

Review

A Comprehensive Review of Vertical Forest Buildings: Integrating Structural, Energy, Forestry, and Occupant Comfort Aspects in Renovation Modeling

Vachan Vanian , Theodora Fanaradelli  and Theodoros Rousakis 

Department of Civil Engineering, Democritus University of Thrace, 67100 Xanthi, Greece; tfanarad@civil.duth.gr

* Correspondence: vvanian@civil.duth.gr (V.V.); trousak@civil.duth.gr (T.R.); Tel.: +30-69-7742-1569 (T.R.)

Highlights

What are the main findings?

- This comprehensive review identifies 36 specific interaction points between structural, energy, forestry, and occupant comfort modeling approaches for vertical forest buildings, revealing that 58% require high integration (direct coupling) and 28% require medium integration (coordination).
- Three distinct finite element modeling approaches for trees are established, as follows: high-fidelity 3D models using LIDAR data with detailed trunk and crown architecture; simplified branch-mass models with distributed masses; and equivalent two-element models for large-scale simulations.

What are the implications of these findings?

- Successful vertical forest building implementation requires coordinated multidisciplinary design approaches rather than isolated domain-specific solutions, fundamentally changing how urban building renovation projects should be approached and managed.
- The systematic tree modeling framework enables practitioners to balance computational efficiency with accuracy based on project requirements and available resources, providing a practical methodology for integrating living forest ecosystems into urban buildings while maintaining structural safety and occupant well-being.



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Abstract

This current review examines modeling approaches for renovating reinforced concrete (RC) buildings for vertical forest (VF) application, taking into account structural retrofitting, energy systems, forestry integration, and occupant comfort. The study assesses research conducted with an advanced 3D finite element analysis and the use of retrofitting modeling techniques, including textile-reinforced mortar (TRM), fiber-reinforced polymer (FRP), seismic joints, and green concrete applications. The energy system modeling methods are reviewed, taking into account the complexity of incorporating vegetation and seasonal variations. During forestry integration, three main design parameters are identified, namely, root systems, trunks, and crowns, for their critical role in the structural stability and optimal environmental performance. The comfort models are identified evolving from static to adaptive models incorporating thermal, acoustic, visual and air quality parameters. The current review consists of more than one hundred studies indicating that the integration of natural systems to buildings requires a multidimensional and multidisciplinary approach with sophisticated systems. The findings of this review provide the basis

for implementing VF models to RC buildings, while highlighting areas requiring further research and validation.

Keywords: vertical forest buildings; building renovation; structural retrofitting; energy modeling; forestry integration; occupant comfort; FEM; textile-reinforced mortar; fiber-reinforced polymer

1. Introduction

The requirements for sustainable but modern structures have been intensified by urbanization and climate change [1]. The main objective is to use natural mechanisms for a sustainable environment with air of high quality and less and controlled humidity, that can provide satisfaction and comfort for inhabitants. Vertical forests (VFs) are aligned with these principles [2,3]. These structures include vegetation in their design and they represent a new type of architectural biodiversity with the objective of mitigating pollution, and promoting energy efficiency [4,5]. Vegetation can be implemented into facades and/or rooftops, offering benefits such as carbon sequestration, improved air quality, and thermal regulation [6,7]. However, their use is challenging, particularly in balancing structural demands, energy systems, and occupant comfort [8].

Recent advancements in materials and modeling methodologies have enabled the development of modern retrofit materials to address the structural and energy challenges of vertical forest buildings. Techniques such as textile-reinforced mortar (TRM) [9] and fiber-reinforced polymer (FRP) [10,11] systems have proven effective in enhancing the resilience of masonry and reinforced concrete structures. At the same time, green concrete [12] and other composite materials [13] have shown an improving sustainability while maintaining structural performance. Complementing these efforts, energy renovation models have explored strategies for integrating renewable energy systems and optimizing building energy use [14]. Another critical aspect of vertical forest buildings is their impact on occupant comfort. Thermal, acoustic, visual, and air quality models play a vital role in ensuring that these structures provide healthy and pleasant living environments [15,16]. Additionally, forestry models offer insights into the mechanical behavior and ecological contributions of the integrated vegetation, further underscoring the complexity of these buildings [17,18].

This review reflects the complexity of VF buildings, where multiple systems must integrate to achieve sustainability and functionality. The current study focuses on the numerical modeling aspect that is critical for an early assessment of VF buildings and does not provide design guidelines that would require another extensive research. The review is organized into four main sections with the following structure: Section 2 examines retrofit models and materials for reinforced concrete structures, emphasizing strengthening techniques including TRM, FRP, polymer seismic joints, and green-concrete, and presents implications for structural engineering and material-development trends. Section 3 investigates energy-renovation models across scales, from building components to regional systems. The analysis encompasses energy models, frameworks, demand–consumption patterns, and methodological tools and classifies modeling approaches, enabling practitioners to select methodologies for varying applications. Section 4 presents forestry-modeling approaches for the built environment, introducing three methodologies based on complexity and computational requirements. The section examines static-tree analysis, wind–tree interaction and root-system models. Section 5 addresses occupant comfort through thermal, acoustic, visual, and air-quality models, examining their interdependence in VF buildings,

where the vegetation affects indoor environmental quality, among others. Each section presents the state-of-the-art potential and limitations as well as the research directions, enabling independent reading whilst maintaining coherence. In each section summary, a comprehensive table for the modeling approaches is provided. The paper synthesizes these approaches and identifies research needs for the proper modeling of vertical forest building.

2. Retrofit Models

The selection and integration of retrofitting techniques for vertical forest buildings requires a multidisciplinary approach that considers not only structural performance but also energy efficiency, environmental impact, and occupant comfort. Recent advances in multi-criteria decision-making frameworks have demonstrated that retrofit selection should be based on comprehensive cost–benefit analyses that incorporate expected annual loss (EAL), life-cycle costs, and stakeholder priorities [19,20]. Research has shown that invasiveness and disruption to occupants are among the most critical factors influencing retrofit decisions, particularly in residential buildings where minimizing tenant displacement is paramount [21]. Furthermore, the integration of seismic retrofitting with energy efficiency measures has emerged as a preferred approach, enabling comprehensive building requalification while optimizing resource utilization [20].

In this context, the current review focus on lightweight, natural, and recyclable materials, such as textile-reinforced mortar (TRM), fiber-reinforced polymer (FRP), seismic connections, and novel green concrete composites, as these materials offer enhanced compatibility with vegetation systems, reduced structural loads, superior deformability, temperature resistance, and minimal impact on building stiffness—characteristics that are fundamental for supporting integrated forestry components while maintaining optimal energy performance and occupant comfort. The research has established significant improvements in computer-aided calculation techniques, mainly finite element techniques (FEM), also referred to as finite element analysis (FEA), enabling more precise representation of the behavior of structures, interaction between different materials, and mechanisms causing their failures under different forms of stress. The advancements of such models led to more complex forms with pre- and post-elaborations, and also the performance optimization of rehabilitated structures. This may include their resistance against earthquakes, their energy efficiency, and overall sustainability. The coupling of experimental testing and computational modeling has led to more realistic and reliable retrofit solutions, not only addressing the safety of structures, but also ecological factors related to the restoration of buildings.

2.1. Textile-Reinforced Mortar (TRM)

Textile-reinforced mortar (TRM) is an advanced material for masonry retrofitting [22,23] and reinforced concrete (RC) structures [24] that can increase ductility, corrosion resistance, and compatibility with the existing structural materials [25]. Several studies use TRMs for seismic retrofitting and many numerical investigations have been carried out. Cao et al. (2024) [26] examined the flexural performance of TRM-strengthened RC beams by using finite element modeling together with experimental validation. They used LS-DYNA software to develop 3D nonlinear models and conduct four-point bending tests. The results showed that by adding TRM layers stiffness and flexural capacity can be improved, while longer textile lengths can improve the ultimate strength and ductility. However, textile mesh sizes larger than 17.5 mm × 17.5 mm had a minimal impact on load capacity but increased ductility. Earlier, Gulinelli et al. (2020) [27] developed finite element models to simulate TRM-strengthened masonry under diagonal compression. They used ABAQUS software and a multiscale approach, and the masonry was simulated as 3D continuum

elements, TRM layers as 2D shell elements, and TRM-wall interfaces as cohesive elements. Numerical modeling is found to provide accurate prediction of load, stiffness and failure modes in TRM systems, e.g., the characteristic two-phase response of glass-TRM. The models need further improvement, particularly in simulating post-peak behavior and diagonal-tension failure mechanisms in basalt-TRM. Karlos et al. (2020) [28] present a new system that integrates TRM with thermal insulation for concurrent seismic and energy retrofitting of masonry buildings. Experimental investigations and finite-element analyses demonstrate that this integrated system substantially enhances out-of-plane strength and deformation capacity. The experimental program establishes that external TRM placement relative to the insulation layer yields superior performance compared with conventional TRM applications. Both analytical and numerical models correlate well with experimental data, validating the system's effectiveness in addressing seismic vulnerability whilst improving thermal efficiency of masonry structures. Thomoglou et al. (2018) [29] examined the seismic behavior of unreinforced masonry (URM) walls strengthened with fabric-reinforced cementitious mortar (FRCM) and fiber-reinforced polymer (FRP). The researchers developed 3D finite element models by using ANSYS software, and the models revealed significant upgrade in the wall shear capacity and validated the reliability of finite element methods for analyzing the URM wall behavior. Finally, D'Ambrisi et al. (2013) [30] researched, experimentally, carbon-FRCM composite bond behavior in masonry strengthening. They carried out double-shear tests in order to characterize bond-slip behavior between masonry substrates and carbon-FRCM. They concluded that debonding happens when the fibers/matrix interface significantly slip, and they confirmed the material is effective as an external reinforcement. The study contributed to a calibrated bond-slip model, essential for the design of carbon-FRCM retrofit systems, particularly relevant for modern seismic code requirements.

2.2. Seismic Joints and Infill Strengthening

Seismic protection systems for RC-framed infilled structures take into account new technologies like polyurethane-flexible joints (PUFJ), fiber-reinforced polyurethane (FRPU) jackets and decoupling mechanisms [31]. A recent investigation by Vanian et al. (2024) [32] examined RC frames with unreinforced masonry (URM) infills strengthened by PUFJ and FRPU systems. Numerical modeling using ANSYS and ABAQUS demonstrates that proper calibration of the material characteristics and precise geometric modeling enhance predictability. The study determines that PUFJ and FRPU installations significantly enhance the ductility and dynamic response of the structure. Earlier, Rousakis et al. (2021) [33] created 3D finite element models using ANSYS software to study the seismic response of RC frames with and without the above interventions. They concluded in their research that FRPU jackets ensured infill integrity for story drift higher than 3.6%, and structures renovated with advanced seismic joints made of PUFJ exhibited a similarly ductile response by avoiding infill disintegration for story drift as high as 3.7%. These studies determine the importance of such advanced materials in achieving high stiffness, base-shear strength and seismic performance, thus encouraging new structural retrofitting techniques. Akyildiz et al. (2021) [34] investigated the use of PUFJ on RC buildings with masonry infills. Based on finite-element analyses—made up of static, modal, and dynamic analyses—they reached the conclusion that PUFJ has good potential to reduce interfacial failure while maintaining structural integrity during seismic loading. There is high potential for its use in new building construction and in retrofitting in high seismic risk zones, as it offers upgraded seismic performance capability. Butenweg and Marinković (2018) [35] studied INODIS (Innovative Decoupled Infill System), which benefits from the employment of elastomeric components in the U-shape to protect masonry-infill panels -reinforced-concrete frame

vulnerable boundary regions. Experimental and numerical analyses demonstrate that INODIS increases deformation capacity, reduces stiffness and base shear, while increasing energy dissipation of the whole bearing system. This solution satisfies Eurocode 8 specifications and renders infill panels non-structural, and hence optimizes the seismic response of the structural bearing frame. Finally, Tsantilis and Triantafillou (2018) [36] developed an isolation technique with cellular materials in the frame–infill interface to isolate infill panels from RC frames. The technique prevents damage under moderate seismic loads by suppressing frame–infill interaction at low-to-medium drift levels. At high drifts, the infills are engaged, increasing their strength and stiffness. Their analytical model, validated experimentally, offers a procedure for avoiding infill damage and improving seismic performance. These tests demonstrate that such methods render infilled RC frames more resilient against earthquakes.

2.3. Fiber-Reinforced Polymer (FRP)

FRP confined concrete elements' application has been explored by extensive experimental and analytical studies towards a more accurate prediction of the performance of these structures. Recently, the flexural behavior of high-strength thin reinforced concrete (RC) slabs strengthened with FRP laminates was evaluated using a 3D nonlinear finite elements analysis by Assad et al. (2022) [37]. Using experimental data, they first validated the numerical data, then they performed a parametric analysis by applying various FRP materials and various concrete strengths. The result indicated that the best material found to enhance the slabs' flexural capacity was carbon fiber-reinforced polymer (CFRP), while other materials' behavior had the same tendency. Al-Saawani et al. (2022) [38] developed an FE model with ABAQUS software simulating the debonding failures that occurred in FRP-strengthening beams by applying a cohesive zone model. They concluded that this analysis has the ability to accurately simulate the debonding failures and indicate the effect of parameters including the shear span-to-depth ratio and the spacing of the stirrups on the performance. The study provides an efficient FE modeling approach for analyzing CFRP-strengthened beams, potentially adaptable for other FRP types and strengthening configurations. The study by Naser et al. (2021) [39] has reviewed FEA approaches toward strengthening by applying FRP on reinforced concrete (RC) beams, focusing on essential parameters including the materials' simulation, bond–slip models as well as various load cases. The study has emphasized the need for applying cohesive zone models simulating the debonding phenomena. The study has found areas for future work, including simulating the long-term behavior and analyzing the fire resistance, as well as providing useful practical application recommendations. Fanaradelli and Rousakis (2020) [40] further advanced the analysis of FRP-confined concrete columns by applying pseudo-dynamic 3D FEA, together with advanced material models, including the Riedel–Hiermaier–Thoma (RHT) concrete model. In this work, a monotonic, as well as seismic (cyclic) axial load, analysis of columns was executed, and it exhibited an accurate capturing of the columns' experimental stress–strain behavior, as well as of the local concrete damage–FRP fracture interactions and accumulation. In addition, this work further explored the axial capacity and deformability of confined concrete through hybrid experimental–analytical approaches. It identified the most vulnerable regions of concrete–FRP damage initiation and offered recommendations for most critical local strain measurements on steel and FRP, verified by experimental results. Finally, rope confinement of concrete with pseudo-dynamic 3D FEA was developed and evaluated. Rousakis et al. (2008) [41] developed a strain-hardening Drucker–Prager-type model for FRP confined concrete, aiming at a more accurate prediction of concrete axial strains. Karabinis et al. (2008) [42] researched strengthening old-type deficient RC columns confined by FRP materials by applying the finite element analysis

(FEA) method, specifically by applying three-dimensional finite elements. In this work, Drucker–Prager type plasticity was developed for concrete behavior, while orthotropic lamina elements were utilized for the FRP material. They concluded that bar buckling may be significantly delayed with FRP confinement and also that it upgrades columns' mechanical behavior. Steel reinforcement detailing and section geometries may also have an effect on the distribution of confining stresses exerted by internal stirrups and an FRP jacket. The study highlights the explicit modeling of the FRP jacket, while their suggested parametric studies have the capacity to facilitate the retrofitting processes.

In conclusion, these studies (among others) highlight the advancement accomplished by the analytical and numerical analysis of FRP-strengthened concrete elements using FEA. They also address very essential issues such as debonding failures, the prediction of axial strain, and performance-under-load cases from monotonic and seismic up to fatigue.

2.4. Green Concrete and Other Composites

Material behavior in RCMs (Reinforced Concrete Models) is effectively captured through combinations of linear, nonlinear, and inelastic features as shown in [43–45]. Linear elastic models assume that concrete and steel are elastic materials whose states of stress and strain are related in direct proportion up to failure. This simplification is appropriate for initial design considerations and for structures experiencing low stress conditions in which material nonlinearity can be considered insignificant [46,47]. Nonlinear models provide a more advanced methodology by integrating behaviors including concrete cracking, yielding of steel reinforcement, as well as strain hardening and strain softening [48–50]. These models consider energy dissipation and dependence on the load history, making them essential for accurate analysis in high loading level, seismic actions, or an assessment of ultimate load-carrying capacity [51–53]. While nonlinear models capture some features of inelasticity, fully inelastic models more comprehensively explain permanent deformations and irreversible changes in material structure [43,54,55]. These sophisticated models are crucial for extreme loading, detailed seismic assessments, fatigue problems, and progressive collapse scenarios as defined by ASCE/SEI 41-17 and CEB-FIP Model Code [56,57]. By including inelastic properties, engineers can interpret the post-yield response of the reinforced concrete structure and develop more resilient and efficient structures. The approach to be chosen will then depend on the scope of the analysis, the importance of the structure, and the available computational resources, balancing simplicity and speed in linear models and accuracy with increased model complexity in nonlinear and inelastic models [58,59].

Green composites and green concrete have undergone extensive research recently. Kytinou et al. (2022) [60] explored RC beam-column joints reinforced by CFRP bars under cyclic load. In this study, full-scale experimental tests supported by a detailed FEA analysis simulated with ABAQUS software adopted a nonlinear concrete behavior model, as well as cohesive modeling, simulating the CFRP concrete bond. The CFRP-RC joint has a substantial capacity for energy dissipation. This aspect allows for further research even towards replacing, in some cases, conventional steel reinforcement with CFRP bars in earthquake-resistant construction. Guan et al. (2022) [61] compared the flexural properties of steel fiber-reinforced recycled aggregate concrete (SFRAC) beams using finite element analysis and experimental four-point bend tests. According to the ABAQUS computer program, nine specimens with varied parameters such as steel fiber percentage, recycled aggregate proportions, and concrete proportions have been investigated. It indicated the enhanced ductility of the SFRAC beams compared with plain concrete beams. Increased steel percentage and concrete proportions improved the capacities of the beams, but higher proportions of the recycled aggregate decreased the capacities. Luo (2022) [62] presented a technique called microstructure-free finite element modeling (MF-FEM) to describe, design,

and formulate fine particulate composites. The simplified procedure removes the need for accurate microstructure geometries, thus significantly minimizing complexity. The study proved that, considering the sufficiently small inclusion-to-Representative Volume Element (RVE) ratios, the composite properties do not depend on the inclusions' shape or size. Mortar et al. (2022) [63] performed a finite element analysis (FEA) using ABAQUS software to study geopolymer concrete-reinforced beams under blast loading. They used the Johnson-Cook damage model for analysis. The findings of the research showed that higher scaled distances were associated with a more elastic response, while shorter distances caused compressive and tensile failures. The research highlighted the need for further studies to investigate the blast resistance of geopolymer concrete in comparison to conventional materials, given the limited research available on its performance under blast loading. Earlier, Al-Osta (2019) [64] conducted a numerical study using finite element analysis via ABAQUS to investigate the response of reinforced concrete (RC) beams retrofitted with Ultra High Performance Fiber Reinforced Concrete (UHPFRC) under impact loading conditions. Experimental data were used for model validation under static loading conditions. The study investigated different strengthening modalities by simulating impact loads. The findings showed that three-side strengthening with UHPFRC resulted in a significant decrease in maximum deflection, and the addition of a 20 mm bottom layer significantly improved structural performance. The main contribution of the study is its provision of useful insights into the response of RC beams under extreme impact loading conditions through finite element simulations.

2.5. Section Summary and Implications Concerning Structural Retrofit Models

In the last couple of years, structural engineering has made significant advancements in terms of retrofit modeling and the development of new materials to further enhance the performance of concrete structures. Innovative materials such as textile-reinforced mortar (TRM), flexible PU seismic joints and flexible PU infill strengthening, fiber-reinforced polymer (FRP), and green concrete and other composites can significantly enhance the durability, sustainability, and performance of new and especially existing structures. The degradation of the infrastructure is being faced constantly with ever-growing events such as seismic activities and extreme loading conditions. Thus, the need for the development of new and effective strengthening methodologies has become important. The current trend toward sustainable construction precipitated an investigation into different materials and techniques. This state of the art focuses on the finite element analyses and modeling of these techniques, that will enable the accurate prediction and improvement of structural performance.

TRM is an advanced method for strengthening masonry and concrete. Several studies [26,27] have shown evidence of the effectiveness of TRM in enhancing flexural capacity and ductility. Accurate finite element models, specifically those with a focus on concrete damaged plasticity, may enable better predictions of improved structural performance using TRM for different load conditions. Flexible PU seismic joints and flexible PU infill strengthening are two innovative techniques to enhance the performance of reinforced concrete frames against earthquakes. The research work done by Vanian et al., 2024, Rousakis et al., 2021, and Akyildiz et al., 2021 [32–34], on polyurethane flexible joints (PUFJ) and fiber-reinforced polyurethane (FRPU) jacketing, respectively, points out a significant ductility gain and energy dissipation enhancement. These studies underline the need for developing new advanced 3D finite element modeling capable of capturing complex structural interactions. Information about the models is provided in Figure 1.

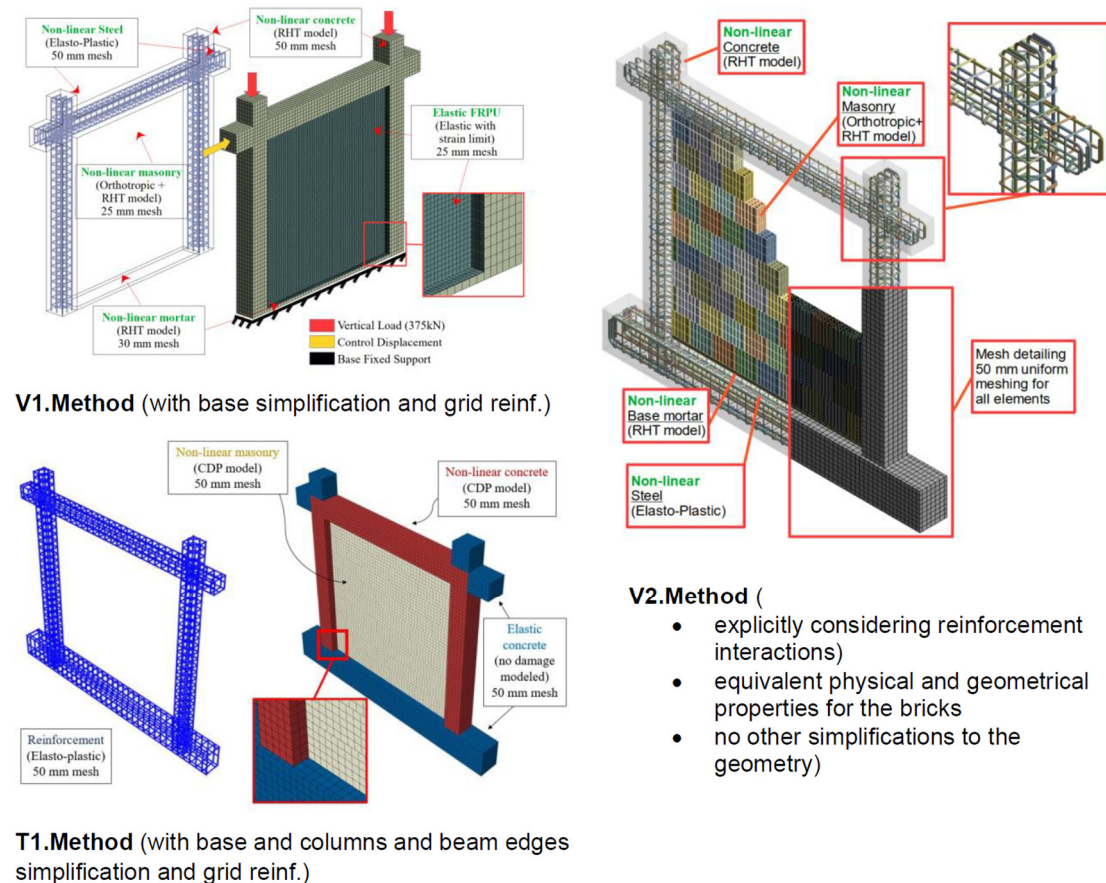


Figure 1. Detailed numerical modeling of RC structures for VF building structural investigation [32].

FRP is still in the forefront of research, considering several practical tests that were conducted [38,42] on the FRP strengthening of concrete beams and columns. The ongoing development of advanced models for predicting debonding failures and overall structural performance has accelerated the progress toward reliable structural design using FRP reinforcement. Recent research has focused on sustainable materials like green concrete and other composites. Studies [61,62] examined materials such as steel fiber-reinforced recycled aggregate concrete and fine-particulate composites. These advanced materials offer both ecological benefits and structural properties that can enhance performance. Finite element modeling techniques continue to evolve across all these areas—from microstructure-free modeling approaches to complex 3D simulations incorporating damage models. These techniques enable researchers and engineers to make accurate predictions about structural behavior and optimize designs. The general description and classification of retrofit models are given in Table 1.

The development of finite element modeling methodologies has allowed a more realistic prediction of complex structural response and interaction using performance-based models like the ones provided in the OpenSees framework, among others. Characteristic information for basic models for concrete and steel are provided in Appendix A—Tables A1 and A2. Such models become indispensable tools for the improvement of design and investigation of effectiveness for various strengthening procedures. While most of the challenges remain, especially regarding long-term performance and standardization of new materials and processes, the tendency of research here is encouraging. Future studies should aim more at bridging the gap between laboratory studies and practice, developing all-round design guidelines, and pushing the modeling effort toward a wider coverage of load conditions and material behaviors. Advanced materials and modeling method-

ologies will be significant in setting the future directions of structural engineering as the construction industry continues to move toward being more resilient and sustainable.

Table 1. Classification of recent research in retrofit modeling and innovative materials for concrete structures.

Category	Application	Key Modeling Techniques	Reference
Textile-Reinforced Mortar (TRM)	Masonry Strengthening	Multiscale FEM, Cohesive Elements	[27]
	Concrete Beam Strengthening	3D Nonlinear FEM, CDP Model	[26]
	Masonry Bond Behavior	Double Shear Tests, Bond–Slip Relation	[30]
	Seismic and Energy Retrofitting	Macro-modeling, Shell Elements	[28]
Seismic Joints and Infill Strengthening	Flexible Joints	PUFJ, FRPU, 3D Explicit Dynamics	[33]
	Infill Wall Protection	PUFJ, Mooney–Rivlin Model	[34]
	Dynamic Modeling of RC Frames	RHT Damage Model, PUFJ, FRPU	[32]
	Damage Reduction System	INODIS, Micro-modeling	[35]
Fiber-Reinforced Polymer (FRP)	Cellular Material Isolation	Single-Strut Elements, Nonlinear Springs	[36]
	Column Strengthening	3D FEM, Drucker–Prager Model	[42]
	Beam Strengthening	Cohesive Zone Model, CDP Model	[38]
	FRP-Confined Concrete	Strain-Hardening Drucker–Prager Model	[41]
	Pseudodynamic Analysis	RHT Model	[40]
	Thin RC Slab Strengthening	3D Nonlinear FEM, Cohesive Elements	[37]
Green Concrete and Other Composites	FRP Modeling Strategies Review	Various FEM Techniques	[39]
	Recycled Aggregate Concrete	Steel Fiber Reinforcement, CDP Model	[61]
	Fine-Particulate Composites	Microstructure-Free FEM	[62]
	Geopolymer Concrete	Johnson–Cook Damage Model	[63]
	Ultra High-Performance Concrete	CDP Model, Explicit Dynamic Analysis	[64]
	CFRP Bar Reinforcement	CDP Model, Surface-Based Cohesive Approach	[60]

3. Energy Renovation Models for VF Building Results

Energy renovation modeling has grown progressively more complex in its ability to address the complex challenge of building efficiency integrating renewable sources and overall regional-wide sustainability. Today’s methodologies converge physics-based methods with data-driven methods, covering a variety of analyses ranging from overall regional-wide energy models down to focused demand-and-consumption assessments, incorporating regional factors and approaches for integrating renewable sources. The available research depicts a clear movement from conventional methods of forecasting towards more complex hybrid methods incorporating a variety of factors, such as the behavior of the building, human interaction, economic impacts, and ecological impacts. Today, such models act as critical tools for policy makers, engineers, and stakeholders working on the planning of transition, the performance optimization of buildings, and achieving decarbonization goals on a scale ranging from single buildings to regions.

3.1. System-Wide Energy Models

Recently, Subramanian et al. (2018) [65] and Kaddoura (2022) [66] highlighted the collaboration between physics-based and data-driven modeling approaches for optimizing

energy systems, focusing on hybrid approaches like physics-informed machine learning. These studies emphasize the importance of optimization and control in enabling an efficient integration of renewable energy resources. The review article by Li et al. (2015) [67] presents pricing policies used in district heating (DH) networks with a focus on their importance in reducing CO₂ emissions as well as energy consumption. The paper categorizes the pricing components under connection fee, standing cost, and unit cost, and compares them to approaches adopted by regulated (cost-plus) as well as deregulated (marginal-cost) markets. They discuss issues related to joint cost allocation in combined heat and power plants, marginal cost, and review innovative pricing practices that can contribute to sustainable, fair, and competitive markets. DeCarolus et al. (2012) [68] address the transparency and reproducibility problems of energy economy optimization models, citing the lack of data and the risks posed by coding errors and hidden assumptions. Finally, they promote the use of open-source software as a way of solving the aforementioned problems, thus enabling improved energy policy-making. When talking of energy modeling issues, Pfenninger et al. (2014) [69] also call for interdisciplinary solutions, openness, and open-source. They address issues such as uncertainty, temporal resolution, and the representation of human behavior, and suggest new solutions for enhancing model applicability.

3.2. Regional Analysis Models

Fragkos et al. (2017) [70] provide a joint energy and economic modeling of the European Union's decarbonization targets. They conclude that a 40% reduction in greenhouse gas (GHG) emissions by 2030 is achievable with relatively limited macroeconomic consequences, including minor GDP losses of 0.4% by 2030. The study calls for electrification, renewables, and energy efficiency in addressing policy-related issues such as eliminating market barriers and changing consumer behavior. Hall and Buckley (2016) [71] provide a systematic review of UK energy system models, classifying them by purpose, technological detail, and mathematical form. Their typology improves model transparency and enhances model transparency and supports decision-making by clarifying model purposes, structures, and applications, potentially aiding policy design. Ekonomou (2010) [72] presents a study on the structure and methodology adopted in forecasting long-term energy consumption in Greece using Artificial Neural Networks (ANNs). To forecast Greek energy consumption for the years 2005–2008, 2010, 2012, and 2015, the researcher developed an ANN model adopting the multilayer perceptron (MLP) structure. The results indicated a very high accuracy level in the ANN model, with an estimated 2% error rate between predicted and actual values of energy consumption. When looking at energy systems in the developing countries, Urban et al. (2007) [73] determine dominant characteristics, such as low levels of electrification, predominance by informal economies, and reliance on traditional biomass, which are typically not addressed by current models. The authors state that it is important for these models to be developed because they give better predictions of future energy conditions and the resultant environmental impacts. In Denmark, Lund and Mathiesen (2009) [74] illustrate the viability of a 100% renewable energy system in 2050 based on biomass, wind, wave and solar integration. They highlight energy efficiency, fossil fuel substitution, and system design integration. While their analysis focuses on Denmark, these findings may have implications for global energy transformations.

3.3. Demand and Consumption Models

A large-scale survey by Nacht et al. (2023) [75] overviews various approaches toward residential energy consumption in domestic settings. These include causal modeling, energy system modeling, mobility modeling, power efficiency modeling, and energy consumption modeling. The study examines approaches implemented across building

envelopes, heating, ventilation, air-conditioning (HVAC) systems, appliances, building management systems, and generation technologies, including solar power (photovoltaics) and micro-scale wind power. The publication also explores future business models, urban energy modeling, and local climatic data. It presents useful findings for researchers, policymakers, as well as industry experts committed to achieving maximum efficiency in energy consumption in buildings. Rebelatto and Frandoloso (2020) [76] carry out extensive analysis of methodological approaches and application areas related to energy modeling, highlighting their importance for building, as well as dwelling energy utilization, while pointing toward the relevance to Sustainable Development Goal 7 (Affordable and Clean Energy). The paper overviews various approaches, including Building Energy Models (BEM) and Urban Building Energy Models (UBEM). Further, it focuses on engineering, statistics, as well as intelligent approaches, while considering occupant behavior as a factor in power utilization. It overviews application areas, quality assessment of models, simulation models, and future issues, while emphasizing the need to unify efficiency approaches with human behavior when deriving models to achieve accurate predictions. Suganthi and Samuel (2012) [77] overview various approaches to forecasting electricity power demands, from traditional approaches to recent approaches, including artificial neural network, as well as fuzzy logic. They support unifying intelligent models to enable efficient management for achieving power utilization with maximum efficiency. The Swan & Ugursal (2009) [78] paper examines both bottom-up building energy use models as well as models that are top-down. The top-down method applies energy use analysis by considering macroeconomic indicators, while the bottom-up approach estimates energy utilization by extrapolating data from single individual dwellings. The paper provides a critical analysis of each technique, focusing on their strengths, shortcomings, and purposes, along with a review of models reported in the literature.

3.4. Renewable Energy Integration

Dagoumas and Koltsaklis (2019) [79] review models used for incorporating renewable energy sources (RES) into generation expansion planning (GEP), a process that leads to emissions reduction and decarbonization. The paper classifies GEP models into optimization models, equilibrium models, and other models, analyzing their strengths and limitations, in addressing the complex technological, economic, as well as environmental challenges of GEP. Through its systematic review of cutting-edge methods, the paper makes an important contribution to policymakers and researchers, informing future strategic choices and research in sustainable energy planning. Ringkjøb et al. (2018) [80] summarize energy models designed for high shares of renewables, emphasizing challenges related to representing variability and highlighting the importance of including consumer participation in models. They promote increased transparency and increased sectoral coordination in future models. In the case of Great Britain, Pfenninger and Keirstead (2015) [81] investigate future plans for the blending of renewables, nuclear, and fossil fuels. Cost, emissions, and energy security trade-offs are demonstrated with grid-scale storage being key to reaching high renewable levels at low cost. Kaldellis et al. (2013) [82] analyze Greek people's attitudes toward renewables and identify broad support for wind, solar, and hydro technologies despite aesthetic, noise, and land use concerns. The authors indicate that exposure to renewable systems increases public support.

3.5. Methodology and Tools

The methodology and tools of open data play a crucial role in energy research, according to Pfenninger et al. (2017) [83]. They emphasize leveraging established models and data sets to foster collaboration, transparency, and policymaking. They claimed that energy

research lacks the openness compared to other disciplines, and they suggested the need to address ethical and practical issues. Earlier, Connolly et al. (2010) [84] listed the computational tools for renewable energy integration, analyzing their capabilities for specific objectives. They claimed that no single tool is universally ideal, advising users to choose tools for their goals while considering factors like time resolution and technology coverage.

3.6. Feasibility and Planning

Heard et al. (2017) [85] consider the feasibility of powering the grid by 100% renewables, identifying areas little recent work has covered, e.g., poor simulation of the grid, and poor simulation demands. They argue that the burden of proof for excluding non-renewable low-carbon technologies, such as nuclear power, is high and not sufficiently justified. Leopold (2016) [86] provides an orderly overview of system dynamics (SD) models for energy issues for the period 2000–2015, whereby studies fall under four themes, that is, fossil fuels, power from renewable, electricity systems, and other energy sources. The overview includes applications of SD toward forecasting reserves, the analysis of market dynamics, the analysis of implications from policy, and support toward decision-making during power system changes. The review provides key findings, summarizes methods in tabular form, and gives perspectives on future research directions, particularly energy system transition, renewable energy integration, and modeling for policy and investment decision-making. Connolly et al. (2016) [87] deal with transforming the EU into a 100% renewable energy system by 2050, emphasizing sector coupling for flexibility and the economic benefit of renewable investments, including the generation of jobs. Bhattacharyya and Timilsina (2010) [88] provide an analysis of various models of the developing-country relevant energy system, including bottom-up optimization, bottom-up accounting, top-down econometric models, hybrid models, and electricity system models. The paper points out that these models do not consider fundamental developing-country attributes, including the coexistence of informal economies, indigenous fuels reliance, and the inequality of both the urban and the rural areas' accessibility of power, perhaps rendering recommendations by the policies incomplete. Stressing the necessity of improved modeling approaches, the study singles out bottom-up accounting frameworks such as LEAP as more flexible and invites greater efforts towards more accurately capturing the interplay between energy and environmental factors, economic development processes, and climate change impacts in these frameworks. In general, these works illuminate the complexity of energy system modeling, evaluate their strengths and weaknesses in developing-country contexts, and highlight the need for improvements to better inform energy, environment, and climate policies.

3.7. Section Summary and Implications Concerning Energy Models

This current review of energy system modeling methodologies raises several challenges. One of the more noticeable general trends is a shift toward more complicated and multi-sector modeling, which is motivated in part by the requirement to study systems with high levels of variable renewable energy. Models are becoming more advanced in their capacity to provide the necessary temporal and spatial precision for representing renewables variability, energy storage, and grid restrictions.

However, Pfenninger et al., 2014 [69] observed that this increased sophistication from several perspectives results in greater challenges, such as computational burden, input data, and model transparency. The literature available emphasize an imbalance between top-down economic models and bottom-up engineering approaches; however, recent attention appears to shift towards hybrid models that incorporate components of both. Top-down approaches are likely to capture macro-economic effects, but the bottom-up

approaches provide the technological depth required to evaluate individual transitions. Indeed, Bhattacharyya and Timilsina (2010) [88] argue that many contemporary models cannot capture crucial features of the energy systems of developing countries and therefore require tailored analyses. A common thread running through these is the need for models to be flexible, adaptable, and context-sensitive, particularly for application in developing countries. DeCarolís et al. (2012) [68] make a strong case for repeatable analysis in energy-economy optimization models, while Pfenninger et al. (2017) [83] strongly advocate open data and software in energy research. All these different efforts towards openness contribute to trusting model results and the collaborative improvement of modeling tools. The feasibility of high renewable energy scenarios is a topic of broader debate, although not directly addressed in these publications. While studies like Connolly et al. (2016) [84] project the technical feasibility of 100% renewable energy systems in Europe, others like Heard et al. (2017) [85] argue that proposed 100% renewable electricity systems fail to meet key feasibility criteria. This disagreement underlines the relevance of transparency in assumptions and methodologies during energy system modeling. Analysis reveals an increasing interest in embedding human behavior and social influences within energy modeling frameworks. Traditional techno-economic approaches are thus supplemented with insights from behavioral science that better represent consumer decisions and societal transformations. This is also underpinned by the increased application of agent-based modeling approaches, including the inclusions of behavioral variables within system models. Recent advances in artificial intelligence (AI) and machine learning have reached a point where they influence energy system modeling. For example, the work of Ekonomou (2010) [72] uses the capacity of artificial neural networks in order to forecast long-term energy consumption. Further works investigate the use of AI for demand forecasting and system optimization. Those techniques enable the handling of larger datasets and the extraction of complex nonlinear dependences within energy systems. Literature highlights that energy storage will play a critical role in the development of high-renewable energy scenarios. New modeling advances the representation of different storage technologies and their operating characteristics. However, longer-duration and seasonal balancing remains one of the challenging factors in effective modeling. Increasingly, there is recognition that broader sustainability indicators beyond the simple cost and emissions profile are required. Newer models indeed consider land use, water consumption, and social impact, among other factors. The summary of the models can be found in Table 2.

Table 2. Classification of recent research in energy systems modeling and analysis approaches.

Category	Application	Key Modeling Techniques	Reference
System-Wide Energy Models	District Heating Systems	Cost-plus pricing, Marginal cost pricing, CHP allocation	[67]
	Energy Economy Optimization	Open-source frameworks, Reproducible analysis	[68]
	Energy System Challenges	Temporal-spatial modeling, Uncertainty analysis	[69]
	Process Systems Engineering	Computational, Mathematical, Physical models	[65]
	Simulation and Optimization	Physics-based, Data-driven, PIML approaches	[66]

Table 2. Cont.

Category	Application	Key Modeling Techniques	Reference
Regional Analysis Models	Developing Countries	Bottom-up approaches, Traditional fuel modeling	[73]
	European Union Systems	PRIMES model, GEM-E3 model	[70]
	UK Energy Systems	Purpose-based classification, Mathematical approaches	[71]
	Danish Energy System	Hour-by-hour simulations, Renewable integration	[74]
	Greek Energy System	Artificial Neural Networks, Time series analysis	[72]
Demand and Consumption Models	Residential Energy Use	Top-down methods, Bottom-up approaches	[78]
	Demand Forecasting	Time series, Regression, Econometric models	[77]
	Residential Approaches	Causal modeling, Energy efficiency modeling	[75]
	Building Energy Systems	BEM, UBE, Behavioral modeling	[76]
Renewable Energy Integration	Generation Planning	Optimization, Equilibrium models	[79]
	Variable Renewables	High-resolution modeling, Storage integration	[80]
	Great Britain Power Sector	Cost-emission trade-offs, Storage impacts	[81]
	Public Acceptance	Survey analysis, Statistical methods	[82]
Methodology and Tools	Computer Tools Review	Integration assessment, Scenario analysis	[84]
	Open Data Advocacy	Transparency frameworks, Collaborative methods	[83]
	System Dynamics	Fossil fuel dynamics, Market behavior modeling	[86]
Feasibility and Planning	100% Renewable Systems	Technical feasibility assessment, Economic analysis	[85]
	Smart Energy Europe	Sector coupling, System integration	[87]
	Energy System Models Review	Comparative analysis, Framework assessment	[88]

4. Forestry Models

Forest modeling has undergone significant improvements in the last couple of years with the use of complex computational methods for the biomechanical behavior of trees, their stability, and their relationship with the environment. The use of the finite element method (FEM) has been a key tool for tree response under different forms of environmental stress, such as wind, and has encouraged extensive research on root, branch, and urban tree policy. There has been extensive peer-reviewed research, suggesting a significant shift from simple mechanical models towards complex three-dimensional simulations with root-soil coupling, architectural tree crown traits, and boundary conditions. Today's forestry models also include a variety of methodologies, including terrestrial laser scanning (TLS), computational flow and heat transfer (CFD), and quantification of tree structure models (QSMs), and hence, there has been a holistic approach towards understanding tree behavior under natural and urban environments.

4.1. State of the Art on Forestry Models

Recently, Zhang (2024) [89] presented a nonlinear physics-based formulation (validated by FEM) simulating massive tree deformations by hurricane-force winds (45 m/s). In terms of a sympodial branching system, coupled by aerodynamic damping, the formulation simulated distributions of stresses and self-similar curvature profiles along branches, together with exponential drag reduction. Finite difference validation confirmed the model's accuracy. In revealing stress hot spots at the trunks and first-order branches, the study has limitations due to two-dimensional formulation and simplified leaf models, together with assumption of isotropic materials.

Karapetkov et al. (2023) [90] study the influence of inertial forces on car passengers while frontal collisions happen against static obstacles utilizing FEM with ABAQUS Explicit solver. A detailed simulation has been developed, including six degrees of freedom, tire rigidity, suspension stiffness, and various forces acting on the car. Both regimes—the impact and the post-impact—were simulated, indicating dominance by the translational inertial forces during the impact phase, while centrifugals together with Coriolis forces play a leading role in the post-impact phase. Inertial force magnitudes are greatly influenced by angular velocity around the vertical axis. Seat belts greatly maintained passengers' stability, preventing injury during collisions. The analysis successfully simulated maximum inertial force magnitudes, while exposing detailed information about passenger behavior inside the car cabin. The FEM approach proves highly accurate in simulating impact scenarios and provides deeper insight into occupant protection. Although the study focuses primarily on frontal collisions, the approach has the potential to be generalized to other types of collisions and vehicle models. The findings hold important implications for vehicle safety system concepts and crash test protocols, offering substantial potential to reduce collision-related injuries.

Coleman et al. (2022) [91] conducted a review of 429 papers discussing the structural attributes, function, and value of urban street trees. The paper documents increased research from the late 1990s, focusing on ecosystem functions, cooling, waste utilization, and environmental equity. Contributions are mostly from North America, although research output from Asia and Europe has been steadily increasing since 2010. The review identifies persistent gaps in bridging biophysical drivers and human drivers, determinants of tree longevity and development. The authors advocate for coupled studies, economic assessment, and financial impediment identification toward managing forestry in the city. The synthesis provides findings for scholars, urban planners, and decision-makers, maximizing benefits from the city's street trees.

Lee et al. (2021) [92] introduced an earthquake-resistant curtain wall system utilizing displacement control fasteners, substantiated by extensive tests and a three-dimensional (3D) finite element analysis. The study compares the seismic performance of conventional and seismic curtain wall systems under various directional load cases using FEM simulations to analyze stress distributions and identify potential failure points. The proposed curtain wall system outperformed conventional designs by significantly reducing stress transmission and enhancing seismic resilience. In addition, the system accomplished significant thermal insulation, air tightness, watertightness and wind load-bearing resistance. The study documents FEM analysis necessity while creating curtain wall earthquake-resistant systems. It emphasizes movable fastener merits, modular inter-story separations, toward earthquake-induced stresses minimization.

The study by Moravčík et al. (2021) [93] bridged finite element analysis (FEM) and terrestrial laser scanning (TLS) to simulate static behavior, hazard, and tree failure in an urban environment. A *Tilia cordata* Mill. tree was modeled as a beam structure by means of the application of 44 variable cross-sections with geometrical data derived from TLS.

The internal decay was incorporated through acoustic tomography. A structural analysis conducted using SCIA Engineer software (version 20) evaluated the tree's response to self-weight, foliage, and wind loads showing maximum displacements, alongside maximum stresses, of 280.4 mm, +8.8 MPa (tensile), and −8.9 MPa (compression), respectively. These values were below the safe threshold, showing minimal hazard probability. Although the study provides an accurate platform for tree stability analysis, it emphasizes the need for further experimental validation and computer-aided design generation processes, alongside root–soil interaction simulations.

Dounar et al. (2020) [94] simulated the chestnut tree branch's biomechanical failure by means of complex finite element analysis (FEA). The study integrated three-dimensional (3D) modeling and nonlinearity, alongside both isotropic and orthotropic material models to analyze stress distributions due to crown masses varying under wind pressures. The analysis suggested that the branch acted as an “equal-strength console” with stress concentrations distributed along its length rather than at the trunk–branch junction. Nonlinear modeling predicted a 33% increase in displacement and a 35% rise in stress compared to linear approaches, showing the relevance of accounting for geometric nonlinearity for accurate prediction. The study generally provides insights toward bionic design alongside urban forestry but highlights the need for dynamic analysis and improved crown simulation in future works.

Jackson et al. (2019) [95] further advanced the field of TLS modeling by utilizing FEM coupled with quantitative structure models (QSMs) created by TLS. Broadleaf tree models with power-law profiles simulated under wind forces were created utilizing ABAQUS software. Dynamical measurements of strain had excellent correlation ($R^2 > 0.79$) with experiment data, whereas predictions of the critical velocities exhibited lower accuracy. The approach established the possibility of coupling FEM with high-resolution TLS data but also raised issues with scalability and the critical need for accurate material property data.

Jian et al. (2018) [96] evaluated the performance of tree canopy windbreaks using computational fluid dynamics (CFD) considering the geometry, configuration, and porosity of the canopy. In conducting this assessment, canopy porosity—defined numerically and informed by previous wind tunnel data—played a crucial role; notably, lower porosity values did not necessarily ensure effective wind reduction near ground level. The study also found that simplified canopy representations, such as cylindrical models, may be sufficient for practical applications. While this work offers a solid foundation for future research on windbreak design, upcoming studies will need to incorporate more complex canopy structures and enhance turbulence modeling for greater accuracy.

This experimental–numerical study by Aly et al. (2013) [97] evaluated tree–wind relations for trees integrated into vegetated building envelopes. Through miniature-scale channel tests, as well as full-scale Wall of Wind tests, it indicated that shape changes caused by increased wind velocity significantly reduced the wind loads on trees. Previous FEM analyses cited in the study suggested that geometric factors significantly affect tree response to wind, highlighting implications for support system design. The authors recommended future testing in turbulent wind conditions to capture effects not addressed under the smooth-flow conditions used in the Wall of Wind experiments.

Mickovski et al. (2011) [98] performed a finite element analysis (FEA) to analyze the reinforcement mechanisms provided by roots. They established two dimensional (2D) and three dimensional (3D) models in Plaxis and Diana software to simulate rooted and unrooted soils under direct shears, while considering elastic–plastic soil behavior and linear elastic roots properties. The presence of roots increased the shear strength of soil, with multi-rooted models showing significantly greater resistance compared to single-rooted configurations. Based on the study, the three-dimensional models predicted higher max-

imum stresses and more realistically represented root–soil interactions compared to the two-dimensional models. Laboratory tests also agreed with the simulations, showing increased ductility and shearing strength by rooted samples. Concluded, the study highlights the need for improved data on root properties, consideration of soil hydrological conditions, and validation through field measurements to advance vegetation-based soil stabilization design.

In this study, Wang et al. (2017) [99] explore optimizing mechanical harvesters for various trained fruit tree types using FEM to model their dynamic responses to shaker excitations. Three-dimensional models of spindle, open center, and vertical plane trees were created in Pro/Engineer and imported into ANSYS for analysis. Modal and harmonic response analyses examined tree responses to reciprocal, orbital, and multidirectional shaker excitations. The results indicated that tree morphology greatly influences natural frequencies and mode shapes, with resonance frequencies ranging from 7 to 20 Hz. The optimal excitation method varied by tree type: multidirectional excitation at 13.5 Hz was most effective for spindle trees, while orbital excitation at 12.0 Hz yielded the best results for open center trees. The study demonstrates FEM's potential for optimizing harvester designs, allowing for efficient processes without extensive physical prototyping. However, limitations remain due to simplifications of tree structures and material properties, which can lead to deviations from actual behavior. Future research should incorporate damping, soil–root interactions, and more detailed modeling to improve the reliability and applicability of these findings.

James et al. (2018) [100] conducted an overview of recent progress in tree biomechanics, considering mechanical response to wind and recent advancements toward tree form and branching. The main findings suggested that architectural variation in branching patterns and tree form play a more critical role than material properties in governing mechanical behavior. Traditional concepts based on stress were challenged by recent findings that emphasize the adaptive, stimulatory role of strain. Advances, such as optical measurements of strain, gave detailed data regarding strain distribution. The study also noted subtle patterns of wood fibers intertwining near branching attachments, essential for strengthening. Authors advocate for dynamic, strain-mediated models that incorporate architectural structure, branching behavior, and adaptive growth, with implications for hazard assessment and forestry management.

Sagi (2016) [101] examined tree stability due to wind, considering trenching influences, and root–soil interaction. By correlating field tests on mature Norway spruce with wind tunnel experiments on saplings, the study performed a Winkler foundation analysis coupled with a cantilever beam analysis. The findings highlighted the essential role of root–soil interaction in stability, with load transfer strongly dependent on soil type. Aerodynamic damping was found to increase linearly with wind speed, reaching levels three to four times higher than structural damping. The effects of trenching differed markedly between frictional (sand) and cohesive (clay) soils. The study contributes to tree stability modeling with implications for forest management, emphasizing the integration of soil parameters into predictive frameworks.

Manoso and Castro-Gomes (2015) [102] critically analyze green wall systems, providing a comprehensive review of their classification, construction methods, and technological innovations. Green walls are categorized into green facades—comprising direct and indirect systems—and living walls, which include continuous and modular systems. Their analysis outlines key system components, including structural support, growing medium, vegetation types, drainage systems, and irrigation methods. Innovations, including the application of light materials, increased retaining capacity, improved drainage capacity, and the minimization of water and nutrient consumption, are discussed. There is a growing

preference for modular systems due to their ease of installation, simplified maintenance, and reduced need for replacement. Authors also point out the eco-friendly and economic benefits of these systems, including assessments of life cycles, that consider, among others, material use, and climate and plant species. They advocate further studies toward increased geometrical variability, and an increased application of recycled materials and local vegetation. Assessment is presented as an essential tool for planners, researchers, and practitioners involved in sustainable architecture and urban development.

Yang et al. (2014) [103] conducted a finite elements simulation of tree uprooting that incorporated sequential root breakage. ABAQUS software, together with three-dimensional (3D) models, were used to represent the architectural description of the roots, soil, and continuum damage mechanics (CDM)-based failure law for roots. Validation using tree-pulling tests on *Pinus pinaster* indicates good agreement between simulated data and experimentally recorded force-displacement data. The results highlighted that anchorage strength is influenced by the mechanical property of the roots, while thick lateral roots play an essential role. A limitation of the model was the overestimation over initial stiffness suggesting a need for improved modeling of soil–root interactions. The study contributes to advancing research in tree anchorage, forestry management, and risks assessment due to wind.

James et al. (2014) [104] conducted an extensive review of biomechanical studies on trees, with a focus on dynamic analysis approaches and particular attention to open-grown trees typically found in urban environments. The study emphasized the crucial role of tree form and morphology in dynamic wind responses, which were found to be more influential than the material properties of the tree. Simple models disregarding branch dynamics were found inadequate, while multimodal and finite elements presented an accurate description of tree dynamics. The findings highlighted central contributions of branch sway in influencing tree stability, dynamic amplification factors (DAF), as well as processes of nonlinear damping. The study highlighted the need for further research regarding wind loads, torsion forces, and pruning strategies to mitigate wind-induced damage, supporting the use of sophisticated models for urban forestry management and hazard assessment.

Crespi et al. (2013) [105] conducted an examination of the aerodynamic load experienced by trees installed on the balconies of skyscrapers, using both wind tunnel experiments and finite element method (FEM)-based simulations. Across various test scenarios, the measured forces were lower than predicted, and no failures were observed during the experiments. FEM predictions closely matched the experimental results, highlighting the critical importance of accurately estimating drag coefficients in the calculations. The study underscores the significance of evaluating wind effects on balcony-installed trees for the structural safety of high-rise buildings, particularly in hurricane-prone regions.

Tankut et al. (2014) [106] describe finite element analysis (FEM) application in the design of furniture, wood products, and structural building elements. The paper describes the FEM capabilities, such as modeling intricate wood products using beam and spring elements and performing both linear and nonlinear analyses. The ANSYS software for primary FE analysis and IDEAS for 3D modeling are mentioned. The paper highlights that accuracy in simulation relies on the proper simulation of wood orthotropic behavior, alongside the semi-rigid joint behavior. The FEM is capable of simulating both static and dynamic load cases, as well as accurately predicting stress distributions and deformations, particularly when validated against experimental results. Nevertheless, accurately simulating the complex behavior of wood remains challenging, particularly for intricate 3D models, which also require significant computational resources. The paper concludes that FEM is

a powerful and efficient tool in wood product design, with the potential to transform the field by enabling innovative, cost-effective, and optimized solutions.

Raunonen et al. (2013) [107] introduce an automatic method toward the generation of accurate shapes of 3D trees from terrestrial laser-scanned data. Their approach reconstructs tree geometry using small surface patches and models the structure with interconnected cylinders. The method captures detailed branching and trunk architecture, enabling fast, scalable, and accurate tree analysis. It is especially effective for larger woody parts, though fine branches may be less reliable due to scan limitations. This tool supports forestry applications like biomass estimation and structural analysis. However, foliage is not included in the modeling process.

Chave et al. (2009) [108] aggregate extensive datasets toward wood attributes—including density, hydraulic conductance, mechanical, and chemical composition—toward proposing the concept of a “wood economics spectrum” (WES), which relates these attributes to plant performance and resource-use strategies. The authors identify key trade-off in the wood traits, for the attributes of the datasets, and propose that WES integrates these traits with broader aspects of plant ecology (among others growth, mortality, and nutrient cycling). They recommend adding wood features into Dynamic Global Vegetation Models (DGVMs) to improve the accuracy of climate change projections. Finally, they emphasize that for improving the forest understanding and global processes, more comprehensive datasets and models alongside further research are needed.

The study by Moore and Maguire (2008) [109] examines the dynamic behavior of twenty year old Douglas-fir trees under wind load using finite element simulation. Unlike previous models that treated branches as discrete masses, this study modeled them as cantilever beams, improving predictions of natural frequency, particularly in trees with large crowns. Three trees were analyzed using detailed measurements and ANSYS software under various loading scenarios. Results showed that branch oscillations significantly enhanced structural damping, especially with lower stiffness. The study highlights the importance of accurately modeling branch architecture and identifies the need for better data on branch properties, refined stem modeling, and aerodynamic considerations. These insights support improved forest management and tree breeding for wind resistance.

Hu et al. (2008) [110] developed two finite-element tree models (realistic and symmetric) simulating tree swaying in a windy field, both considering fluid–structure interaction (FSI) and vortex-induced vibration (VIV), which were analyzed under leafless and leaved conditions. The main findings indicate that asymmetrical material properties lead to complex, looping tree swaying, while the presence of leaves enhances the aerodynamic force and increases swaying primarily along the wind direction. The simulations demonstrate that branch interactions play a crucial role in preventing resonance-induced swaying. The study uses a simplified representation of leaves through a virtual shell and does not explicitly incorporate root–soil dynamics, which may limit the model’s realism in capturing full tree–ground interaction. This work contributes to the field of tree biomechanics by offering insight into tree stability under wind loading, with potential implications for biomimetic design and forestry management

Dupuy et al. (2007) [111] developed an extensive FEM considering realistic root system architecture, together with soil mechanics. The study emphasized that soil cohesion had significant implications for uprooting resistance and noted that simulated anchorage forces tended to be overestimated, likely due to assumptions such as rigid root–soil interactions. Although the model successfully visualized root–soil failure interactions, the authors acknowledged limitations such as the absence of anisotropic root material properties and the lack of time-dependent soil behavior in the simulations.

Sellier et al. (2006) [112] developed a finite-element model to investigate how crown architecture affects tree oscillations and associated damping mechanisms. The models accurately simulated swaying frequencies and revealed that aerodynamic drag from needles accounts for approximately 80% of total damping. Simplified crown models that reduced architectural complexity tended to overestimate swaying frequencies by up to 20%. Future extensions of the model include coupling with wind flow and plant growth models and improving realism through explicit consideration of root–soil interaction.

Clair et al. (2003) [113] examined the behavior of buttressed trees under bending stresses by field experiment as well as beam modeling. The results suggested that under minor stresses, the buttresses exhibit linear and elastic behavior. However, the sides of the buttresses are significantly more vulnerable to shear and tangential stresses. These findings challenge the constant stress hypothesis, suggesting that stress distribution during buttress development is not always steady or uniform. The study also emphasizes how the buttress's precise form influences its mechanical behavior.

4.2. Section Summary and Implications Concerning Forestry Models

In the field of structural engineering and biomechanics, the finite element method (FEM) has emerged as a crucial tool for analyzing complex biological structures such as trees. The application of FEM to tree modeling presents a unique set of challenges and opportunities, primarily due to the intricate and variable nature of tree morphology. Three distinct approaches to FEM modeling of trees (see Figure 2), each representing a different level of abstraction and computational complexity, are proposed based on an extensive literature review, presented in a previous subsection, and the tabular summary can be found in Table 3.

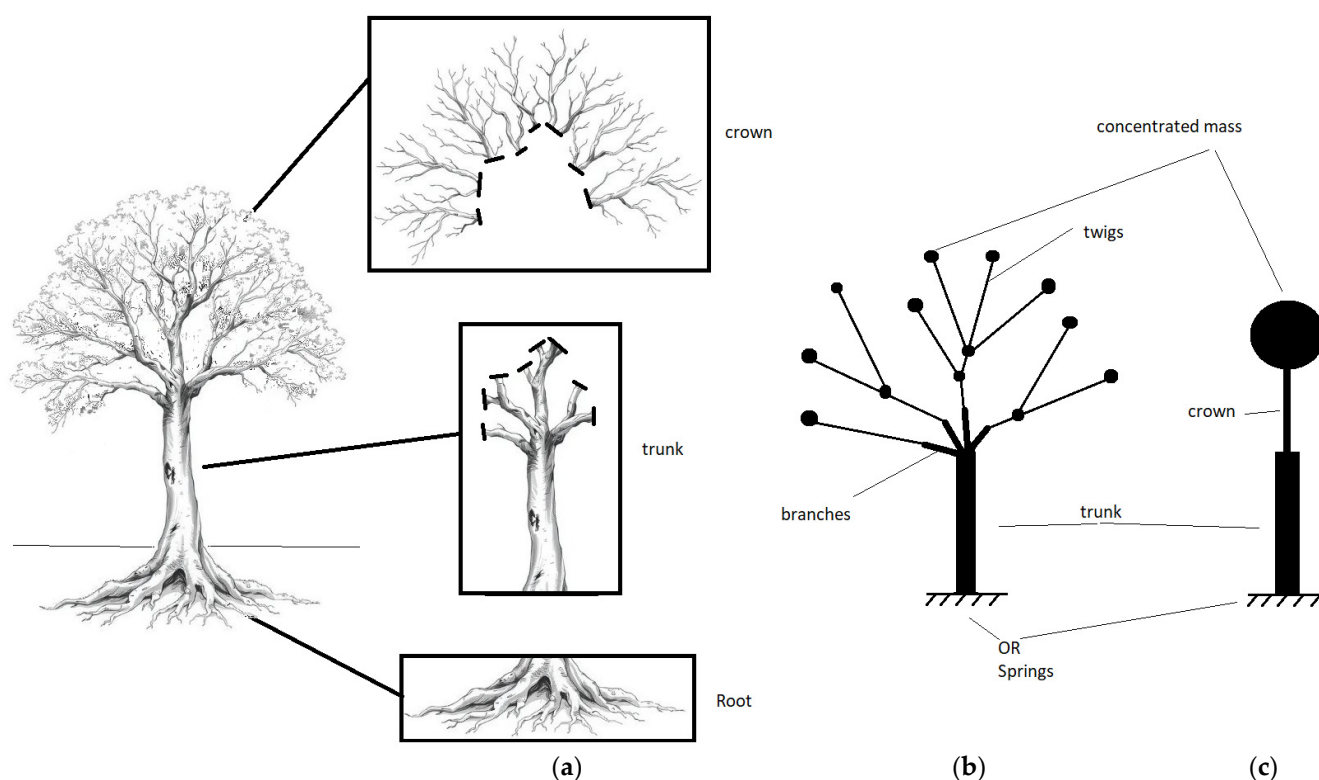


Figure 2. Finite element method (FEM) modeling approaches for tree structures, showing increasing levels of abstraction from left to right. (a) High-fidelity 3D model. (b) Simplified branch-mass model. (c) Equivalent two-element model.

Table 3. Classification of key forestry modeling and analysis approaches.

Category	Application	Key Modeling Techniques	Reference
Static Tree Analysis	Single Tree Risk Assessment	- 3D laser scanning - Acoustic tomography - Beam structure FEM	[93]
	Biomechanical Structure Analysis	- 3D modeling - Linear/nonlinear FEA - Isotropic/orthotropic materials - Strain gauge measurements	[94]
	Buttressed Tree Analysis	- Beam theory modeling - Cross-sectional analysis	[113]
Wind-Tree Interaction	Dynamic Wind Response	- TLS-based modeling - QSM generation - Dynamic FEA	[95]
	Large Deformation Analysis	- Symptodial branching patterns - Nonlinear PDEs - FDM with Newton–Raphson - Wind tunnel testing	[89]
	Building-Integrated Trees	- Full-scale experiments - Multi-scale analysis - Porous media approach	[97]
	Windbreak Performance	- CFD simulation - Modified k-ε turbulence	[96]
Root System Models	Soil–Root Interaction	- 2D/3D FEM - Mohr–Coulomb soil model - Direct shear simulation - Root breakage modeling	[98]
	Tree Stability Analysis	- Continuum damage mechanics - ABAQUS/Explicit - Winkler foundation model	[103]
	Foundation Effects	- Strain gauge monitoring - Dynamic analysis - 3D FEM	[101]
	Root Architecture	- Automatic mesh generation - Root–soil coupling	[111]
Tree Dynamics	Branch Motion	- FEM with beam elements - Asymmetric properties - VIV and FSI analysis - Timoshenko beam elements	[110]
	Aerial Architecture	- Modal analysis - Direct time integration - Branch cantilever modeling	[112]
	Douglas-fir Behavior	- Time domain analysis - Spectral analysis	[109]
Biomechanical Review	Dynamic Analysis Review	- Multi-modal analysis - Form and morphology focus - Damping mechanisms - Strain-based modeling	[104]
	General Biomechanics	- Optical measurement - Branch attachment analysis	[100]
Applied Analysis	Wood Material Properties	- 3D solid modeling - Orthotropic properties - Joint behavior analysis - Pro/Engineer modeling	[106]
	Fruit Tree Harvesting	- SOLID186 elements - Harmonic response analysis - Load cell measurements	[99]
	Wind Forces Assessment	- Construction stage analysis - FEM validation	[105]
Impact Analysis	Vehicle–Tree Collision	- 6-DOF modeling - ABAQUS/Explicit - Inertial force analysis	[90]

The most detailed representation, as illustrated in model (a), is a high-fidelity 3D model. This methodology employs LIDAR (Light Detection and Ranging) data to capture the tree geometry at high resolution [107]. The resultant model comprises detailed trunk architecture, branching patterns, root systems (primarily in experimental configurations where root access is feasible) and foliage elements. However, the generation and manipulation of such models requires substantial computational resources and processing time, due

to big data. These high-fidelity models utilize specialized databases—including the Forest Inventory and Analysis Database [114], the Global Wood Density Database [115], and Wood Handbooks [116]—to characterize the heterogeneous material properties throughout the tree structure.

For further simplification, model (b) may be considered as an intermediate model between information and computational efficiency. A tree in this model may be visualized as a system of connected lines and point masses. In other words, there would be one main vertical line, at times with inclining lines representing the trunk and secondary lines accounting for the major branches and tertiary lines for the smaller ones or even twigs. One crucial feature included is that of the distributed masses, represented by the black circles at the terminus of the branches. These masses have important implications for obtaining precise transient analyses, especially when the response of the tree is tested for dynamic forces due to wind or seismic excitations. This sort of approach to modeling is based on the work by James et al. [104], who provided the basic infrastructure necessary for developing such effective but simplified models.

The most abstracted representation model reduces the tree to its very basic elements. This highly simplified model consists of a single vertical line, but slanted lines can be employed for the trunk, a thinner line at the top for the crown, and a large black dot that represents the overall mass of the entire crown system (model (c)). Although this may be a somewhat over-simplified model, it nonetheless serves a major role in large simulations or situations when speed of analysis is important. Such an equivalent mass on the crown can thus be justified based on several items in the literature referring to the dynamic properties of trees, such as that of [109] that establishes methods for the estimation of natural frequencies.

Each of these approaches embodies a critical trade-off between the goals of the research, the available computational resources, and the scale of the inquiry. Detailed explanations of different aspects related to the modeling are given in Table 4.

Table 4. Comparative analysis of FEM tree modeling approaches (based on Figure 2).

Aspect	High-Fidelity 3D Model (a)	Simplified Branch-Mass Model (b)	Equivalent Two-Element Model (c)
Level of Detail	Highest	Intermediate	Lowest
Main Components	- Detailed trunk - Complex branching - Root system - Individual leaves/clusters	- Main trunk line - Branch lines - Twig lines - Distributed masses	- Single trunk line - Crown line - Single crown mass
Geometric Representation	Full 3D geometry	Interconnected lines	Two connected lines
Mass Distribution	Distributed throughout structure	Concentrated at branch ends	Single point at crown top
Computational Complexity	Highest	Moderate	Lowest
Typical Data Source	LIDAR or detailed 3D scans	Field measurements, simplified scans	Basic tree measurements
Best Suited For	- Individual tree analysis - Detailed stress studies - Wind load analysis	- Small forest studies - Urban tree assessment - Wind–tree interaction	- Large-scale forest simulations - Preliminary urban planning - Rapid assessments
Key Advantage	Highest accuracy	Balance of detail and efficiency	Computational efficiency
Main Limitation	High computational demand	Reduced local detail	Limited individual tree information
Transient Analysis Capability	Highly detailed	Good, with distributed masses	Basic, using single crown mass
Scalability	Limited to few trees	Moderate, suitable for small groups	Highly scalable, large forests

Note: (a), (b), and (c) refer to the modeling approaches shown in Figure 2.

5. Comfort-Related Models

Comfort-related models constitute a systematic framework for the assessment and prediction of occupant well-being in the built environment across multiple sensory and psychological dimensions. These models incorporate thermal, acoustic, visual and air-quality parameters, together with their combined effects and psychological aspects, offering essential guidance for the design and operation of buildings to optimize occupant comfort and satisfaction. The subsequent sections analyze each model category, from fundamental physical-comfort metrics to sophisticated integrated approaches that address the multidimensional nature of occupant comfort, bridging the gap between theoretical predictions and observed occupant response.

5.1. Thermal Comfort Models (TCMs)

Grassi et al. (2022) [117] review 166 papers published between 2017 and 2021 dealing with thermal comfort models and building control approaches. The Predicted Mean Vote (PMV) model remains the predominant approach, although adaptive and data-driven alternatives are also widely employed. The analyzed control approaches include rule-based, model predictive control (MPC), machine learning, and optimal techniques. Though PMV models are widely coupled with MPC for simulations, rule-based simple approaches find more frequent use in prototypes. The review indicates significant shortcomings with regard to thermal comfort needs for the vulnerable and limited use of enhanced control methods in real environments. The study points towards the need for enhanced interaction between architects, engineers, and comfort experts for developing personalized and energy-efficient thermal comfort solutions.

Davidsson et al. (2013) [118] conduct research on hybrid and heat-recovery systems of mechanical ventilation with the use of simulations from TRNSYS. The study contrasts base-line heat-recovery-free mechanical ventilation with hybrid ventilation and heat recovery systems, wastewater heat recovery configurations, and alternative heat source systems. The study finds that hybrid systems with 86%-effective heat exchangers perform on the same terms with 75%-heat recovery systems and with 400 kWh of saved annual electricity. The study identifies heat exchanger efficiency as the key determinant of system performance, with supplementary measures such as ground-sourced heat exchangers offering minimal additional savings. Challenges associated with hybrid ventilation systems include managing airflow, maintaining clean heat exchanger surfaces, and mitigating noise transmission. The study offers valuable insights into low-energy ventilation strategies, highlighting the potential of hybrid systems for residential applications.

In addition, D'Ambrosio Alfano et al. (2011) [119] research the reliability of the Humidix index against conventional indicators of traditional heat, including the wet-bulb globe temperature (WBGT), predicted heat strain (PHS), and predicted mean vote (PMV). The study finds a systematic under-estimation by Humidix of higher-temperature environments, with greater impacts being registered with low-heat generation environments and low-humid environments. The model finds substantial shortcomings in treating critical temperature parameters, including clothing resistance, heat from human metabolism, and uneven temperature field. The authors conclude Humidix's unsuitability for indoor heat estimation and suggest, instead, utilizing the higher quality of performance of the rational methods of such approaches such as the use of PHS and PMV. Future research may focus on novel indices, such as the Universal Thermal Climate Index (UTCI), to enable broader and more accurate thermal environment assessments.

Djongyang et al. (2010) [120] review theoretical frameworks and applications for heat comfort, contrasting and comparing the rational heat-balance model (e.g., PMV and PPD indexes) with adaptive approaches. The study describes heat-exchanging mechanisms

between human and environment, i.e., conduction, convection, radiation, human heat generation processes, and clothing resistance. The study addresses thermal comfort in varying environments—educational spaces, healthcare structures, and outdoor spaces. The study references adaptive predictive comfort and future research directions, with specific references made towards outdoor heat comfort. The review provides a complete source of references for academics and specialists in HVAC system optimization and building performance.

Nicol and Humphreys (2002) [121] contend that conventional thermal comfort models, established via experimental tests, are not able to satisfactorily represent real-environmental comfort. The authors' adaptive model defines indoor comfort temperature and outdoor environment parameters with a correlation represented by the equation $T_c = 13.5 + 0.54T_o$. The authors present the notion of 'adaptive opportunity' and emphasize the capacity of people to change their environment and behavior towards achieving thermal comfort. Variable temperature set-points that adjust to outdoor conditions are recommended to reduce energy consumption in conditioned spaces while promoting the use of natural ventilation. The transition towards adaptive standards, including climatic factors, architectural features, and human behavior, supports the design of energy-efficient and sustainable structures.

Brager and de Dear (2001) [122] report on an adaptive comfort criterion for naturally ventilated structures from research of more than 21,000 datasets for 160 structures on four continents. Defining structures in terms of two categories, centrally air-conditioned (HVAC) and naturally ventilated (NV), and employing regression analysis, authors established relationship between indoor and outdoor comfort temperature. In derived format, this suggests people working in NV structures can tolerate a higher range of temperature compared with people working in HVAC structures, and points towards the contribution of psychological adaptation and changing expectations. Also, an 80% and 90% acceptance band for the optimal temperature of comfort were established—of value in real-world design. Some of the future research directions include heat variability, between-individual variations in comfort, and coupling indoor air quality with the utilization of energy. The adaptive model has massive potential in terms of NV building design and energy-efficiency; its employment for mixed-mode structures and task-ambient conditioning needs investigation. The study suggests a transition towards context-specific, adaptive approaches of thermal-comfort appraisals, away from conventional heat-balance methods.

Raja et al. (2001) [123] conducted research on the use of indoor temperature comfort controls by office personnel in naturally ventilated workplaces in the United Kingdom, with field measurements made in Oxford and Aberdeen. The study indicates that 62% of responses were from the use of windows, whose use correlated with temperature fluctuations. Conversely, the use of fans had a relatively lower rate of 38%, and solar-control systems, mainly for lowering luminance, contributed 24% of responses. Also, a greater provision of environmental controls indicated negative correlation with thermal dissatisfaction, highlighting the paramount significance of adaptive methods in architectural design. The study supports incorporating methods of occupant control into computer simulations of naturally ventilated structures for improving temperature performance and energy use.

5.2. Acoustic Comfort Models (ACMs)

Torresina et al. (2018) [124] present a thorough review of experimental studies concerned with the cumulative effects of several factors in indoor environments—acoustic, thermal, visual, and air quality—upon performance and perception in humans. In an analysis of 45 laboratory studies, the review clarifies interactions between factors and architectural implications for architectural design. Thermal factors dominate in the review, with less consideration for visual, acoustic, and air quality factors. Evidence shows that

interactions vary by case—for instance, high temperature and humidity affect perceived air quality—but inconsistencies across studies make generalization difficult. Despite less consideration in studies, even for performance, trends can be discerned, and high temperatures impair both cognitive and physical performance. Differences in methodologies make comparisons between studies on acoustic comfort models challenging. Authors note a demand for standardized experimental protocols and multi-model frameworks for consideration of dynamic relations, occupant behavior, and factors over time. In addition, translating such information into standards for buildings can inform methodologies for enhancing design. In future studies, development of models, expansion of experimental studies into real-life settings, and consideration of individual variation must be addressed. Existing studies are synthesized in the review, and several aspects of indoor environments present in it form a basis for future improvements in indoor environments and occupant comfort and well-being. Aletta and Kang (2018) [125] present a predictive model for urban vibrancy that integrates both aural and visual dimensions of soundscapes. Vibrancy is defined as a multivariate perceptual concept, inherently linked with aural dimensions such as human speech, variation, loudness, and music, and visual cues such as presence of persons and activity. Employing data acquired in 46 UK and Chinese urban locations, the authors conducted experiments, in which participants rated vibrancy, pleasantness, and eventfulness. According to the regression analysis, five significant predictors, namely, roughness, fluctuation strength, loudness, presence of people, and music, predicted 76% of vibrancy variance. According to the results, vibrancy is closely related to eventfulness, but its relationship with pleasantness is not strong. In addition, the visual environment plays a significant role in assessments of pleasantness, and variation in loudness yields a nonlinear contribution towards vibrancy perception. This work conforms to ISO 12913-1:2014 [126] and extends soundscape evaluation through vibrancy quantification. The predictive model proposed opens avenues for urban planning through actionable insights and identifies a key role for both aural and visual stimulation in creating vibrant public spaces. Hongisto (2005) [127] creates a predictive model for evaluating speech intelligibility impact on performance in an open-plan office environment. Drawing from a thorough review of the relevant literature, the study engages with the issue of speech, with a specific consideration of intelligible speech, and its performance-disruptive impact during cognitively taxing operations such as recalling, reading, and proofreading. Implementation of speech intelligibility is conducted through use of the Speech Transmission Index (STI), with values between 0 (entirely unintelligible) and 1 (totally intelligible). Performance is seen to suffer appreciably, a loss of 7%, when the STI level reaches 0.60, a common state in poorly designed spaces for open-plan use, and performance suffers when below 0.20, a common feature of well-designed private spaces. Identification of a critical range for productivity loss in terms of STI value 0.30 to 0.50, and its use in terms of a target for future studies, is a key contribution of the investigation. In terms of practice, an imperative for an STI level below 0.50 in spaces for use in an open-plan arrangement is stressed, a target that will require a mix of effective techniques, such as high sound absorption, high partition height, and effective speech-masking techniques, and a model for estimating productivity gain through sound improvements should be developed, allowing companies to evaluate return for investment in such interventions. Although valuable, the model has limitations and must be validated through future studies across a range of STI values, using both laboratory and field methods to ensure accuracy. In collating disparate studies into a single theoretical model, Hongisto creates a platform for studying the impact of sound environments and cognitive performance, an impact with significant implications for productivity and workforce efficiency in both office planning and development. Babisch (2003) [128] integrates current studies with regard to sound exposure and its relation to hormonal concentrations of stress,

closely investigating physiologic processes through which such factors can contribute to susceptibility to cardiovascular disease. The investigation specifically identifies three key stress hormones: adrenaline, noradrenaline, and cortisol, acting as bio-messenger chemicals in the autonomous stress reaction system of the body. In coordination with an examination of its prevalence, work-related sound exposure corresponds with high concentrations of stress hormones, with a specific role for noradrenaline, and sources of community sound, such as cars and aircraft, yield mixed results. Methodologic obstacles, such as diurnal fluctuations in hormonal discharge and complications in distinguishing between acute and long-term consequences, complicate an evaluation of findings.

5.3. Visual Comfort Models (VCMs)

Gunay et al. (2017) [129] created an adaptive algorithm for the purpose of controlling a device for determining daylight and covering occupant preferences. Experiments in a real office setting proved the reduction of lighting demand with comfortable levels being sustained with real-time blind and photosensor threshold adjustments. The personalized solution performs satisfactorily with varying occupancy preference, hence maximizing performance and satisfaction. The research conducted by Konstantzos and Tzempelikos (2016) [130] explored perception of glare with regard to usage of window shades, coupled with a modified daylight glare probability (DGP) equation under solar irradiation. A new glare index, with regard to vertical illuminance, was also proposed, enabling quantification of glare with factors such as transmittance and coloration of cloth. The research contributes towards the design of systems of shading for vision-related comfort improvement. Bellia et al. (2014) [131] made a daylight comparison of daylight in three office spaces in Naples, focusing on spectral characteristics and circadian impacts. The main findings outlined indoor spectral properties and related color temperatures between different spaces and daylight requirements. The research underscores the importance of daylight in supporting circadian regulation by evaluating its potential impact on melatonin suppression. The findings aim to inform future design strategies that leverage natural daylight's non-visual benefits. This study by Jakubiec and Reinhart (2012) [132] assesses discomfort glare parameters and puts forth the idea of the "adaptive zone," where the capacity of the occupants for adjusting their location and view direction towards reducing glare has been considered. Using Radiance simulations, the authors conclude Daylight Glare Probability (DGP) as the best predictor for estimating glare in daylight spaces. The adaptive zone approach led to a 10% decrease in average glare inside lit office spaces, highlighting the importance of occupant flexibility for reducing glare. The study also brings daylight parameters and glare analysis into unison for maximizing energy efficiency and visual satisfaction inside building design. The study of Wienold and Christoffersen (2006) [133] established Daylight Glare Probability (DGP), a new parameter for the estimation of glare, with 94% correlation with the human perception of glare. Using CCD camera-based luminance mapping, the authors demonstrated that existing glare indices—such as the Daylight Glare Index (DGI)—exhibited limited predictive accuracy. Daylight Glare Probability (DGP) seamlessly unites vertical eye illuminance with source parameters of glare and hence forms a very useful tool for daylight optimized and sustainable building design.

5.4. Indoor Air Quality Models (IAQMs)

The research by Liu et al. (2017) [134] examines physiological responses under raised temperature (35 °C) and CO₂ levels (3000 ppm) under experimental conditions. The subjects experience raised tympanic and skin temperature, raised heart rate, and weight reduction, accompanied by lower arterial O₂ saturation and cardiac interval variability—a marker of thermophysiological stress. The cognitive performance and air quality perception are

reduced considerably. Elevating CO₂ levels to 3000 ppm did not produce additional significant physiological effects beyond those caused by thermal exposure alone. The data affirm 35 °C as a limiting temperature for necessary limitation of the rate of work and for protecting outdoor working populations, with critical importance for heat-stress prevention under global warming. The study of Wolkoff (2012) [135] considers the contribution of indoor air pollution from VOCs, particulate matter, and ozone-initiated reaction compounds under office settings. Although VOC levels in offices are usually below sensory irritation criteria, some chemicals—such as formaldehyde—may nevertheless create reported discomfort or irritation, especially when mixed with other contaminants. Particulate matter from automotive emissions or from combustion of candles can be harmful for cardio-pulmonary status for sensitive subjects. In addition, ozone–terpene reactions may be able to yield harmful second generation compounds, such as formaldehyde. This analysis suggests the need for target measurement and mitigation techniques, with regard to chemical interactions and individual susceptibilities, to maintain indoor air quality. The study of Fisk and Seppanen (2007) [136] illustrates the economic benefits of enhanced indoor environment quality (IEQ) in office and residential settings, with regard for the thermal environment and air quality. The optimal performance is seen to be achieved best between 21 and 22 °C, with improvements in ventilation rates from 6.5 to 13 L·s^{−1} for every individual achieving a 1% rise in productivity. Benefit–cost ratio values up to 80, and annual per-capita economic gains of EUR 500, substantiate the economic value of IEQ improvements on individuals' health and productivity. The study underscores the need for more research on cognitive performance and low-energy solutions.

5.5. Integrated Comfort Models (ICMs)

A meta-analysis of 41 different methods of field studies of indoor environment quality (IEQ) conducted by Kakoulli et al. (2022) [137] has established biased trends for some parameters, including temperature (75.6%), carbon dioxide (73.2%), and relative humidity (70.7%). Interestingly, the samples' distribution indicated classroom environments had the highest percentage of focus (49%) while underperformance existed for healthcare environments, shopping centers, and transportation infrastructure environments. Systematic shortcomings of the review are the lack of standard calibration processes, the lack of data collection for temporal parameters, and the lack of proper regard for human-related parameters (17.9%). The study has underlined the need for setting measurement frameworks, improvement of data collection methods, and use of complete descriptions of indoor pollutant species, hence enabling evidence-based performance assessments. In addition, research undertaken by Huang et al. (2012) [138] covering a wider range of parameters has conclusively established correlations between temperature, luminance, and acoustics in office environments, in addition to their individual contribution towards overall performance and satisfaction. The research has identified temperature and acoustics as main determinants of environment acceptance and has established undesirable values of these parameters, influencing people's perceptions. The study supports holistic methods in addressing such parameters, and not single-parameter methods, in order to attain optimal indoor environment quality. The study also supports the use of evidence-based design for office environments, where the identification of optimal parameters for satisfaction improvement and task performance becomes necessary. In a related study on spatial configuration, Lee et al. (2010) [139] performed a study of determinants of satisfaction in LEED-registered office spaces, with a specific view on acoustical performance, determinants of privacy, and ease of interaction. The results indicate that open-plan offices with high partitions (high cubicles) often produce lower degrees of satisfaction than enclosed private offices and open-plan offices without partitions (bullpens). Interestingly, the bullpen office

style, despite lacking barriers, showed comparable satisfaction levels to covered shared offices in all assessed areas, including privacy and acoustic quality. The research also finds key office environment design requirements for sustainability, including measurable parameters of satisfaction beyond traditional sustainability parameters. In a different research study, Candido et al. (2010) [140] explore allowable air movement rates for naturally ventilated buildings under tropical and humid climatic regions of Brazil. Empirical data suggest minimum allowable air movement rates must not be lower than 0.4 m/s when temperature levels rise up to 26 °C, with maximum allowable rates up to 0.9 m/s when temperature levels rise up to 30 °C—at which point they approach or even exceed the 0.8 m/s upper limit stipulated by the American Society of Heating, Refrigeration, and Air-Conditioning Engineers Standard 55 [141] for lightly clothed, sedentary occupants. Empirical measurements also find systematic correlations between higher levels of ambient temperature and greater air velocity tolerance among people, contradicting conventional regulations of air movement under air-conditioned spaces. The interaction between temperature and air movement illustrates the greater performance efficacy of adaptive ventilation techniques under naturally ventilated spaces, with performance being optimized under higher temperature and humid levels.

5.6. Psychological and Subjective Comfort Models (PSCMs)

One hundred fifty-four publications, related to occupants' comfort, from the period 2002–2022 were evaluated in Faraji et al. (2023) [142]. The main examined parameters of the study, related to occupant comfort assessment, were thermal, visual, acoustic and indoor air quality. The analysis revealed that many studies focused only on one parameter until 2016, and thereafter there is a significant trend toward a multicriteria approach and machine learning. The investigation identifies significant research gaps, notably in building typology diversity and tropical-climate contexts, whilst emphasizing requirements for longitudinal measurements and physiologically-informed comfort models. This comprehensive review provides methodological direction for future investigations aiming to optimize the interplay between energy efficiency and occupant comfort. Machine-learning frameworks developed by Kim et al. (2018) [143] enabled occupant-specific thermal preference modeling through the analysis of behavioral data from temperature-controlled office seating. Their probabilistic classification methodology achieved 73% median accuracy—exceeding conventional thermal comfort indices—with Random Forest algorithms demonstrating superior predictive capability. Analysis of feature importance identified personal comfort system (PCS) as primary determinants of thermal preferences. These findings establish the viability of data-driven comfort modeling for optimizing both environmental conditioning efficiency and occupant thermal satisfaction. Wei et al. (2014) [144] established a systematic classification of occupant-driven space-heating determinants, identifying 27 parameters across environmental, architectural, behavioral and auxiliary domains. Their critical analysis revealed significant limitations in contemporary building performance simulation, particularly regarding simplified heating-behavior algorithms that omit key parameters—including occupant energy cognition and envelope thermal resistance. The investigation advocates calibrated parameter integration to optimize simulation fidelity whilst managing computational complexity. This work reinforces the need for performing quantitative behavioral studies for understanding the determinants affecting domestic energy use trends and for gaining a better understanding of them. A rigorous statistical examination of occupant satisfaction indicators for different building cohorts ($n = 144$) was performed by Altomonte and Schiavon (2013) [145] between LEED-certified and non-certified buildings. The statistical assessment indicated there were not significant differences between aggregated satisfaction indicators and office environment quality indicators. Though LEED

certification had a marginal improvement in indoor air quality indicators, the indoor environments in LEED-certified spaces had lower levels of occupant satisfaction with regard to luminous environments. This systematic study challenges the hypothesized relationship between certificate protocols and occupant-perceived office environment quality, hence setting up significant implications for performance-oriented certificate protocols in sustainable design. Zhang et al. (2010) [146] created predictive equations for measuring thermal comfort in environments with non-uniform and transient conditions, with data gathered from measurements of 19 individual human body parts. Validated for use in vehicular environments, these equations have the potential for making asymmetrical thermal environments equal if not greater in terms of comfort and with greater efficiency compared to environments of uniform distributions. By focusing on the individual human body part, this research presents a wide range of methodologies for addressing improvements for architectural and automotive thermal design improvements.

5.7. Section Summary and Implications Concerning Comfort Models

A critical review of comfort-related frameworks identified the holistic nature of occupant comfort in the built environment. In that respect, optimal comfort would be considered an integrated approach involving thermal, acoustic, visual, indoor air quality, and psychological parameters. While existing traditional models deal with each of these elements in isolation from one another, complex, multidimensional interactions between the several environmental factors participating in general occupant satisfaction and well-being can hardly be addressed. The import information is summarized in Table 5.

Table 5. Classification of comfort-related modeling and analysis approaches.

Category	Application	Key Modeling Techniques	Reference
Thermal Comfort Model	Naturally Ventilated Buildings	Adaptive comfort model, Regression analysis	[122]
	Residential Buildings	Computer simulations using TRNSYS	[118]
	Building Control Systems	PMV method, Data-driven models, Machine learning	[117]
	Office Buildings	Field surveys, Statistical analysis	[123]
	Indoor Environment Assessment	Temperature–Humidity indices comparison	[119]
	General Building Design	Heat-balance method, Adaptive approach	[120]
	Building Standards Development	Adaptive algorithms, Field studies	[121]
Acoustic Comfort Model	Open-Plan Offices	Speech Transmission Index modeling	[127]
	Multiple Environment Types	Experimental laboratory studies	[124]
	Health Impact Assessment	Stress hormone analysis	[128]
	Urban Soundscapes	Perceptual modeling, Vibrancy prediction	[125]
Visual Comfort Model	Daylit Spaces	Glare metrics, Radiance simulation	[132]
	Office Environments	Spectral analysis, Circadian impact	[131]
	Daylight Environments	CCD camera-based luminance mapping	[133]
	Window Shading Systems	Modified DGP equation	[130]
	Office Lighting Control	Adaptive algorithms, Machine learning	[129]
Indoor Air Quality Model	Non-industrial Workplaces	Cost–benefit analysis	[136]
	Office Environments	VOC assessment, Particle analysis	[135]
	Climate Chamber Studies	Physiological response measurement	[134]

Table 5. Cont.

Category	Application	Key Modeling Techniques	Reference
Integrated Comfort Model	Multiple Building Types	Field measurement studies review	[137]
	Office Environments	Multi-factor interaction analysis	[138]
	LEED-certified Buildings	Privacy and acoustic quality assessment	[139]
	Naturally Ventilated Buildings	Air movement acceptability analysis	[140]
Psychological and Subjective Comfort Model	General Building Assessment	Meta-synthesis review	[142]
	Residential Buildings	Behavioral analysis	[144]
	Office Buildings	Machine learning, Personal comfort systems	[143]
	LEED vs. Non-LEED Buildings	Occupant satisfaction surveys	[145]
	Non-uniform Environments	Local comfort modeling	[146]

Thermal Comfort Models (TCMs) span from static indices such as Fanger’s PMV and PPD to adaptive models, taking as input the dynamic way occupants interact with their thermal environment. Brager and de Dear (2001) and Nicol and Humphreys (2002) [121,122] provided evidence of the role of psychological adaptation and personal control in naturally ventilated buildings. Their inclusion in recent standards, such as ASHRAE Standard 55 and ISO 7730, reflects the fact that, due to occupants’ behavioral adaptations and expectations, occupants are able to accept a wider temperature range.

Acoustic Comfort Models (ACMs) identify sound as a significant parameter on occupant health and productivity. The model by Hongisto (2005) [127], proved that speech intelligibility in open-plan offices decreases cognitive performance. According to Babisch, 2003 [128], with chronic noise exposure, the amount of stress hormones is increased, creating cardiovascular risks. This synthesis of acoustic comfort with other environmental variables, according to Torresin et al. (2018) [124], indicates that acoustic metrics cannot be considered in isolation but interrelate to thermal and visual contexts

Visual Comfort Models (VCMs) focus on both natural and artificial lighting and deal with glare, daylighting, and other circadian issues, as well. New metrics for evaluation such as the DGP developed by Wienold and Christoffersen (2006) [133] offer reliable tools for assessing discomfort glare in rooms lit by daylight. Analyses by Jakubiec and Reinhart (2012) and Bellia et al. (2014) [131,132] have revealed the need to consider a balance in the use of daylight between utilization and visual comfort, taking into account both visible and non-visible (photobiological) effects of the light on occupants.

Indoor Air Quality Models (IAQMs) are important tools used in assessing and improving environmental conditions that have a direct effect on the occupants’ health and comfort. As Fisk and Seppanen (2007) [136] noted, improving indoor environmental quality leads to significant economic benefits due to improved health and increased productivity. Wolkoff’s 2012 [135] review on indoor air pollutants highlights the complexity brought about by indoor air quality problems and furthers stresses the need for accurate measurement and mitigation methods grounded in standards such as ASHRAE Standard 62.1 [147] and ISO 16000 [148].

Integrated Comfort Models (ICMs) represent a holistic approach where a number of comfort variables are interrelated. According to Huang et al. (2012) and Kakoulli et al. (2022) [137,138], research has shown that cumulative effects are needed since both thermal and noise variables have a great combined effect on general satisfaction with the indoor environment. The employment of building performance simulation tools like EnergyPlus and TRNSYS enhances the modeling of complicated interactions, enabling designers to project and optimize multiple elements of comfort at the same time.

Psychological and Subjective Comfort Models (PSCMs) focus on occupant perceptions and satisfaction, recognizing that individual preferences and behaviors significantly influence comfort. Faraji et al. (2023) [142] highlight that while thermal comfort has been extensively studied, there is a growing need to consider all aspects of comfort collectively. Kim et al. (2018) [143], demonstrate that personal comfort models using machine learning for predicting individual thermal preference result in better occupant satisfaction. POE and principles of environmental psychology are also useful in understanding design elements affecting occupants' well-being.

Analysis results highlight standards and guidelines as the key drivers of comfort models and construction methodologies. Important standards and guidelines, such as ASHRAE Standards 55 [141] and 62.1 [147] and ISO 7730 [149] and EN 12464-1 [150], provide a critical framework of assessment and design with respect to comfort. Indeed, these standards involve both conventional and adaptive models, which, upon consideration, offer flexibility toward meeting comfort standards in an expansive range of buildings and climatic conditions.

In conclusion, comfort and sustainability in built environments are a result of an integral approach in understanding the dynamic and interacting features of various comfort variables. Future research would do well to continue exploring how these environmental factors interact, develop occupant-specific comfort interventions, and refine modeling approaches to capture occupant diversity and adaptive behaviors. This means that by applying advanced modeling tools and adhering to evolving standards, designers and engineers can maximize a building's system interactions on behalf of the occupants to produce a positive effect on well-being and productivity.

6. Conclusions

This manuscript examines the modeling approaches for the renovation of vertical forest reinforced concrete buildings, taking into consideration four main aspects: structural, energy, forestry, and occupant comfort. This new concept of architecture differs from traditional zero-energy building concepts in the way it embeds real forest ecosystems into urban buildings, targeting high-density urban forestation with an attempt to bring sustainability into urban areas, while embedding green infrastructure into an existing building stock. The complexity of VF building systems necessitates a systematic understanding of domain interactions. Figure 3 presents an integration matrix derived from this comprehensive review, identifying 36 specific interaction points between structural, energy, forestry, and comfort modeling approaches. The analysis demonstrates that 58% require high integration (direct coupling) and 28% require medium integration (coordination), with only 14% involving minimal or no interaction, emphasizing the need for coordinated multidisciplinary design approaches rather than isolated domain-specific solutions.

Technical analysis in small subcomponent systems, renovated or not, is proposed with advanced modeling techniques, such as advanced 3D finite element modeling using Explicit Dynamics (e.g., ANSYS, ABAQUS) and complex material models for concrete, steel, infill, mortar, and composites. This methodology couples structural integrity and environmental benefits by using comprehensive modeling in the renovation of urban buildings. For more extensive systems, including whole buildings or a group of buildings, the use of sophisticated engineer packages, focused on a performance based approach with advanced beam and truss elements, is proposed (e.g., OpenSees). This framework will enable practitioners to better balance computational efficiency and accuracy, hence allowing them to choose modeling approaches that best meet the project requirements, available resources, and desired analytical outcomes.

Domain Interaction Matrix - Research-Based Connections						
Integration Aspect	Structural ↔ Energy	Structural ↔ Forestry	Structural ↔ Comfort	Energy ↔ Forestry	Energy ↔ Comfort	Forestry ↔ Comfort
Load Transfer	Thermal Loads	Wind + Growth	Vibration	Seasonal	Equipment	-
Material Interface	Insulation	Root-Concrete	Acoustics	Substrate	Finishes	Bio-materials
System Control	Smart Systems	Monitoring	Automation	Irrigation	HVAC	Biophilic
Maintenance Access	Equipment	Plant Care	Cleaning	Energy Systems	Filters	Pruning
Performance Feedback	Efficiency	Deflections	Occupancy	Consumption	Satisfaction	Well-being
Modeling Coupling	Co-simulation	Bio-FEM	CFD-FEM	Growth Models	BEM+Comfort	Psychometric

■ High Integration (Direct Coupling Required)
 ■ Medium Integration (Coordination Needed)
 ■ Low Integration (Minimal Interaction)
 ■ No Direct Interaction

Figure 3. Domain interaction matrix for vertical forest building systems showing integration levels between structural, energy, forestry, and occupant comfort modeling approaches. Classification based on coupling requirements: high (direct coupling required); medium (coordination needed); low (minimal interaction); and none (independent operation). Note: Double-headed arrows (↔) indicate bidirectional data exchange between domain models.

During the literature review three primary forestry design parameters were identified: root systems, trunks, and foliage. It is important to model the root system more carefully because it is highly related to structural stability and soil–structure interaction. Detailed analysis at the microscale of soil–root interfaces and their mechanical behavior provides the essential inputs for the foundation of vertical forest buildings. Trunk modeling requires biomechanical analysis for numerous loading conditions and growth patterns, whereas foliage modeling has to take into consideration seasonal variations, wind loads, and the dynamic nature of living systems. This multiscale approach, ranging from micro-level soil–root interaction to macro-level structural considerations, provides a comprehensive understanding of integrated forest elements in the built environment.

Energy system modeling has evolved for vertical forest buildings to include the increasing intricacies of modern low-carbon transitions while maintaining transparency in their decision-making processes. Models need to account for the peculiar integration of vegetation with systems by considering natural shading, evaporative cooling, and seasonal variations of energy demand. While open data and reproducible analysis strengthen model credibility, the field acknowledges the inherent challenges in predicting long-term energy performance of these innovative building systems.

Other important aspects include comfort modeling, which entails the thermal, acoustic, visual, and air quality parameters of the buildings with forest elements incorporated within them. The field has evolved from comfort modeling as static indices to adaptive models that better reflect occupant–environment interactions. In the development of Thermal Comfort Models (TCMs), special attention should be given to the varying microclimates-integrated vegetation, humidity, air movement, and radiant temperature. Visual Comfort Models (VCMs) must balance natural daylighting benefits with dynamic foliage shading patterns, while Indoor Air Quality Models (IAQMs) must incorporate plant biological processes and their impact on air quality. These comfort models integrated into the vertical forest buildings provide modern insights into occupant well-being, integrating seasonal variations and occupant behavioral patterns through Psycho-Social Comfort Models for an integrated evaluation framework.

The combination of natural systems with built infrastructure has, indeed, great potential to define a path to more sustainable urban environments. Success in this area calls for ongoing refinement of modeling approaches, validation through post-occupancy studies, and the development of best practices for the design and implementation of vertical forest

buildings. Future research should focus on enhancing the integration and accuracy of these different modeling approaches while maintaining practical applicability for design professionals. The given comprehensive model framework demonstrates that living systems can be integrated into the structure of urban buildings while achieving optimum structural performance, energy efficiency, and comfort for occupants using sophisticated analytical techniques.

Despite the current in-depth analysis of numerical modeling, further research is required to identify the biomechanical influence of trees on structural performance. A practical application could include the construction of prototype physical and digital buildings for research and optimization purposes. The specimens could help optimize resilience against hazards, manage disaster risk, and educate students to increase societal awareness. Finally, based on the results, practical guidelines for the renovation of existing buildings into VFs considering combined structural, energy, forestry, and comfort aspects could be generated.

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Appendix A

Informative section on main material properties for a performance-based analysis of VF structures using the open-source FEM package OpenSees.

Table A1. Basic concrete models in OpenSees.

Model Name	Description	References
Concrete01	The Concrete01 material models a uniaxial concrete object following the Kent–Scott–Park model with no tensile strength and features degraded linear unloading/reloading stiffness. It is typically used to simulate the nonlinear, inelastic behavior of concrete under compressive loads, making it applicable for both static and dynamic analyses.	[48,151,152].
Concrete02	The Concrete02 material is a uniaxial concrete material model with linear tension softening that is generally adopted for the simulation of nonlinear behavior under both static and dynamic loading conditions. It incorporates provisions for tension softening, compressive unloading/reloading stiffness, and damage developed.	[151–153].
Concrete04	Concrete04 is a uniaxial OpenSees material model, where the Popovics model is considered for concrete in tension and compression, while the degrading linear unloading/reloading stiffness is considered by the Karsan–Jirsa’s model. The Concrete04 model can be used for nonlinear and inelastic analysis because this model traces the development of damage under cyclic loadings.	[48,151,152,154,155].

Table A1. *Cont.*

Model Name	Description	References
Concrete06	Concrete06, a uniaxial concrete material that models both compressive and tensile responses with nonlinear tension stiffening and compressive curves based on the Thorenfeldt curve, is one of the most used materials for both static and dynamic analyses while modeling complex behaviors like tension cracking and compression damage.	[151,152,154,156,157].
Concrete07	The Concrete07 material is based on the model developed by Chang and Mander. It is primarily applied for the simulation that involves confined and unconfined concrete under cyclic loading and includes simplified protocols for unloading and reloading. It is a versatile model that can represent nonlinear and inelastic response in both static and dynamic conditions for reinforced concrete elements with ease.	[151,152,158].
Concrete01 WithSITC	Material Concrete01WithSITC improved from the material of Concrete01, takes into consideration “Stuff In The Cracks” (SITC), defining the effect of microcrackings with regard to stiffness loss in concrete under cyclic loading. This model describes nonlinear inelastic behavior, and it allows for dynamic and static analysis of the damage.	[151,152,159].
Confined Concrete01	The OpenSees material model ConfinedConcrete01 represents a nonlinear concrete formulation that was developed in confined concrete, including details regarding transverse reinforcement and external Fiber Reinforced Polymer (FRP) wraps. It is intended for performance modeling of confined concrete under both static and dynamic loading conditions.	[151,152,155,160–162].
ConcreteD	ConcreteD is a one-dimensional element constitutive model of concrete implemented in OpenSees, with its basis on the concrete design code of China. Compressive and tensile behaviors of concrete have been modelled by employing individual parameters of plasticity.	[151,152,155,163–166].

Table A2. Basic steel models in OpenSees.

Model Name	Description	References
Steel01	The Steel01 material model represents a uniaxial bilinear steel material characterized by kinematic hardening and with the possibility of isotropic hardening to simulate nonlinear and inelastic responses under static as well as dynamic loading conditions.	[151,152,167]
Steel02	Material Steel02 is based on the Menegotto–Pinto model, enhanced with an isotropic strain hardening rule that accounts for nonlinear and inelastic responses caused by both static and dynamic loadings.	[151,152,167,168]
Steel4	Material Steel4 (uniaxial) combines the kinematic and isotropic hardening mechanisms and provides nonsymmetrical behavior. It gives an ultimate strength limit beyond which the material response may be considered plastic. The model has been commonly used in static and dynamic analyses.	[151,152]

Table A2. Cont.

Model Name	Description	References
ReinforcingSteel	The ReinforcingSteel material is based on the Chang and Mander model, adding some new functionality for buckling and fatigue based on the Coffin–Manson relationship. It includes isotropic hardening, a descending yield plateau, and the accumulation of plastic strain to further refine simulations with respect to the behavior of reinforcing steel bars. It has characteristic features concerning cyclic degradation and fatigue modeling necessary for simulating the fatigue failure in reinforcing bars.	[151,152]
Dodd_Restrepo	The Dodd–Restrepo steel material represents a uniaxial material model of reinforcing steel developed to simulate the cyclic behavior of reinforcement under both tensile and compressive stresses. The model is particularly useful in analyzing the response of steel members under seismic or cyclic loading, considering the Bauschinger effect, strain hardening, and typical strain reversals developed during such loadings.	[151,152,169]
Ramberg OsgoodSteel	The Ramberg–Osgood steel material models the nonlinear stress–strain relationship of structural steel using the Ramberg–Osgood relationship. This will be useful in replicating hysteretic behavior for steel under cyclic loading conditions. The Ramberg–Osgood model provides a smooth transition from elastic to plastic behavior and plays a major role in realistically representing the behavior of steel members under repeated load reversals.	[151,152,170]
SteelMPF	SteelMPF represents an advanced version of the Menegotto–Pinto steel model. This model represents a number of developments compared to other steel models, such as Steel02, for example, with regard to cyclic behavior handling and isotropic hardening. It finds a wide application in the simulation of reinforced concrete (RC) elements, such as walls and columns, under a reversed cyclic loading condition.	[151,152]
Steel01 Thermal	Material Steel01Thermal represents an upgraded version of the Steel01 material model, especially developed for the temperature-dependent behavior of Eurocode 3. The main area of its application is the thermomechanical analysis of the changes within mechanical properties of steel at higher temperatures. This material model can be utilized for both beam and column elements under thermal analyses, especially in the case of thermal expansion evaluation or heat that is considered to affect structural integrity.	[151,152]

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