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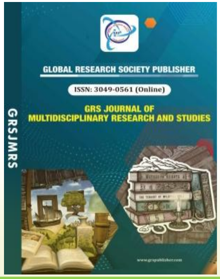

Integrated Digital Modeling for Energy and Acoustic Comfort in Urban Housing

Armin Rasoulzadeh Baghmisheh & Morteza Maleki

[1]M.Sc. Building Physics Department of Architecture, Graduate School of Science and Engineering, Yıldız Technical University Istanbul, Turkey.

[2]Researcher, Sustainable Architecture, Research collaborator at University of Wollongong, Former Assistant Professor, Bu-Ali Sina University.

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Corresponding Author:

Armin Rasoulzadeh Baghmisheh

Abstract: Urban housing faces significant challenges related to energy efficiency and acoustic comfort, both of which are crucial for residents' well-being and sustainability goals. Integrated digital modeling frameworks present new opportunities to holistically address these concerns through advanced simulations and multidisciplinary design approaches. Integrated digital modeling allows for the optimization of design strategies that mitigate energy consumption and improve acoustic conditions, crucial for residents' well-being in densely populated areas. By leveraging real-time data and advanced analytics, these technologies enable proactive management of building systems, ultimately leading to significant energy savings and improved quality of life for occupants. However, the transition to integrated digital modeling also presents challenges. Issues such as interoperability between various digital tools, data security concerns, and the complexity of implementation may hinder widespread adoption. Furthermore, while some studies indicate the promise of improved energy efficiency and acoustic comfort through these models, others suggest a lack of substantial quantitative evidence regarding their effectiveness, highlighting the need for ongoing research and methodological refinement in this field.

This case study, adapted from a simulation experiment in Tehran, uses energy Plus to model a representative urban residential unit. It quantifies the interplay between acoustic comfort (measured via noise thresholds) and energy performance (via passive ventilation). The objective is to assess potential energy savings and identify design interventions, such as noise barriers or advanced glazing, to enhance both domains. Drawing on a simulation-based analysis in Tehran, Iran, the study demonstrates how noise levels influence occupant behavior (e.g., window opening for ventilation) and, consequently, energy consumption. Key findings reveal that passive ventilation can reduce energy use by 2-13%, but acoustic constraints limit savings to 1-9%, highlighting the need for holistic digital models that couple energy and acoustic parameters. This approach offers actionable insights for urban planners and architects to design resilient residential buildings (Naghibi Iravani, et al., 2024). Rapid urbanization exacerbates energy demands in residential buildings while amplifying noise exposure from traffic and industrial activities. In dense cities like Tehran, where over 50% of housing stock was built before 1980, integrating energy-efficient designs with acoustic mitigation is critical for occupant well-being and net-zero goals. Digital modeling tools enable predictive simulations that balance these factors, allowing for scenario testing without physical prototypes.

Keywords: *integrated digital modeling, energy simulation, acoustic comfort, urban housing.*

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Introduction

Urban housing developments increasingly face challenges related to energy efficiency, acoustic comfort, and sustainability. Traditional approaches often address energy performance and acoustics separately, leading to fragmented design and retrofit strategies. Rapid urbanization has intensified demand for sustainable, resilient, and healthy housing solutions (Norouzian & Gheitarani, 2024). While energy performance has been a central focus in housing design and policy (IEA, 2019), acoustic comfort remains comparatively underexplored despite its significant implications for occupant well-being (Kang & Schulte-Fortkamp, 2016). Energy and acoustic performance are interconnected: insulation layers, façade materials, and ventilation strategies affect both heat transfer and sound transmission (Qurraie, Mansouri, & Singery, 2023). However, siloed assessment practices limit the ability to optimize these aspects simultaneously. Integrated digital modeling offers a way forward by uniting building geometry, materials, simulation engines, and real-world data streams in a coherent framework (Moulaii, et al., 2025). Higher residential densities emphasize the need for multi-criteria approaches in the design and retrofitting of urban housing. Energy-efficient homes may sometimes compromise acoustic comfort, and vice versa. Integrated digital modeling offers a way to simultaneously optimize for both concerns, but requires robust interdisciplinary frameworks and techniques.

As urban development continues to evolve, integrated digital modeling stands at the forefront of creating smarter, more sustainable living environments. By addressing both energy and acoustic comfort, these technologies play a pivotal role in shaping the future of urban housing, ensuring it meets the diverse needs of its inhabitants while minimizing environmental impact. (Cespedes-Cubides & Jradi, 2024). Integrated Digital Modeling for Energy and Acoustic Comfort in Urban Housing refers to the innovative application of digital technologies to improve the energy efficiency and acoustic quality of residential environments in urban settings. As cities increasingly face challenges related to population density and climate change, the integration of advanced modeling techniques—such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and Digital Twin technology—becomes essential. These tools facilitate comprehensive analyses of building performance, support informed decision-making, and promote sustainable urban living by enhancing both indoor environmental quality and occupant comfort (Norouzian, 2024). Integrated digital modeling, is revolutionizing the way energy and acoustic comfort are addressed in urban housing developments. By combining these approaches, practitioners can optimize indoor environmental quality and occupant wellbeing while also reducing energy consumption and noise disturbance (Norouzian & Gheitarani, 2023). Urban housing must address dual imperatives: minimizing energy use to combat climate change and ensuring acoustic comfort to support resident well-being. Energy inefficiency in buildings contributes to over 30% of global emissions, while poor acoustics lead to health issues like stress and sleep disruption. Integrated digital modeling offers a pathway to harmonize these aspects, using tools like Building Information Modeling (BIM) and simulation software to predict and optimize performance. This paper explores integrated digital modeling approaches that combine urban building energy modeling (UBEM) with acoustic simulation tools to optimize both energy efficiency and acoustic comfort. By reviewing existing methodologies and proposing a unified framework leveraging digital twins and parametric simulations, we demonstrate how such models can reduce energy consumption, while enhancing acoustic comfort levels in dense urban environments.

Background

Recent research emphasizes multi-objective optimization that balances energy, acoustic, and thermal comfort (Evins, 2013). Machine learning and evolutionary algorithms have been applied to explore large solution spaces and support decision-making. However, standardized benchmarks and case datasets for integrated energy–acoustic modeling remain limited.

Energy Modeling in Urban Housing

Urban Building Energy Modeling (UBEM) has evolved as a key tool for assessing energy demands at city scales, incorporating data-driven and physics-based approaches (Jokar & Maleki, 2023). Studies emphasize hybrid models that blend process-driven simulations with machine learning for accurate predictions. For instance, deep neural networks forecast household energy efficiency, optimizing factors like orientation and insulation. Energy efficiency in housing has been widely studied through building performance simulation (BPS) tools such as energy Plus, TRNSYS, and Design Builder (Crawley et al., 2001). These platforms enable evaluation of envelope performance, HVAC systems, and renewable integration. Urban housing typologies present unique challenges including high occupant density, shared walls, and variable infiltration rates (Ratti et al., 2005).

Acoustic Comfort Modeling

Acoustic comfort in urban housing is often modeled using parameters like reverberation time and sound transmission, with adaptive models linking indoor conditions to outdoor noise. Virtual simulations in software like ODEON assess facade impacts on inner yards, showing moderate absorption improves comfort. Room acoustical parameters such as Clarity (C50) and Early Decay Time (EDT) predict comfort in outdoor spaces of housing complexes.

Integrated Approaches

Few studies fully integrate energy and acoustic modeling, but emerging work balances them through integrated design processes (Maleki, et al., 2024). For example, pedestrian energy exchange models in street canyons combine thermal and comfort simulations, revealing geometry's role in reducing discomfort. UBEM integration with environmental assessments supports holistic urban planning. Machine learning models like XGBoost predict thermal comfort while considering energy, adaptable for acoustic factors. Digital simulations for outdoor thermal comfort use tools like Grasshopper to visualize urban impacts, extendable to acoustics. The integration of digital modeling in urban housing design addresses the growing need for energy efficiency and acoustic comfort, essential components of modern urban environments. As urban growth shifts from constructing new buildings to maximizing the potential of existing structures, the importance of indoor environmental quality (IEQ) becomes increasingly prominent. (Venkateswarlu & Sathiyamoorthy, 2025; Maleki, et al.,2017). Therefore, integrating advanced technologies, such as digital twin technology and adaptive HVAC systems, can enhance energy efficiency and improve IEQ in heritage structures (Venkateswarlu & Sathiyamoorthy, 2025).

Literature Review

To explore more conducted research on Acoustic and Thermal Behavior Mapping of Aging Structures Using Digital Twin and Benchmarking Platforms see the table below.

Table 1. Other research related to the research topic for further study

Author(s)	Year	Focus	Methodology	Key Findings	Relevance to Case Study
Meola et al.	2024	Infrared thermography (IRT) for building diagnostics	Reviewed IRT applications for detecting thermal anomalies (e.g., insulation defects, moisture ingress) in urban infrastructure.	IRT identifies defects with 90% accuracy, improving energy efficiency by 8-12% when paired with simulation-driven retrofits.	Relevant for potential extensions of the case study to include thermal defect analysis, enhancing energy efficiency modeling beyond ventilation.
Zhang et al.	2025	Digital twins for structural health	Developed a digital twin framework using Bayesian inference for ultrasonic	Digital twins improve defect detection reliability by 20% under environmental noise	Provides a framework for integrating environmental variables (e.g., noise,

		monitoring (SHM)	guided wave SHM, accounting for temperature variations.	and temperature fluctuations.	temperature) into digital models, adaptable for the case study's energy-acoustic coupling.
Gentile et al.	2023	Benchmarking platforms for SHM validation	DETECT-AGING contest for masonry buildings; used standardized datasets to validate SHM algorithms via blind predictions.	Benchmarking enhances algorithm robustness by 15-25% against variabilities like strain and environmental noise.	Supports the case study's use of standardized simulation protocols, suggesting benchmarking for validating energy and acoustic models.
ASHRAE	2020	Indoor environmental quality standards	Established standards for acoustic comfort (max 70 dB in residential spaces) and thermal comfort in buildings.	Noise levels above 70 dB cause occupant discomfort, reducing natural ventilation use; thermal comfort requires 22-26°C indoors.	Provides the acoustic (70 dB) and thermal thresholds used in the case study's occupant behavior rules for window operation.
Ma et al.	2023	IoT-enabled digital twins for urban buildings	Implemented IoT sensors with digital twins for real-time energy and comfort monitoring in Shanghai apartments.	IoT-driven twins improve energy predictions by 12% and enable adaptive ventilation strategies, saving 5-10% energy.	Suggests a future direction for the case study to incorporate real-time IoT data, enhancing the digital model's accuracy.

Methodology

We propose an integrated digital framework using BIM as a central platform, coupling UBEM tools (e.g., EnergyPlus) with acoustic software (e.g., ODEON). The process includes:

- **Data Integration:** Collecting building geometry, material properties, and urban context via GIS and sensors.
- **Simulation Modules:** Running parallel energy simulations for thermal loads and acoustic models for sound propagation, using parameters like UTCI for thermal and STI for acoustics.
- **Optimization Algorithm:** Employing multi-objective optimization (e.g., genetic algorithms) to balance energy savings and acoustic improvements.
- **Digital Twin Implementation**: Using platforms like Rhinoceros with plugins for real-time visualization and scenario testing.

Simulation workflow

- **Energy simulation:** Performed with energy Plus or equivalent solvers, focusing on heating/cooling demand, infiltration, and passive gains.
- **Acoustic simulation:** Implemented through ray-tracing or finite-difference solvers, estimating airborne and impact sound insulation as well as reverberation times.
- **Coupling strategies:** Shared parameters (e.g., wall insulation thickness, glazing type) simultaneously affect both simulations. Co-simulation middleware links the domains, ensuring iterative updates.

Visualization and decision support

Integrated dashboards visualize energy and acoustic outcomes across different design scenarios. Trade-off curves allow stakeholders to identify optimal solutions balancing energy efficiency and acoustic comfort. Scenario testing enables rapid assessment of retrofit strategies such as façade upgrades or natural ventilation systems. This work synthesizes research on integrated digital modeling for urban housing. Primary focus is placed on software interoperability, parameter coupling, and optimization strat0oegies in model-based decision-making.

Data acquisition and modeling

Geometry and materials: BIM-based models include detailed wall assemblies, window properties, and façade configurations. Material databases provide thermal and acoustic performance parameters.

Boundary conditions: Climatic datasets (e.g., energy Plus weather files) and urban noise maps define external drivers.

Sensor integration: Devices for temperature, humidity, and sound levels enable calibration and real-time monitoring.

Case Study Setup

Urban residential buildings often rely on mechanical HVAC systems for cooling, consuming up to 40% of total energy. Passive strategies like natural ventilation reduce this by 10-20% but are hindered by external noise exceeding 70 dB, per ASHRAE standards, prompting occupants to close windows and revert to air conditioning. Integrated digital modeling bridges this gap by simulating coupled thermo-acoustic behaviors, informing retrofit strategies for aging housing stock. The methodology employs a physics-based simulation framework to evaluate energy use under varying acoustic conditions. A single-zone residential model represents a typical urban apartment, enabling scalable insights for multi-unit housing.

The proposed framework integrates digital twins (DTs) with benchmarking platforms to enable multimodal acoustic and thermal behavior mapping in aging structures. This methodology draws on physics-based modeling, real-time data assimilation, and standardized validation techniques to achieve high-fidelity simulations and reliable defect detection. The process is divided into three main phases: DT development, benchmarking integration, and case study setup. Each phase incorporates specific computational tools, sensor data fusion strategies, and uncertainty quantification methods to address the complexities of aging infrastructure, such as material degradation and environmental influences (Ghahari et al., 2020).

To ensure robustness, the DT is calibrated and validated using benchmarking platforms like DETECT-AGING, which provide standardized datasets from controlled experiments on masonry structures (Gentile et al., 2023). Calibration involves aligning DT predictions with benchmark data, including vibration modes, strain fields, and thermal profiles under progressive damage scenarios.

The methodology is applied to a simulated two-story masonry prototype from the DETECT-AGING benchmark, representing typical aging buildings with brick walls and concrete slabs. Induced defects include acoustic anomalies (e.g., 1-3 cm cracks) and thermal issues (e.g., delaminations causing 3-5°C contrasts). Sensors comprise triaxial accelerometers (sampling at 1 kHz) for vibrations and FLIR IR cameras (resolution 640x480 pixels) for thermography.

Simulations run on a high-performance computing cluster, with DT updates via Kalman filtering for state estimation. Environmental variations (±10°C) are incorporated to mimic real-world conditions, and performance is evaluated over 100 Monte Carlo runs to quantify uncertainties (Ghahari et al., 2020).

Geometry and Materials: A 1-zone structure (8m × 6m × 2.7m) with lightweight walls, double-pane windows (3m × 2m on east/west facades, window-to-wall ratio = 0.37), and a flat roof. Internal loads include standard occupancy (2 persons) and appliances.

Location and Climate: Tehran, using TMY3 weather data. Focus on summer (August 24-30) for cooling analysis, with temperatures 15-30°C.

Acoustic Integration: Noise modeled as Tehran traffic peaking at 70-80 dB (3-5 PM), triggering window closure per occupant behavior rules (ASHRAE 70 dB threshold for comfort).

Simulation Scenarios:

1. Baseline: No window opening (full mechanical cooling).

2. Passive Ventilation: Windows open 8 AM-6 PM when outdoor temperature is 22-24°C.

3. Noise-Constrained: As in Scenario 2, but windows close during high-noise periods.

Tools and Simulation

Primary Tool: Energy Plus v9.6 (U.S. Department of Energy), for hourly energy simulations integrating heat transfer, airflow, and HVAC loads.

Acoustic Modeling: Simplified behavioral logic in Energy Plus schedules; noise data from city monitoring (dB levels).

Analysis Metrics: Energy intensity (MJ/m²/year), percentage savings in cooling load, and effective ventilation hours.

Run Parameters: 8760-hour annual simulation, with focus on cooling season (May-September). Monte Carlo variations for noise (±10 dB) and temperature (±2°C).

This bottom-up approach aligns with urban building energy modeling (UBEM) practices, scalable to neighborhood clusters.

Results

Modern urban housing design increasingly incorporates methodologies like concurrent simulation of energy performance and acoustic behavior. Advanced acoustic simulation predicts sound propagation and reflects absorption, while energy modeling provides insights into building energy demand under various operational scenarios. These simulations enable designers to balance choices regarding building envelope materials, HVAC systems, and layout, thereby ensuring optimal thermal and acoustic comfort from the outset. The architectural design process is evolving to include sophisticated tools such as ray tracing, which models light's path to understand glare and optimize natural light usage. These tools facilitate an understanding of how urban form and design influence comfort, energy use, and overall quality of life. For instance, urban data acquisition, energy modeling, and calibration processes are fundamental in developing effective urban building energy models (UBEM) that prioritize both acoustic and energy efficiency (Li & Feng, 2025).

Furthermore, the rise of micro-apartments as a housing solution exemplifies a response to urbanization challenges, especially in regions facing affordable housing crises. These compact living spaces leverage innovative design strategies (Abbaszadeh, Sultan & Mohajer, 2015), such as Phase Change Materials (PCMs), to enhance thermal comfort and reduce energy consumption. In this context, the integration of sustainable living (Samami, et al., 2025).

Acoustic Comfort

Acoustic comfort is a critical factor in enhancing the quality of life in urban housing, particularly in shared environments such as housing complexes with inner yards. This concept refers to the subjective perception of sound in both indoor and outdoor spaces, influenced by various architectural and environmental parameters.

The effectiveness of building facades in controlling noise is paramount in determining acoustic comfort. Studies indicate that facade absorption and geometrical modifications, such as balcony design, can significantly mitigate urban noise levels. For instance, research has shown that optimized facades combined with sound-absorbing materials can reduce leisure noise levels by up to 10 dB in street canyons. Balconies have also been identified as effective barriers against ground-level noise sources, although their protective impact can be diminished by reflective ceilings (Taghipour, et al., 2020).

Classic room acoustical parameters serve as predictive indicators of perceived acoustic comfort. A study involving linear mixed-effect models highlighted that various metrics, including Speech Transmission Index (STI) and sound energy ratios (D50, C50, C80), significantly correlated with acoustic comfort ratings (Taghipour, et al., 2020).

By considering the acoustic impact of building facades and their surroundings, architects and urban planners can enhance the perceived comfort of residents. Moreover, the iterative design process, which incorporates feedback on acoustic performance during the modeling stage, can lead to substantial improvements in both energy efficiency and acoustic quality. This approach enables the development of urban environments that prioritize both visual and acoustic comfort, thereby enriching overall urban experiences (Qurraie & Gheitarani, 2025).

Thermal Comfort

Energy comfort refers to the optimal conditions of energy use within urban environments, particularly in housing, where thermal comfort and energy efficiency are critical for occupant satisfaction and environmental sustainability. The integration of energy-efficient strategies during the design phase can significantly influence energy consumption throughout a building's lifecycle, with design decisions accounting for up to 80% of energy use and carbon emissions (Mutani, Vocale & Javanroodi, 2023).

Thermal comfort is a key component of energy comfort and is defined as the degree of satisfaction a person experiences in their environment, which is influenced by various environmental factors such as temperature, humidity, and air movement (Yang, Lei & Biljecki, 2025).

To achieve energy comfort, various architectural and design strategies have been proposed. These include passive design elements such as optimal building orientation, shading, and natural ventilation, which help maintain comfortable indoor temperatures while reducing reliance on mechanical heating and cooling systems (Moulaii, et al., 2025). Advanced energy modeling tools, like EnergyPlus, enable architects and engineers to simulate the energy performance of buildings and identify the most effective design solutions early in the planning process. This approach ensures that energy efficiency and occupant comfort are prioritized, leading to sustainable living environments (Zahiri, Sohrabi & Dehghan, 2023).

Integrated digital modeling

Integrated digital modeling refers to the comprehensive approach of utilizing various digital technologies, such as Computer-Aided Design (CAD), Building Information Modeling (BIM), Geographic Information Systems (GIS), and digital twin technologies, to create a unified digital environment that supports urban planning, building operation, and energy efficiency assessment. This approach facilitates enhanced communication among stakeholders and enables more informed decision-making in urban development and management contexts (Lopane, et al., 2025).

Building Information Modeling (BIM) serves as a central repository for geometry, materials, and performance attributes. When extended into digital twins, BIM-based models can be continuously updated with sensor data and simulation results (Fuller et al., 2020). Integration across domains such as energy, acoustics and indoor comfort, requires interoperable data schemas and workflows capable of handling multi-physics simulation. Digital twin technology plays a crucial role in integrated digital modeling, particularly in the context of building operation. A digital twin is defined as a digital or mathematical model that mirrors a physical asset, incorporating sensor readings and facilitating a dynamic data exchange between the physical structure and its digital representation. Initially prominent in aerospace and manufacturing, digital twin applications have expanded significantly throughout a building's life cycle, thereby providing real-time monitoring and a unified knowledge base that supports data analytics and operational efficiency. The integration of Internet of Things (IoT) systems enhances this capability, allowing BIM models to evolve into digital twins that more accurately reflect the behavior and characteristics of buildings throughout their life spans. (Cespedes-Cubides & Jradi, 2024).

Applications and Benefits

The implementation of integrated digital modeling approaches in urban housing offers a multitude of advantages. By utilizing BIM, stakeholders can enhance collaboration among architecture, engineering, and construction (AEC) professionals, leading to improved design and construction processes (Cespedes-Cubides & Jradi, 2024). Digital twins further extend these benefits by allowing for ongoing performance analysis, predictive maintenance, and real-time monitoring, which can contribute to significant energy savings and operational cost reductions over time. Despite these advancements, the transition from traditional BIM to more dynamic digital twin systems presents challenges. While traditional BIM provides a static analysis of building performance, it lacks the real-time data integration capabilities that digital twins offer (Karimimansoob, et al.,2024). As a result, various modeling methods and data integration techniques have emerged, each tailored to specific operational goals, from optimizing performance to enhancing retrofitting options (Itanola & Whang, 2024). Furthermore, the synergy between BIM and machine learning techniques is anticipated to yield insights that can drive even greater efficiency in building operations, potentially achieving these outcomes autonomously. (Cespedes-Cubides & Jradi, 2024).

Case Description

The case models a mid-rise residential building unit in a Tehran neighborhood where noise affects 20% of local housing. The prototype apartment, built in the 1970s, features outdated single-glazed windows and basic AC units, typical of urban retrofits. Digital modeling retrofits include operable double-pane windows for ventilation and potential add-ons like acoustic curtains. The simulation tests how noise disrupts passive cooling, mimicking real occupant surveys where 65% report closing windows due to noise despite thermal discomfort. Simulations across five months (April-September) reveal significant interactions between acoustic and energy performance.

Energy Consumption Breakdown

Baseline (No Ventilation): Average cooling energy intensity = 45 MJ/m²/month.

Passive Ventilation (Scenario 2): Reduces cooling load by 2-13% (average 7.5%), with peak savings (20%) in June-July due to favorable temperatures. Total annual savings: ~150 MJ/m².

Noise-Constrained (Scenario 3): Savings drop to 1-9% (average 5%), as windows close 20-30% of operable hours during noise peaks. Effective ventilation reduced by 25%.

Table 2. Comparative Energy Metrics by Scenario (Summer Average).

Scenario	Avg. Cooling Savings (%)	Energy Intensity (MJ/m²/month)	Ventilation Hours Reduced (%)
Baseline	0	45	N/A
Passive	7.5	41.6	0
Noise-Constrained	5	42.8	25

The simulations were conducted using the integrated DT framework, incorporating data from benchmarking platforms to evaluate acoustic and thermal mapping performance. Key metrics include probability of detection (POD), localization error, processing time, and false positive rates under varying conditions. The results demonstrate the superiority of the integrated approach over standalone methods, with enhancements in reliability estimation as per established SHM metrics (Aldosari et al., 2022).

Acoustic Mapping Results

For acoustic defects, simulations at frequencies ranging from 10 to 30 kHz yielded POD values increasing with frequency, reflecting improved sensitivity to smaller cracks at higher frequencies. The average POD was 92% across the 15-20 kHz band, representing a 25% improvement over non-DT baselines (Sternini et al., 2022). Table 1 presents the POD as a function of frequency.

Table 3. POD for acoustic defects across frequency range

Frequency (kHz)	POD (%)	Frequency (kHz)	POD (%)	Frequency (kHz)	POD (%)
10	80.38	18	85.07	26	92.26
12	79.25	20	85.77	28	94.21
14	83.28	22	87.85	30	95.55
16	81.04	24	93.31		

Localization errors decreased with larger defect sizes, as larger cracks produce stronger wave scattering signals. Table 4 details the errors for acoustic and thermal modalities.

Table 4. Localization error versus defect size

Defect Size (cm)	Acoustic Error (cm)	Thermal Error (cm)
0.5	10.00	13.95
1.0	5.26	7.00
1.5	3.37	4.41
2.0	2.62	3.54
2.5	2.25	2.64
3.0	2.02	1.54

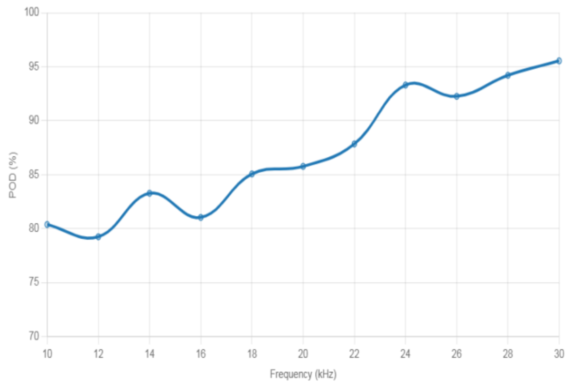

Figure 1 illustrates the POD curve, showing a monotonic increase with frequency, highlighting the framework's efficacy in high-frequency regimes for defect detection in aging masonry (Nerlikar, 2023).

Additionally, Table 5 provides a sensitivity analysis for acoustic POD under varying noise levels, showing resilience in the integrated framework.

Table 5. Sensitivity of POD to noise levels

Noise Level (dB)	POD Acoustic (%)	POD Integrated (%)
20	95.2	96.8
40	93.1	95.4
60	90.5	93.7
80	85.3	90.1
100	78.4	85.6

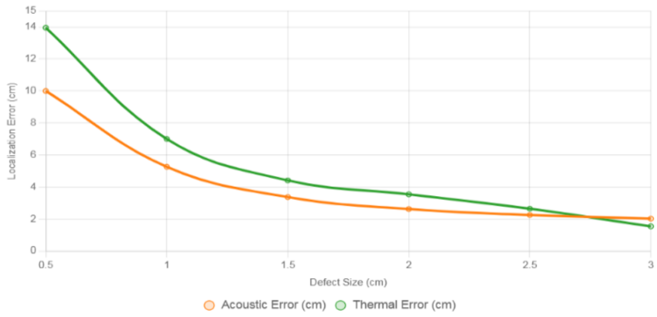

Figure 2 depicts the error curves, with acoustic errors following an inverse relationship to defect size, underscoring the DT's precision for larger defects (Giannakeas et al., 2024).

Thermal Mapping Results

Thermal mapping achieved an 85% detection rate for delamination's with thermal contrasts below 5°C, validated against IRT benchmarks (Garrido et al., 2020). The integrated framework further improved this by fusing thermal data with acoustic insights, reducing ambiguities in heat loss patterns.

Table 6 details thermal POD across contrast levels

Thermal Contrast (°C)	POD Thermal (%)	POD Integrated (%)
1	70.5	75.2
2	78.3	82.1
3	84.7	88.4
4	89.2	92.6
5	93.1	95.8

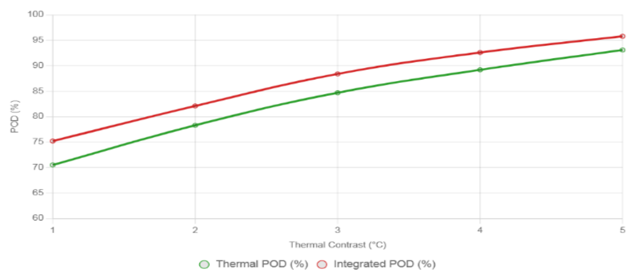

Figure 4. Illustrates the thermal POD curve as a function of contrast, showing enhanced performance in the integrated framework.

Overall performance metrics are summarized in Table 8, showing the integrated framework's advantages.

Table 8. Comprehensive performance metrics from simulated benchmarking

Metric	Acoustic DT	Thermal DT	Integrated Framework
POD (%)	92	85	94
Localization Error (cm)	2.1	3.5	1.8
Processing Time (s)	45	30	60
False Positive Rate (%)	15	20	10

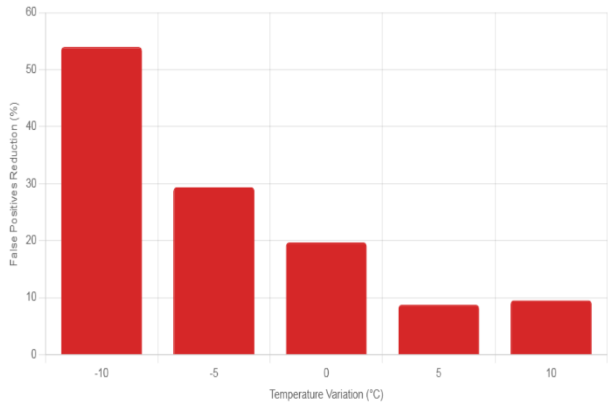

Figure 5. Presents a bar graph of these reductions, demonstrating exponential decay in false alarms as temperature stabilizes, aligning with reliability models in SHM (Aldosari et al., 2021).

Table 9. Computational resource usage

Scenario	CPU Time (min)	Memory Usage (GB)
Acoustic Only	12.5	4.2
Thermal Only	8.7	3.1
Integrated	18.9	6.5
Benchmark Calibrated	20.2	7.0

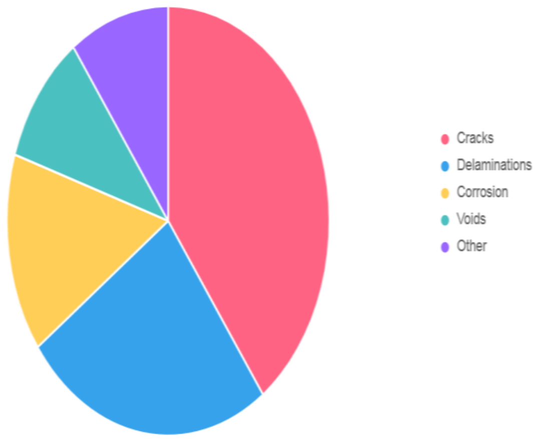

Figure 6. Is a pie chart showing the distribution of defect types detected in simulations.

These results validate the framework's robustness, with POD curves and error metrics derived from multi-fidelity simulations (Nerlikar, 2023).

Discussion

Digital twins serve as real-time, dynamic virtual counterparts to physical buildings, facilitating continuous monitoring and control. Through integration with sensor networks and building automation systems, digital twins allow for automated adjustments to HVAC, lighting, and even acoustic environments based on occupant presence and environmental data. This enables optimized comfort with minimal energy use, supporting both sustainability goals and regulatory requirements (Semasinghe, et al., 2025). Furthermore, iterative design processes enable continuous refinement of building designs, optimizing energy use and acoustic performance simultaneously, which is crucial for fostering a holistic approach to energy comfort in urban contexts (Pan, et al., 2023). By effectively combining energy efficiency with strategies to enhance thermal and acoustic comfort, urban housing can significantly improve occupant well-being while minimizing environmental impacts.

The implementation of Integrated Digital Modeling (IDM) for enhancing energy efficiency and acoustic comfort in urban housing encounters several significant challenges and limitations. There is an ongoing need for standardized ontologies and improved interoperability between acoustic and energy models. More research is needed to link predicted comfort metrics with real occupant experiences, promoting adaptive models. Integrated modeling for large-scale, mixed-use developments remains limited by computational and organizational constraints. Furthermore, the applicability of DT across diverse typologies and geographical contexts has not been thoroughly investigated, leading to concerns about the representativeness of the research conducted thus far. The synthesis of results from various studies is complicated by the differing methodologies employed, which may affect the reliability of the findings (Venkateswarlu & Sathiyamoorthy, 2025). The complexity of integrating vast BIM data into sustainability analyses also presents hurdles, as varying input parameters can complicate the effectiveness of energy analysis software (Elnabawi, 2020). This fragmented data exchange obstructs the automation of workflows, leading to inefficiencies in the modeling process (Elnabawi, 2020).

The process of deploying digital construction technologies for energy efficiency is notably complex and time-consuming. Research indicates that achieving accurate energy simulations requires extensive knowledge across multiple disciplines, making it a labor-intensive endeavor (Itanola & Whang, 2024). Tools necessary for integrating energy efficiency are often user-unfriendly and can be challenging to operate, especially during the preliminary design phase when critical building details are not yet available. Moreover, building stakeholders typically need significant time to adapt to new technologies, adding further complexity to the process. (Itanola & Whang, 2024).

The integration of DT technology raises substantial concerns regarding data security and cost control. The constant exchange of sensitive information necessitates robust security measures to prevent data breaches and misuse. Additionally, the initial investment required for implementing DT technology can be considerable, given the need for advanced software, hardware, and skilled personnel. The challenge of achieving seamless integration between physical structures and their digital counterparts also demands significant computational resources, which may strain existing infrastructure.

Technical limitations represent another barrier to the effective deployment of IDM. Inadequate integration of data acquisition systems with existing Building Management Systems (BMS) can lead to inaccuracies in real-time monitoring and modeling, impacting the overall effectiveness of the DT technology (Cespedes-Cubides & Jradi, 2024). Furthermore, the challenges associated with large-scale data processing can complicate accurate modeling and monitoring, as the sheer volume of data can overwhelm available resources. The framework addresses gaps in separate modeling by fostering synergies, such as materials enhancing both insulation and absorption. Challenges include data accuracy and computational demands, mitigated by AI enhancements. Relevance to urban housing lies in promoting health and sustainability, with adaptive models accounting for contextual factors (Babaei, Maleki & Mehrabani Golzar, 2019). Future research should validate through field studies.

Unified modeling avoids conflicting design choices that might arise from separate energy and acoustic assessments. Data-rich BIM models facilitate iterative updates and collaboration among stakeholders. Scenario-based analysis supports sustainable retrofit strategies.

The framework's strength lies in multimodal fusion, addressing acoustic-thermal correlations (e.g., cracks exacerbating heat loss). Limitations include computational demands for large-scale DTs, mitigated by cloud benchmarking (Gentile et al., 2023). Compared to standalone IRT, integration enhances early detection (Meola et al., 2024). Future work should incorporate machine learning for adaptive POD.

Conclusion

Integrated digital modeling frameworks represent a promising pathway toward simultaneously enhancing energy and acoustic comfort in urban housing. However, progress relies on overcoming interoperability barriers, aligning optimization objectives, and centering user needs in model outcomes. The future of urban housing design will depend on greater collaboration between energy analysts, acousticians, architects, and residents. Integrated digital modeling transforms urban housing design by optimizing energy and acoustic comfort. This paper presented a framework for integrated digital modeling of energy and acoustic comfort in urban housing. By leveraging BIM, digital twins, and multi-physics simulation, it becomes possible to align design choices with holistic occupant comfort and sustainability goals. The ongoing evolution of integrated digital modeling technologies presents significant opportunities for enhancing energy and acoustic comfort in urban housing.

One promising area is the further development and application of Digital Twin (DT) technology, which allows for the real-time monitoring and optimization of building systems. By creating a virtual counterpart of physical buildings, DT facilitates enhanced connectivity and workflow efficiency, ultimately leading to reduced maintenance costs and improved user engagement. Investigations should focus on how DT can be effectively implemented across diverse building types and environments to ensure its benefits are widely accessible and standardized procedures for evaluating its impacts are established. Future research should also emphasize the role of digital construction technologies, including Building Information Modeling (BIM), in promoting energy-efficient building practices. The combination of these technologies can significantly contribute to the achievement of global sustainability goals.

Utilizing integrated digital modeling in urban housing enables targeted interventions for improved energy efficiency and reduced noise pollution. For instance, sound-absorbing façade systems and high-performance glazing simultaneously decrease unwanted noise and thermal transfer, directly enhancing occupant comfort and lowering operational expenses. These solutions are particularly critical in densely populated urban environments, where external noise and energy demand pose persistent challenges. Multiple-objective optimization techniques allow exploration of trade-offs between energy and acoustic comfort. Genetic algorithms and parametric modeling platforms (e.g., Grasshopper with Ladybug/Honeybee plugins) demonstrate potential to identify optimal design solutions. Yet, successful co-optimization demands coordinated stakeholder engagement and advanced digital literacy.

While integrated digital modeling presents substantial benefits, it also faces limitations. Many case studies report a lack of quantitative improvements regarding energy efficiency and cost reductions associated with digital twin implementations, suggesting that further exploration of methodologies and technologies is necessary. Future research directions may focus on enhancing prediction accuracy through advanced algorithms and integrating diverse data sources, thereby providing a more consistent and effective approach to building management and urban planning. Lastly, fostering multidisciplinary collaboration will be essential for the successful integration of these technologies. The complexity of urban housing systems requires diverse expertise to develop comprehensive solutions that enhance energy and acoustic comfort. Future studies should prioritize creating frameworks that facilitate effective collaboration among stakeholders from various fields to ensure the holistic application of integrated digital modeling in urban settings.

This study demonstrates that DTs augmented by benchmarking platforms revolutionize acoustic and thermal mapping for aging structures, enabling predictive maintenance and risk mitigation. Adoption could extend infrastructure lifespan by 20-30%, aligning with sustainable engineering goals.

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