

## Digital Twins for Integrated Energy and Structural Performance Assessment of Buildings: A Systematic Review and Research Gap Analysis

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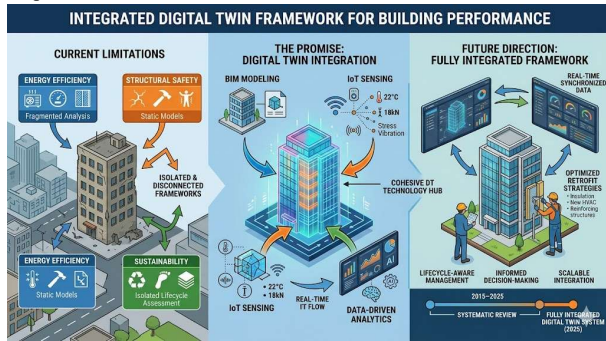
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### INTRODUCTION & AIM

Buildings are critical for energy efficiency and structural safety, yet these aspects are typically assessed using **isolated frameworks**, limiting holistic lifecycle decision-making.

**Digital Twin (DT)** technology integrating BIM, IoT, and data-driven analytics offers a pathway for **real-time, integrated performance assessment**. However, existing research is largely **domain-specific**, with limited interoperability, weak data exchange, and minimal real-time validation.

This study presents a **systematic review (2015–2025)** of DT-based approaches for integrated energy and structural assessment, providing a **quantitative synthesis**, identifying key research gaps, and outlining a **future research agenda** for scalable and interoperable DT frameworks.



### METHOD

A systematic literature review was conducted following PRISMA guidelines to identify and analyze Digital Twin (DT) applications for integrated energy and structural performance assessment.

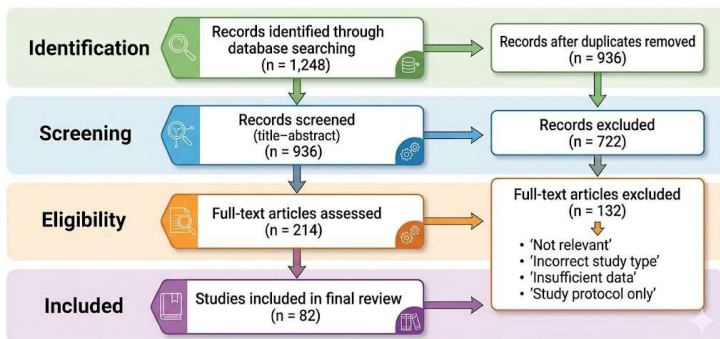
A total of 1,248 records were retrieved from Scopus, Web of Science, and IEEE Xplore using structured keyword combinations including “digital twin,” “BIM,” “energy performance,” “structural health monitoring,” and “building assessment” for the period 2015–2025.

After removing duplicates ( $n = 312$ ), 936 records underwent title–abstract screening. Subsequently, 214 articles were assessed for full-text eligibility, resulting in 82 studies included in the final review.

The selected studies were analyzed using a combined quantitative and thematic synthesis framework, focusing on:

- DT architectures and system design
- BIM integration and interoperability
- Energy simulation techniques
- Structural analysis and SHM approaches
- Sensor data integration and real-time synchronization
- Validation strategies and implementation scale

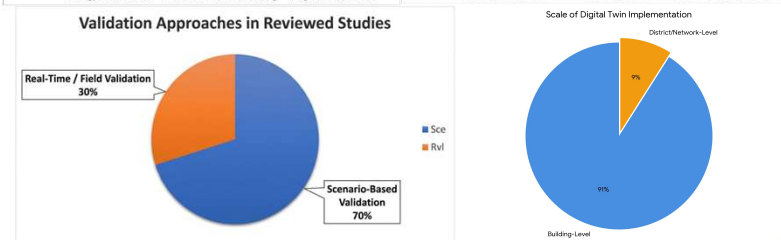
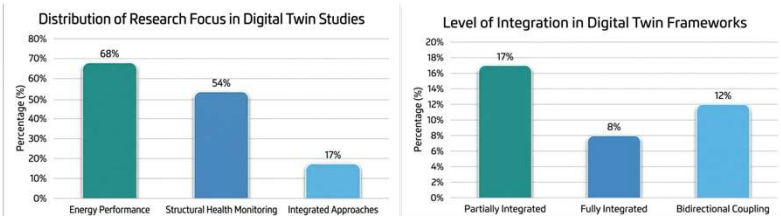
### Standard PRISMA 2020 flow Diagram



### RESULTS & DISCUSSION

The analysis of 82 studies shows a strong focus on single-domain Digital Twin applications, with limited progress toward integrated frameworks. About 68% focus on energy performance, while 54% address structural health monitoring (SHM). Only 17% propose partially integrated systems, and fewer than 8% achieve full interoperability. Bidirectional data exchange between energy and structural domains appears in just 12% of studies. Validation is mostly scenario-based (~70%), with limited real-time or long-term field testing. Large-scale implementations are rare, covering only 9% of studies.

Overall, the results highlight major gaps in interoperability, real-time integration, and lifecycle scalability, showing that fully integrated Digital Twin systems are still an emerging research area.



Aspect	Current State	Identified Gap
Domain Focus	Energy or Structural (separate)	Lack of integrated multi-domain systems
Interoperability	Limited platform connectivity	No seamless data exchange
Data Coupling	Mostly unidirectional	Lack of bidirectional interaction
Validation	Scenario-based	Limited real-time validation
Scale	Building-level focus	Lack of district-scale DTs
BIM Integration	Partial usage	Lack of standardized workflows
Lifecycle Coverage	Design/operation focused	Limited full lifecycle integration

### CONCLUSION

- This review highlights that Digital Twin research in the built environment is still largely fragmented, with energy and structural performance mostly addressed separately. True integration and fully interoperable, bidirectional systems remain limited.
- Most studies rely on scenario-based validation, with few real-world or large-scale implementations, indicating a gap between research frameworks and practical deployment.
- Overall, integrated energy–structural Digital Twins are still emerging, with future progress depending on improved interoperability, real-time IoT integration, and scalable, AI-driven modeling approaches.

### FUTURE WORK

- Develop interoperable BIM–IoT Digital Twin frameworks for seamless energy–structural integration.
- Move from scenario-based studies to real-time, sensor-driven validation using long-term field data.
- Scale Digital Twin applications from building to district/city level for lifecycle assessment.
- Integrate AI-based surrogate models and uncertainty-aware analytics for efficient and reliable predictions.