Growth measurements - Inspection logs	H.1.1: Plant mass exceeds structural limits
H.1.2: Root penetration	Root Management	UCA-4: No root barriers UCA-5: Wrong root pruning UCA-6: Missed checks	SC-2: Must contain root system	SR-2.1: Root barrier system SR-2.2: Root monitoring SR-2.3: Inspection schedule	'- Barrier integrity tests - Root imaging - Check records	H.1.2: Root penetration
H.2.1: Water leakage	Irrigation Control	UCA-7: Excess water flow UCA-8: Wrong timing UCA-9: No monitoring	SC-3: Must prevent water infiltration	SR-3.1: Leak detection SR-3.2: Flow control SR-3.3: Moisture monitoring	'- Leak sensors - Flow meters - Moisture data	H.2.1: Water leakage
H.2.2: Drainage failure	Drainage Management	UCA-10: No cleaning UCA-11: Wrong maintenance UCA-12: Blocked flow	SC-4: Must maintain drainage	SR-4.1: Flow monitoring SR-4.2: Cleaning protocol SR-4.3: Blockage detection	'- Flow rates - Maintenance logs - Sensor data	H.2.2: Drainage failure
H.3.1: Irrigation system failure	System Control	UCA-13: No water supply UCA-14: Wrong settings UCA-15: System shutdown	SC-5: Must maintain irrigation	SR-5.1: Backup systems SR-5.2: Alert protocols SR-5.3: Emergency response	'- System status - Alert logs - Response times	H.3.1: Irrigation system failure
H.3.2: Uncontrolled growth	Growth Control	UCA-16: No pruning UCA-17: Wrong technique UCA-18: Missed areas	SC-6: Must control growth	SR-6.1: Growth monitoring SR-6.2: Pruning schedule SR-6.3: Coverage checks	'- Growth data - Maintenance records	H.3.2: Uncontrolled growth

					- Coverage maps	
H.4.1: Falling debris	Maintenance	UCA-19: No removal UCA-20: Wrong timing UCA-21: Incomplete check	SC-7: Must prevent debris fall	SR-7.1: Debris monitoring SR-7.2: Removal protocol SR-7.3: Safety checks	- Inspection reports- Removal logs- Safety audits	H.4.1: Falling debris
H.4.2: Unsafe access	Access Control	UCA-22: No safety gear UCA-23: Wrong procedure UCA-24: Missed checks	SC-8: Must ensure safe access	SR-8.1: Safety protocols SR-8.2: Access systems SR-8.3: Safety training	- Safety records- Training logs- Audit reports	H.4.2: Unsafe access
H.5.1: Energy efficiency loss	Coverage Control	UCA-25: Coverage gaps UCA-26: Wrong density UCA-27: No monitoring	SC-9: Must maintain coverage	SR-9.1: Coverage monitoring SR-9.2: Density control SR-9.3: Gap prevention	- Coverage data- Thermal imaging- Efficiency tests	H.5.1: Energy efficiency loss
H.6.1: Control system failure	System Management	UCA-28: No monitoring UCA-29: Wrong settings UCA-30: System conflicts	SC-10: Must maintain control	SR-10.1: System redundancy SR-10.2: Fault detection SR-10.3: Backup protocols	'- System logs - Error reports - Backup tests	H.6.1: Control system failure
Hazard	**Control Action**	**Unsafe Control Action**	**Safety Constraint**	**Safety Requirements**	**Verification Method**	**Hazard**

Now we link the results from STPA analysis to a fixed 5x5 risk matrix.

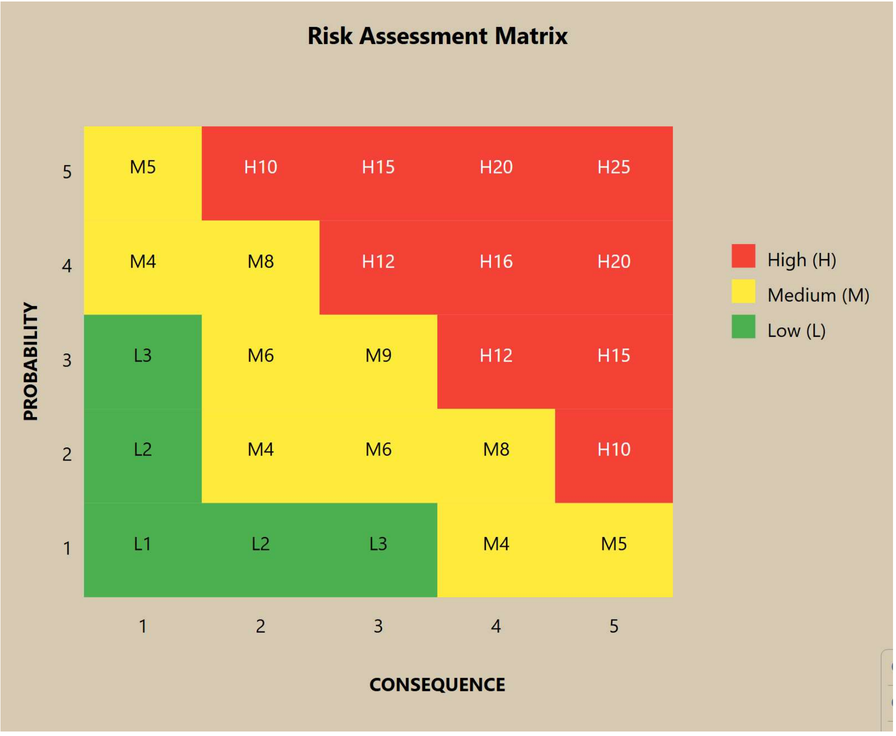


Figure 9 Risk Matrix for Living Wall System

RISK MATRIX NUMBERING EXPLANATION

Level	**(Consequences) - Scale 1-5**		**(Probability) - Scale 1-5**	
1	Minor	- Temporary sensor drift within range - Minor plant health issues - Short irrigation interruptions - Small drainage blockages - Documentation delays	Very Low	- Rare maintenance issues - Highly unlikely failures - Minimal environmental stress - Strong preventive measures - No historical precedent
2	Moderate	- Localized root barrier stress - Partial drainage system blockage - Minor load distribution issues - Limited plant growth problems - Non-critical control issues	Low	- Annual maintenance needs - Uncommon sensor issues - Limited environmental exposure - Regular inspections - Rare in similar systems
3	Significant	- Complete irrigation failure - Multiple sensor failures - Significant plant die-off - Moderate structural stress - Water management issues	Medium	- Monthly maintenance needs - Regular sensor calibration - Moderate environmental exposure - Standard maintenance - Known in similar systems

4	Severe	- Major structural loading issues - Critical monitoring failure - Extensive water damage - Severe root penetration - Multiple system failures	High	- Weekly maintenance needs - Frequent adjustments - High environmental stress - Basic preventive measures - Common in similar systems
5	Catastrophic	- Complete structural failure - Total system collapse - Severe building damage - Complete control failure - Critical water infiltration	Very High	- Daily system stress - Constant exposure - Multiple risk factors - Minimal prevention - Frequently observed

Risk Level Calculations (Examples)		
Low Risk (L) Scenarios	**Medium Risk (M) Scenarios**	**High Risk (H) Scenarios**
L1 (1,1): Minor sensor calibration with rare occurrence	M4 (2,2): Plant care system requiring recalibration	H10 (5,2): Critical structural monitoring system failure
L2 (2,1): Temporary irrigation interruption during maintenance	M5 (3,1): Single control loop failure with backup systems active	H12 (4,3): Major load distribution anomaly
L3 (3,1): Single non-critical sensor failure with backup	M6 (2,3): Nutrient delivery system temporary malfunction	H15 (5,3): Complete plant support system failure
	M8 (4,1): Non-critical monitoring system interruption	H16 (4,4): Severe structural stress detection
	M9 (3,3): Multiple non-critical sensor failures	H20 (4,4): Multiple critical control system failures
	M4 (2,2): Plant care system requiring recalibration	H25 (5,5): Catastrophic structural failure with multiple contributing factors

Risk Matrix Mapping to Consolidated Analysis Table			
Structural Integrity (S.1)	Water Management (S.3, S.4)	Plant System (S.5, S.6)	Control Systems (S.10)
H20: Severe structural loading (4,4)	H12: Major water infiltration (4,3)	M6: Growth control issues (2,3)	M4: Minor control issues (2,2)
H25: Complete structural failure (5,5)	M8: Drainage system issues (4,2)	H15: Complete system failure (5,3)	H16: Critical system failure (4,4)

4 DISCUSSION

4.1 MONTE CARLO ANALYSIS

The Monte Carlo analysis results of the four main categories have shown complex patterns in risk distribution and interdependencies in the reinforced concrete buildings (Spyridis & Strauss, 2020; Kudszus et al., 2020), especially when transformed into green structures. Looking through the results of common RC buildings, one would come across a dominant clustering in the medium risk category with 100% of cases falling within this range, while the mean score overall stood at 9.47. This distribution would suggest that whilst there are major issues in traditional RC buildings, these are typically within manageable limits using established engineering frameworks. However, analysis has highlighted particular concern about the reinforcement-related issues where the mean scores consistently scored about 11.15 and with majority of cases classified as high-risk with percentage around 35.3%. This skewing toward high risk in reinforcement matters, more so in areas such as slippage, shear cracking, and connection failures, points to an area of critical concern that requires focused attention in structural maintenance and renovation planning.

While structural performance of green buildings is considered, the analysis provides a much higher risk profile than that of conventional RC structures, with a mean score of 9.72. This elevated level of risk appears to be driven primarily by the new challenges associated with moisture introduced by both evapotranspiration and irrigation systems. The consistent high-risk rating of moisture-related issues, with scores averaging 11.74-11.75, underscores the complexity added by integrating living systems into structural components. Especially striking is the relative uniformity of earthquake-related parameters, all scoring about 11.75 with very little variance, which may be an indication that seismic considerations become even more critical in green building applications. The moderate levels of risk associated with root penetration issues, while lower than moisture-related concerns, still indicate a major area requiring careful monitoring and management.

The assessment of the performance of greenery has emerged to be the category with a high risk profile overall, along with a mean score of 11.41 and an excellent classification of 99.97% for a medium-risk case and 0.03% for a high-risk. The widespread classification as having a high risk is testimony of the challenges associated with having the living systems in a built environment. Moisture management, in the form of either excess or shortfall, became the most prevalent type of risk. This finding indicates that the biological needs inherent in vertical forest systems represent a whole new dimension of risk, far more complex than conventional building management issues. The several degrees of risk from bio-debris-related moderate impacts to extreme ones regarding structural effects reveal how environmental factors may interact with green building systems in complex ways.

Human welfare aspects relating to green buildings showed comparable high-risk profiles, which showed a mean score of 11.00 with all cases falling in the medium-risk category. The continued towards high-risk scores associated with fire and wind safety (11.73-11.76) underscore additional complexities arising from adding plant life into building systems. This study particularly points to the critical role that management of moisture plays for occupants' health, indicating significantly towards high-risk scores (11.74-11.78) in this regard. This discovery indicates that, while environmentally sustainable buildings hold promises of potential benefits to human health and welfare, it presents new challenges that require careful management in order to ensure occupants' safety and comfort.

The in-depth analysis shows a clear trend of increased risk complexity during the transition from traditional reinforced concrete structures to environmentally friendly building systems. The increased risk profiles appear to be more related to the introduction of biological systems and their associated maintenance requirements rather than to structural factors. The results indicate that to be successfully implemented, a change in the management of buildings must occur by directing attention to moisture regulation, environmental oversight, and integrating safety mechanisms. Further analysis is indicated that although each factor could be neutralized in theory, the interrelation among factors and the overall impacts of the accumulated risks contribute to a more complex risk situation than with traditional buildings. This should translate to the development of green building-specific design standards as well as management protocols specific to green building, realizing benefits of urban greening while maintaining structural integrity as well as safety for occupants.

4.2 STPA ANALYSIS

The System-Theoretic Process Analysis (STPA) conducted on the vertical forest (VF) balcony system and the living wall system reveals a complex interdependency between structure, biology, and controls that represent unique hazards for each configuration. Thus, this analysis provides highly relevant insights into system vulnerabilities along with potential hazard scenarios that must not be overlooked during the design and operational phases.

The analysis of the VF balcony system identified four key accident categories that correspond to different hazards, thus exposing the intricate interplay between structural integrity, plant systems, control mechanisms, and interaction with the environment. The analysis of the control structure indicated a multilevel framework of safety management that requires an interplay between facility management, maintenance personnel, and automated control systems to ensure the safety within the system. Significantly, the hazardous action and inaction of UCAs obtained through load monitoring is mainly observed at the dangerous action leading to hazardous conditions; hence, failing to turn the emergency system when load conditions present dangerous values is considered highly dangerous because the act leads to hazards in such unnecessary shutdown cases when the load presents within the acceptable limit.

The risk matrix analysis for the VF balcony system highlighted several high-risk scenarios that need immediate attention. Among these critical combinations are H10 (5,2) concerning the failure of the structural monitoring system and H25 (5,5) that involves catastrophic structural failure with multiple contributing factors. The risk level distribution analysis indicated that, although many operational factors fall within permissible limits, there are specific combinations of potential consequences and probabilities that yield intolerable risk levels, particularly in situations that pertain to structural integrity and failures within control systems.

It revealed a unique set of problems that were identified with the interaction between the building envelope and the biological system. This is indicated in six major categories of accidents ranging from structural integrity to operational problems, thus indicating how broad the scope of failures could be for such a system. The control structure analysis recognized the role that irrigation management assumes in a structural integrity context, in which water management becomes the critical factor between success or failure in the system.

Particular to the evaluation of the living wall system are water-related hazards. High-risk scenarios have been seen in the risk matrix about how water is managed. For instance, risks that regard water infiltration (H12, 4,3) and critical system failure (H16, 4,4) have proved to be at a great risk and therefore need unique controls. How these risks have been interconnected has been in regard to how water management might go to compromise structural integrity and the health of plants with potential for cascade failure events.

Comparing the two systems, there are important differences in their risk profile and control requirements. It is common to the both systems to have risks for structural integrity and water-related issues, but it was found that the balcony of the VF system has much more sensitivity to load distribution and issues of structural support, and a living wall system showed the vulnerability of water infiltration, envelope integrity, etc. This is also reflected in their control structures. For instance, the living wall system places more emphasis on moisture management and envelope protection, while the VF balcony system places more emphasis on load monitoring and distribution control.

The two systems showed safety limitation and specification requirements, for instance, with redundant mechanisms for monitoring, consistent strategies in terms of maintenance and adequate response measures in emergency cases. The notable features regarding the VF balcony system are related to the assessment of loads as well as the verification of structural integrity, while requirements are explicitly set in relation to the need for real-time monitoring and automatic shutdown at 85% capacity. Conversely, the living wall system necessitates that sophisticated moisture monitoring and control systems be put in place to prevent water infiltration while ensuring that the plants are adequately hydrated.

Analysis further suggests how important both human operators as well as maintenance personnel are within these two systems. With respect to maintenance-related UCA identified, the relevance of training, procedure clarity, and clear communication protocols stands forth, highlighting an essential element- human factor- particularly when scrutinized at the risk matrices for these two systems where the risk scores are dominantly recorded, under maintenance-related scenarios placed within medium to high risks.

Both analyses indicate the importance of advanced safety management and an approach toward safe and secure systems in terms of green vertical greening when used. Adding a level of complexity in the handling of risk through integrating biology systems with structural elements may incorporate automated control mechanisms to those human operational protocols designed into the system. In brief, the future improvements on such systems should be more related to raising the reliability of control and refining techniques on managing moisture and enhancing strategies to better maintain such equipment.

4.3 COMPARATIVE ANALYSIS OF MONTE CARLO AND STPA RESULTS

The comparative analysis of Monte Carlo simulation with the findings of STPA reveals complementary insights that are relevant to risk assessment and safety management regarding the implementation of vertical forests. By analyzing these two distinct analytical methods simultaneously, significant correlations and unique perspectives offered by each method can be discerned.

Structural Integrity Findings

The Monte Carlo analysis of structural performance in green buildings indicated a mean score of 9.72 with most cases falling into medium to high-risk categories. This was closely in agreement with the STPA findings, especially in the VF balcony system analysis, where structural hazards (H-1.1 through H-1.4) were identified as major concerns. Both analyses emphasized the importance of load management and structural support systems.

Under the action of seismic forces, the Monte Carlo analysis reported that the risk scores have sharply been pushed up to 11.75 with more than 98% of the cases classified into high-risk categories. This happens to be in line with the STPA risk matrix wherein H10 (Failure of Critical Structural Monitoring Systems) and H25 (Catastrophic failure of structures) are located in the high-risk category. A correspondence like this vindicates both methods and throws light on the monitoring and control systems of the structures.

Moisture Management Correlation

Risks correlated with moisture. Monte Carlo analysis emphasized the importance of moisture management, as there is persistence in the towards high-risk scores for hazards associated with evapotranspiration and irrigation: 11.74-11.75. This is also supported by the findings of the STPA analysis for the living wall system that ranked hazards related to water as major concern to be controlled H.2.1 through H.2.3.

The STPA analysis provided further insight into what control mechanisms might be needed to mitigate those risks, thus identifying specific unsafe control actions associated with irrigation systems. It is meant to complement the Monte Carlo outcome by outlining useful control strategies in the scenarios of high risks identified within the probabilistic assessment.

Plant System Integration

Monte Carlo analysis of greenery performance indicates the highest overall risk profile with a mean score of 11.41 and 100% cases in the high-risk category. STPA also explains this finding through the detailed breakdown of plant system hazards, that is, H-2.1 through H-2.4 in the VF balcony system, in the way it shows that integration of the biological system produces complex interactions requiring control at more than one level.

Both analysis explained this basic link of relationship of plants with their health and structural integrity. Monte Carlo simulation has underscored such relationships by increasing risk scores over the areas of plant growth affecting structural components, and it is in STPA that particular controls are defined in relation to monitoring these interactions.

Control System Effectiveness

The STPA analysis provided further detailed insight into the needs of control systems that explain high risk scores identified by the Monte Carlo simulation. Specifically, the Monte Carlo analysis pointed out that failures in the control system have a high impact on overall risk profiles while the STPA analysis clearly identifies specific unsafe control actions and their consequences, creating a basis for understanding and mitigating such risks.

Human Factors and Maintenance

Both analyses focused on the human factor and maintenance. Monte Carlo analysis for human welfare presented a mean score of 10.99 with 100% cases in the high-risk category. STPA identified specific unsafe control actions concerning maintenance activities and decisions made by the human operator. The two are, therefore correlated to each other and mean that considerations of the human factor will be critical both in terms of risk assessment and in safety management.

Environmental Interaction

The Monte Carlo analysis showed that environmental factors, particularly the influence of wind and seismic activity, significantly contribute to risk. The STPA analysis further developed these conclusions by articulating the control needs for effective management of environmental interactions, particularly in the risk matrices where environmental hazards typically appeared in the medium to high-risk classifications.

Implementation Implications

The integrated findings of the two analyses reveal that vertical forest systems require

- Advanced monitoring systems that would address the identified high-risk situations in the Monte Carlo analysis and the specific control needs identified in the STPA analysis.
- An integrated methodology for moisture management considering the probabilistic risk distribution obtained from the Monte Carlo analysis and the special control measures outlined in the STPA analysis.
- Such maintenance practice accounting for the probabilistically calculated likelihood of failures due to the Monte Carlo simulation and specific unsafe control action identified by the STPA analysis.

This comparative analysis shows that while the Monte Carlo simulation results are quite good at illustrating risk probability and distribution, the STPA analysis will offer a more enhanced insight of how such risks may be governed and controlled. A combination of these tools, therefore, will better portray the challenges and needs in complete vertical forest implementation.

5 CONCLUSION

This is the complex interface of structural engineering, environmental design, and safety management in seismically active regions, encompassed through a comprehensive research on retrofitting vertical forests in reinforced concrete structures. Various analytical approaches used are Monte Carlo simulations, STPA analyses, detailed hazard assessments, among others; therefore, these provide much-critical information to develop the most reliable damage metrics associated with hazards, thus supporting an integrated approach to vertical forest retrofitting.

Monte Carlo simulations illustrated that the green building modifications typically present a higher risk profile compared to traditional RC buildings, especially when it comes to moisture management, structural integrity, and plant system integration. The analysis proved that the traditional RC buildings tend to cluster primarily within the medium risk categories (100% with a mean score of 9.47), whereas the complexities introduced by the green building modifications push up the risk profiles (mean scores between 9.72 and 11.41). It can also be very apparent in areas that consist of interplay between the biological systems and structural components.

Further analysis with the STPA on both the vertical forest balcony system and the living wall implementation has advanced risk understanding through identification of specific control requirements and safety constraints. In fact, such analyses help reveal essential interrelationships among structural integrity, water management, and plant health systems, which should be monitored and controlled very tightly. Identifying hazardous control actions and their effects forms the basis of developing extensive safety management systems.

Adding seismic factors makes it another dimension of complexity, as both types of analysis indicate that all the parameters related to earthquakes inherently carry a risk score of about 11.75 with minor variation. The result puts a great emphasis on incorporating seismic resilience in the renovation of vertical forests, especially in areas with seismic potential.

From this broad analysis, several key recommendations are developed:

- The structural and biological characteristics must be considered in the integrated monitoring system, especially with regards to moisture management and load.
- Safety management systems should be multiple layer controls mechanisms, especially over the critical parameters identified through both Monte Carlo and STPA analyses.
- There should be developed maintenance procedures that are based on the probabilistic nature of failures and specific control requirements identified through STPA analysis.
- The design standards for vertical forests renewal must clearly address the connection of structural elements with biological elements especially under seismic conditions.

The findings of this study improve the overall understanding of sustainable urban transformation and simultaneously highlight the specific challenges related to the integration of vertical forests in seismically active regions. This study demonstrates that successful execution requires an integrated approach balancing structural stability, environmental efficiency, and safety for residents.

Anticipating future developments, this study indicates a need for:

- The particular need for design codes that are specialized, directed at the unique needs of vertical forest renovations:
- Development of general monitoring systems that can monitor structural, biological, and environmental variables.
- Standardized maintenance procedures addressing both the conventional requirements of structural needs and the particular needs of biological systems.
- Advanced control systems to detect the intricate relationships between the structural and biological components will be placed.

The success of vertical forest restorations would depend on reviewing and using this information judiciously, particularly in seismically active regions where the structural integrity needed is balanced by ecological and visual goals. This work provides a stepping stone toward the advancement of more resilient and robust urban settings with the guarantee of safety and performance in vertical forest deployments.

6 REFERENCES

Aithal, A., & Aithal, P. S. (2020). Development and Validation of Survey Questionnaire & Experimental Data – A Systematical Review-based Statistical Approach. International Journal of Management, Technology, and Social Sciences (IJMTS), 5(2), 233-251.

Alkhdour, A., & Shraa, T. (2024). Machine learning approaches to soil-structure interaction under seismic loading: predictive modeling and analysis. Asian Journal of Civil Engineering, 25, 5781–5792.

Arup (2014). Cities Alive: Rethinking Green Infrastructure. Arup.

Avşar, Ö., Yakut, A., & Caner, A. (2014). Examination of the code requirements for the inter-story drift ratio limits.

Baker, J. W. (2013). Introduction to Probabilistic Seismic Hazard Analysis. Stanford University Publication.

Baker, J. W., & Cornell, C. A. (2006). Vector-Valued Ground Motion Intensity Measures for Probabilistic Seismic Demand Analysis. Pacific Earthquake Engineering Research Center.

Baker, J.W., & Cornell, C.A. (2008). Vector-Valued Intensity Measures Incorporating Spectral Shape for Prediction of Structural Response. Journal of Earthquake Engineering, 12(4), 534–554.

Bažant, Z. P., & Jirásek, M. (2002). Nonlocal integral formulations of plasticity and damage. ASCE Journal of Engineering Mechanics, 128(11), 1119–1149.

Bažant, Z. P., & Oh, B.-H. (1983). Crack band theory for fracture of concrete. Materials and Structures, 16, 155–177.

Beres, A., Pessiki, S., White, R., & Gergely, P. (1996). Implications of experimental on the seismic behaviour of gravity load designed RC beam-column connections. Earthquake Spectra, 12(2), 185–198

Bergamo, P., Fäh, D., Panzera, F., Cauzzi, C., Glueer, F., Perron, V., & Wiemer, S. (2023). A site amplification model for Switzerland based on site-condition indicators and incorporating local response as measured at seismic stations. Bulletin of Earthquake Engineering, 21, 5831-5865.

Bhardwaj, M.K., Kapania, R.K., Reichenbach, E., & Guruswamy, G.P. (1998). Computational Fluid Dynamics/Computational Structural Dynamics Interaction Methodology for Aircraft Wings. AIAA JOURNAL Vol. 36, No. 12Bhardwaj, M.K., Kapania, R.K., Reichenbach, E., & Guruswamy, G.P. (2000). Computational Fluid Dynamics/Computational Structural Dynamics Interaction Methodology for Aircraft Wings. NASA Technical Report.

Böse, M., Danciu, L., Papadopoulos, A., Clinton, J., Cauzzi, C., Dallo, I., Mizrahi, L., Diehl, T., Bergamo, P., Reuland, Y., Fichtner, A., Roth, P., Haslinger, F., Massin, F., Valenzuela, N., Blagojević, N., Bodenmann, L., Chatzi, E., Fäh, D., Glueer, F., Han, M., Heiniger, L., Janusz, P., Jozinovic, D., Kästli, P., Lanza, F., Lee, T., Martakis, P., Marti, M., Meier, M.-A., Mena Cabrera, B., Mesimeri, M., Obermann, A., Sanchez-Pastor, P., Scarabello, L., Schmid, N., Shynkarenko, A., Stojadinovic, B., Giardini, D., and Wiemer, S.: Towards a Dynamic Earthquake Risk Framework for Switzerland, EGUsphere Buciumeanu, M., Palaghian, L., Miranda, A.S., & Silva, F.S. (2010). Fatigue life predictions including the Bauschinger effect. International Journal of Fatigue, 32(8), 1231-1239Böse, M., Danciu, L., Papadopoulos, A., Clinton, J., Cauzzi, C., Dallo, I., ... & Wiemer, S. (2023). Towards a dynamic earthquake risk framework for Switzerland. Natural Hazards and Earth System Sciences, 24, 583-607.

Buciumeanu, M., Palaghian, L., Miranda, A.S., & Silva, F.S. (2010). Fatigue life predictions including the Bauschinger effect. International Journal of Fatigue, 32(8), 1231-1239

Bullock, Z., Dashti, S., Liel, A., Porter, K., & Karimi, Z. (2017). Ground-Motion Prediction Equations for Arias Intensity, Cumulative Absolute Velocity, and Peak Incremental Ground Velocity for Rock Sites in Different Tectonic Environments. Bulletin of the Seismological Society of America, 107(5), 2293–2309.

C40 Cities (2019). Green and Healthy Streets. C40 Knowledge Hub.

Calvi, G. M., Moratti, M., & Pampanin, S. (2002). Relevance of beam-column damage and collapse in RC frame assessment. Journal of Earthquake Engineering, 6(1), 75–100.

Calvi, G. M., Priestley, M. J. N., & Kowalsky, M. J. (2008). Displacement-based seismic design of structures. IUSS Press

Cantagallo, C., De Risi, R., Terrenzi, M., Camata, G., & Spacone, E. (2024). Sufficiency assessment of intensity measures for natural and spectral-matched ground motion records. Bulletin of Earthquake Engineering, 22, 6305–6326.

Caterino, N., Iervolino, I., Manfredi, G., & Cosenza, E. (2013). Approximate methods to evaluate storey stiffness and interstory drift of RC buildings in seismic area

Charalampidou, S., Zeleskidis, A., & Dokas, I. M. (2024). Hazard analysis in the era of AI: Assessing the usefulness of ChatGPT4 in STPA hazard analysis. Safety Science, 178, 106608.

Chatterjee, S. K., Das, S., Maharatna, K., Masi, E., Santopolo, L., Mancuso, S., & Vitaletti, A. (2016). Exploring strategies for classification of external stimuli using statistical features of the plant electrical response

Christopoulos, C., Pampanin, S., & Priestley, M. J. N. (2004). Seismic Design and Response of Buildings Including Residual Deformations. 13th World Conference on Earthquake Engineering

Cristiano, E., ten Veldhuis, M.-C., & van de Giesen, N. (2017). Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas. Hydrology and Earth System Sciences, 21(8), 3859–3878.

Davis, B.N., & LeVeque, R.J. (20172020). Analysis and Performance Evaluation of Adjoint-Guided Adaptive Mesh Refinement for Linear Hyperbolic PDEs Using Clawpack. ACM Transactions on Mathematical Software, 9(4), 39

Díaz-Oreiro, I., López, G., Quesada, L., & Guerrero, L. A. (2019). Standardized Questionnaires for User Experience Evaluation: A Systematic Literature Review. Proceedings, 31(1), 14. Lallemand, C., Gronier, G., & Koenig, V.I. Díaz-Oreiro, G. López , L. Quesada and L. A. Guerrero (2019). Standardized Questionnaires for User Experience Evaluation: A Systematic Literature Review. Proceedings, 31(1), 14.

Duque, J., Tafili, M., Seidalinov, G., Mašín, D., & Fuentes, W. (2022). Inspection of four advanced constitutive models for fine-grained soils under monotonic and cyclic loading. Acta Geotechnica, 17(10), 4395-4418 Fuentes, R. (2021). Inspection of four advanced constitutive models for fine-grained soils under complex cyclic loading. Acta Geotechnica, 16, 1656-1678.

Edwards, B., Michel, C., Poggi, V., & Fäh, D. (2013). Determination of Site Amplification from Regional Seismicity: Application to the Swiss National Seismic Networks. Seismological Research Letters, 84, 611-621.

Estrada, J. S., Fuentes, A., Reszka, P., & Auat Cheein, F. (2023). Machine learning assisted remote forestry health assessment: a comprehensive state of the art review. Frontiers in Plant Science.

Fäh, D., Giardini, D., Kästli, P., Deichmann, N., Gisler, M., Schwarz-Zanetti, G., Alvarez-Rubio, S., Sellami, S., Edwards, B., Allmann, B., Bethmann, F., Wössner, J., Gassner-Stamm, G., Fritsche, S., Eberhard, D., 2011. ECOS-09 Earthquake Catalogue of Switzerland Release 2011. Report and Database. Public catalogue, 17.4.2011. Swiss Seismological Service ETH Zürich, ReportFäh, D., Giardini, D., Kästli, P., Deichmann, N., Gisler, M., Schwarz-Zanetti, G., ... & Eberhard, D. (2011). ECOS-09 Earthquake Catalogue of Switzerland Release 2011 Report and Database. Swiss Seismological Service ETH Zurich.

Fardis, M. N. (2009). Seismic design, assessment and retrofitting of concrete buildings: based on EN-Eurocode 8. Springer

Fathalia, M.A., & Vaez, S.R.H. (2022). Probabilistic performance-based optimal design of low-rise eccentrically braced frames considering connections type layout. Steel and Composite Structures, 46(5), 683-696.

FEMA 356 (2000). Prestandard and Commentary for the Seismic Rehabilitation of Buildings. Federal Emergency Management Agency.

Filippou, F. C., & Fenves, G. L. (2004). Methods of analysis for earthquake-resistant structures. In Earthquake Engineering: From Engineering Seismology to Performance-Based Engineering

Gameiro Lopes, A. M., Duarte, N. G. L., Sánchez, O. H., Daus, R., & Koch, H. (2021). Numerical Prediction of the Boundary-Layer Flow Over the Bolund Hill: Assessment of Turbulence Models and Advection Schemes. Boundary-Layer Meteorology, 178, 1–27.

Ghobarah, A., & Said, A. (2002). Shear strengthening of beam-column joints. Engineering Structures, 24(7), 881–888.

Ghosh Dastider, J., Pal, D., & Mishra, P. K. (2024). Evidence of Kolmogorov-like scalings and multifractality in rainfall events. arXiv preprint arXiv:2405.03463.

Göttlich, S., & Knapp, S. (2020). Artificial Neural Networks for the Estimation of Pedestrian Interaction Forces. In N. Bellomo & L. Gibelli (Eds.), Crowd Dynamics, Volume 2: Theory, Models, and Applications (pp. 11-32). Springer.

Haselton, C., Deierlein, G., Bono, S., Ghannoum, W., Hachem, M., Malley, J., ... & Cedillos, V. (2016). Guidelines on nonlinear dynamic analysis for performance-based seismic design of steel and concrete moment frames. In 2016 SEAOC Convention.FEMA. (2016). Guidelines on Nonlinear Dynamic Analysis for Performance-Based Seismic Design. Federal Emergency Management Agency Report.

Hu, X., Zhang, H., & Yu, H. (2023). Numerical simulation study on the hygrothermal performance of building exterior walls under dynamic wind-driven rain condition. Building Simulation, 17, 207–221.

IBM. (2023). What Is Monte Carlo Simulation? https://www.ibm.com/topics/monte-carlo-simulation

Jaiman, R.K., & Joshi, V. (2021). Computational Mechanics of Fluid-Structure Interaction. Springer.

Jayathissa, P., Quintana, M., Abdelrahman, M., & Miller, C. (2020). Humans-as-a-sensor for buildings: Intensive longitudinal indoor comfort models.

Jiang, W., & Liou, F. (2002). Finite Element Analysis of Residual Stresses and Deformations in Direct Metal Laser Sintering Process. Solid Freeform Fabrication Proceedings

Kaczmarek, Ł. D., & Popielski, P. (2019). Selected components of geological structures and numerical modelling of slope stability. Open Geosciences.

Kareem, A. (2020). Emerging frontiers in wind engineering: Computing, stochastics, machine learning and beyond. Journal of Wind Engineering and Industrial Aerodynamics, 200, 104134

IE Kavvadias, GA Papachatzakis, KE Bantilas, LK Vasiliadis, A Elenas (2017). Rocking spectrum intensity measures for seismic assessment of rocking rigid blocks. Soil Dynamics and Earthquake Engineering 101, 116-124

Kudszus, R., Klemencic, R., & Spyridis, P. (2020). Basic Concepts of Engineering Risk Management for Fastenings and Risk Register Based on Industry Survey. CivilEng, 1(3), 275-290.

L. Martins, R. Delgado, R. Camposinhos, T Silva (2012) Seismic Behavior of Point Supported Glass Panels, Challenging Glass 3Camposinhos, R. (2011). Seismic Behavior of Point Supported Glass Panels. Glass on Web

Lagomarsino, S., Cattari, S. (2014). Fragility Functions of Masonry Buildings. In: Pitilakis, K., Crowley, H., Kaynia, A. (eds) SYNER-G: Typology Definition and Fragility Functions for Physical Elements at Seismic Risk. Geotechnical, Geological and Earthquake Engineering, vol 27. Springer, Dordrecht.

Lazaridis, P.C.; Kavvadias, I.E.; Demertzis, K.; Iliadis, L.; Vasiliadis, L.K. (2022). Structural Damage Prediction of a Reinforced Concrete Frame under Single and Multiple Seismic Events Using Machine Learning Algorithms. Appl. Sci. 2022, 12, 3845. https://doi.org/10.3390/app12083845

Leveson, N. G. (2012). Engineering a Safer World: Systems Thinking Applied to Safety. MIT Press.

Leveson, N. G., & Thomas, J. P. (2018). STPA Handbook.

Li, Y., Wei, M., & Hu, X. (2023). Damage monitoring of the planting balcony in vertical greenery buildings using the EMI method. *Smart Materials and Structures, 32*(3), 035038.

Lim, H. B., Ling, K. V., & Sharma, T. (2005). Sensor Grid: Integration of Wireless Sensor Networks and the Grid. In Proceedings of the IEEE Conference on Local Computer Networks 30th Anniversary (pp. 91-99).

Liu, R., Zhu, W., & Yang, X. (2023). Screening Image Features of Collapsed Buildings for Operational and Rapid Remote Sensing Identification. Remote Sensing, 15, 5747.

Liu, X., & Wang, Y. (2021). Probabilistic simulation of entire process of rainfall-induced landslides using random finite element and material point methods with hydro-mechanical coupling. Computers and Geotechnics.

Ma, H., Liu, Y., Ren, Y., & Yu, J. (2020). Detection of Collapsed Buildings in Post-Earthquake Remote Sensing Images Based on the Improved YOLOv3. Remote Sensing, 12, 44.

Ma, Y., Richards, M., Ghanem, M., Guo, Y., & Hassard, J. (2008). Air Pollution Monitoring and Mining Based on Sensor Grid in London. Sensors, 8(6), 3601-3623

Mazzoni, S., McKenna, F., Scott, M. H., & Fenves, G. L. (2007). OpenSees Command Language Manual. Pacific Earthquake Engineering Research Center.

Memari, A.M., Behr, R.A., & Kremer, P.A. (2003). Seismic Behavior of Curtain Walls Containing Insulating Glass Units. Journal of Architectural Engineering, 9(2), 70-85.

Micro-Measurements. (n.d.). Concrete, https://www.micro-measurements.com/applications/concrete

Minitab. (2023). The 4 Simple Steps for Creating a Monte Carlo Simulation with Engage or Workspace. https://blog.minitab.com/en/the-4-simple-steps-for-creating-a-monte-carlo-simulation-with-engage-or-workspace

Monjo, R. (2016). Measure of rainfall time structure using the dimensionless n-index. Climate Research, 70(2-3), 161–172.

Moon, H., Yoon, H. J., & Han, H. (2017). The effect of airport atmospherics on satisfaction and behavioral intentions: testing the moderating role of perceived safety. Journal of Travel & Tourism Marketing, 34(6), 749-763.

Nazarzadeh, M., & Sarbishe-ee, S. (2017). Probabilistic Analysis of Shallow Foundation Settlement considering Soil Parameters Uncertainty Effects.

Nishida, R., Onishi, M., & Hashimoto, K. (2023). Crowd simulation incorporating a route choice model and similarity evaluation using real large-scale data. arXiv preprint arXiv:2302.10421

Olesen, B. W. (2004). International standards for the indoor environment. Indoor Air, 14(s7), 18-26.

Pampanin, S., Christopoulos, C., & Nigel Priestley, M. J. (2003). Performance-Based Seismic Response Of Frame Structures Including Residual Deformations. Part Ii: Multi-Degree Of Freedom Systems. Journal Of Earthquake Engineering, 7(1), 119–147 Pampanin, S., Christopoulos, C., & Priestley, M. J. N. (2005). Performance-Based Seismic Response of Frame Structures Including Residual Deformations. 13th World Conference on Earthquake Engineering.

Pérez, G., Rincón, L., Vila, A., González, J. M., & Cabeza, L. F. (2011). Green vertical systems for buildings as passive systems for energy savings. Applied Energy, 88(12), 4854–4859

Perini, K., Ottelé, M., Haas, E.M. et al. Vertical greening systems, a process tree for green façades and living walls. Urban Ecosyst 16, 265–277 (2013). Perini, K., & Rosasco, P. (2016). Vertical greening systems, a process tree for green façades and living walls. Urban Ecosystems, 19, 659–674

Pham, T.-Q., Kamusella, A., & Neubert, H. (2011). Auto-Extraction of Modelica Code from Finite Element Analysis or Measurement Data. In Proceedings of the 8th International Modelica Conference (pp. 657-665).

Piccioni, V., Grobe, L. O., Hischier, I., & Schlueter, A. (2024). From layer to building: Multiscale modeling of thermo-optical properties in 3D-printed facades. Energy and Buildings, 314, 114222. Naboni, R., & Paoletti, I. (2019). From layer to building: Multiscale modeling of thermo-optical behavior in 3D printed façade systems. Energy and Buildings, 199, 72-84

Pogfay, T., Watthanawisuth, N., Pimpao, W., Wisitsoraat, A., & Mongpraneet, S. T. Lomas (2010). Development of Wireless Electronic Nose for Environment Quality Classification. In 2010 International Conference on Electrical Engineering/Electronics Computer Telecommunications and Information Technology (pp. 1017-1021).

Porter, K. A. (2003). An overview of PEER's performance-based earthquake engineering methodology. ICASP9

Robalino, A. F., Zaruma, S. R., & Sánchez, T. A. (2020). Study of story drift limits in steel buildings subjected to seismic forces. Structural Stability Research Council

RST Instruments Ltd. (n.d.). Strain Gauges & Strain Meters https://rstinstruments.com/product-category/instruments/strain-gauges-strain-meter/

Sandıkkaya, M.A., Akkar, S (2017). Cumulative absolute velocity, Arias intensity and significant duration predictive models from a pan-European strong-motion dataset. Bull Earthquake Eng 15, 1881–1898 Akkar, S., Sandıkkaya, M.A., & Bommer, J.J. (2016). Cumulative absolute velocity, Arias intensity and significant duration for the NGA-West2 database. Bulletin of Earthquake Engineering, 14, 1565–1593.

Skolnik, D. A., & Wallace, J. W. (2010). A critical assessment of interstory drift measurements. Canadian Association for Earthquake Engineering

Spyridis, P., & Proske, D. (2021). Revised comparison of tunnel collapse frequencies and tunnel failure probabilities. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 7(3), 04021025.

Spyridis, P., & Strauss, A. (2020). Robustness assessment of redundant structural systems based on design provisions and probabilistic damage analyses. Buildings, 10(12), 213.Aithal, A., & Aithal, P. S. (2020). Development and Validation of Survey Questionnaire & Experimental Data – A Systematical Review-based Statistical Approach. International Journal of Management, Technology, and Social Sciences (IJMTS), 5(2), 233-251.

Tabatabaiefar, S. H. R., Fatahi, B., & Samali, B. (2013). Seismic behavior of building frames considering dynamic soil-structure interaction. Soil Dynamics and Earthquake Engineering, 44, 85–97.Greco, R., Raimondo, M., & Martino, S. (2012). Non-linear finite element analysis for prediction of seismic response of soil-structure interaction systems. Natural Hazards and Earth System Sciences.

Tam, S., & Wong, J. (2021). Seismic performance of a green roof structure. *Sustainability, 13*(8), 4278.

Thomson, E. (2024, January 2). Cities are using nature to cut urban temperatures – by 2°C in one case. World Economic Forum. https://www.weforum.org/stories/2024/01/nature-positive-cities-tackle-extreme-heat/

United Nations (2019). World Urbanization Prospects 2018: Highlights. United Nations.

V. Jamora, C. Wu, A. Kravchenko (2020). Residual Deformation Analysis In Composite Shell Structures Manufactured Using Automated Fiber Placement, Langley Research CenterNASA. (2020). Residual Deformation Analysis in Composite Shell Structures. NASA Technical Reports Server.

Vargas-Alzate, Y.F., Hurtado, J.E. & Pujades, L.G. (2022) New insights into the relationship between seismic intensity measures and nonlinear structural response. Bull Earthquake Eng 20, 2329–2365 Vargas-Alzate, Y. F., Montejo, L. A., & Pardo-Bosch, F. (2021). New insights into the relationship between seismic intensity measures and nonlinear structural response. Bulletin of Earthquake Engineering, 19, 4515–4540.

Vecchio, F. J., & Collins, M. P. (1986). The modified compression-field theory for reinforced concrete elements subjected to shear. ACI Journal, 83(2), 219–231.

Virnodkar, S.S., Pachghare, V.K., Patil, V.C. et al. Remote sensing and machine learning for crop water stress determination in various crops: a critical review. Precision Agric 21, 1121–1155 (2020). Patil, M. A., & Jha, S. K. (2020). Remote sensing and machine learning for crop water stress determination in various crops: A critical review. Precision Agriculture, 21, 1121–1155.

Wächter, M., Heißelmann, H., Hölling, M., Morales, A., Milan, P., Mücke, T., Peinke, J., Reinke, N., & Rinn, P. (2012). Wind Energy and the Turbulent Nature of the Atmospheric Boundary Layer

Wald, D. J., Quitoriano, V., Worden, C. B., Hopper, M., & Dewey, J. W. (2010). USGS "Did You Feel It?" Internet-based macroseismic intensity maps. U.S. Geological Survey Fact Sheet, 30-01.

Wang, D. R., Guadagno, C. R., Mao, X., Mackay, D. S., Pleban, J. R., Baker, R. L., Weinig, C., Jannink, J. L., & Ewers, B. E. (2019). A framework for genomics-informed ecophysiological modeling in plants. Journal of Experimental Botany, 70(9), 2561–2574.

Wang, T., Shang, Q., & Li, J. (2021). Seismic force demands on acceleration-sensitive nonstructural components: a state-of-the-art review. Earthquake Engineering and Engineering Vibration, 20, 39–62.

Wikipedia. (2023). Monte Carlo method. https://en.wikipedia.org/wiki/Monte_Carlo_method

Willam, K. J., & Warnke, E. P. (1975). Constitutive models for the triaxial behavior of concrete. Proceedings of the International Association for Bridge and Structural Engineering, 19, 1–30.

Wong, N. H., & Yu, C. (2005). Study of green areas and urban heat island in a tropical city. Habitat International, 29(3), 547–558.

Xiang, Y., Arora, J. S., & Abdel-Malek, K. (2010). Physics-based modeling and simulation of human walking: a review of optimization-based and other approaches. Structural and Multidisciplinary Optimization, 42, 1-23

Zeleskidis, A., Charalampidou, S., Dokas, I. M., & Papadopoulos, B. (2023). A preparedness drill scenario development and system safety competency assessment based on the STAMP Model. In International Conference on Human-Computer Interaction (pp. 484-500).

Zhu, H., Sun, Y., Zhao, W., Zhuang, F., Wang, B., & Xiong, H. (2020). Rapid Learning of Earthquake Felt Area and Intensity Distribution with Real-time Search Engine Queries. Scientific Reports, 10, 5437.

Zhu, X., Yang, X., Huang, W., Liu, M., & Wang, X. (2024). Modeling Bauschinger effect through the reversibility of dislocation slip in an Al–Cu–Li alloy. Materials Science and Engineering: A, 146574.