Design of Energy-Neutral Smart Buildings: An Ontological Framework to Integrate LCA, BIM and PLM

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Abstract

The smart built environment (SBE) exhibits a dynamic integration between the physical and digital environment, where the physical elements, such as spaces, walls, windows, doors, roof, and floor, interact with the digital sensing elements, such as sensors, actuators, control systems, and networking systems. Energy neutrality is a concept dealing with the lifecycle energy performance of energy-saving sensing devices integrated into the SBE, such as the smart sensor-actuator system (SSAS). Ontology is a concept of representing and organising information (and their inter-relationships) about a specific domain with the intention of managing complexity, enhancing understanding, and promoting problem-solving skills. Employing semantic web technologies, a framework for designing and simulating energy-neutral, sensor-embedded smart buildings is proposed, which exhibits an ontological integration of Lifecycle Assessment (LCA), Building Information Modelling (BIM), and Product Lifecycle Management (PLM). A preliminary implementation of the proposed framework is demonstrated using OWL (Ontological Web Language) in Protégé software. After that, a design interaction matrix between buildings (and their components), building designers, product designers, and lifecycle practitioners is developed to provide efficiency, optimisation, and sustainability in the design process. This integration framework would streamline the design process, providing a collaborative simulation platform for cross-field designers to enhance the environmental performance of the SBE. In the future, this framework could be employed to create a robust real-time integrated IoT-based platform for designing and modelling energy-neutral smart buildings.

1. Introduction

The design and modelling of smart buildings is a complex process compared to conventional buildings (Kumar & Mani, 2019; Panteli et al., 2020). The smart built environment dynamically integrates the physical and digital environments, with physical elements—such as spaces, walls, windows, doors, roofs, floors, lights, HVAC and so on—interacting with digital sensing elements such as sensors, actuators, control systems, and networking systems (Dasgupta, 2018; Kumar et al., 2022). The challenges in this interactive relationship stem from the need for a real-time information exchange between physical and digital environments, emphasising the importance of decisions made during the early stages of building design. For example, luminaire technology (LED/CFL), integrated occupancy sensors, and real-time interactions (or feedback) are critical for occupant comfort, well-being, and energy efficiency in the lighting subsystem of smart buildings (Khanna et al., 2019; Kumar et al., 2018; Nair et al., 2018 and 2019). Despite recent advances in information technology and computational intel-ligence, the architecture, engineering, construction, and operations (AECO) industry manifests a sub-stantial digital divide in technology adoption (Ayinla & Adamu, 2018; Saka et al., 2022). The computing industry's technical know-how, such as semantic web technologies, could be leveraged in the AECO industry to bridge this burgeoning gap (Pauwels et al., 2017).

Smart building design (SBD) is a cross-functional domain involving multiple stakeholders, including building designers (architects, civil engineers, structural engineers), computer and electronic engineers, sensor designers, control engineers, LCA practitioners, interaction designers and data scientists (Kumar & Mani, 2017a). As a result, incorporating smart sensor-actuator systems (SSAS) into the construction, information, operation, and control systems of smart buildings takes time and resources. The SBD requires a constant knowledge exchange and

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information feedback from cross-functional domains to optimise performance. LCA, BIM, and PLM are domains involved in various SBD stages but are fragmented in process/data integration and stakeholder management, resulting in data redundancy, complexity, and inefficiency.

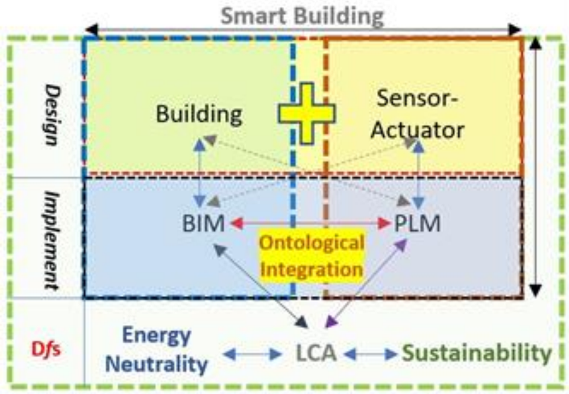


Fig. 1 – Design of energy-neutral smart buildings: conceptual structure of the research study integrating LCA, BIM and PLM

This paper proposes a framework for designing and modelling energy-neutral, sensor-embedded smart buildings using an ontological integration of LCA, BIM and PLM employing semantic web technologies. Fig. 1 presents the conceptual structure of the study.

Integrating collaborative knowledge of various designers and domains—at the early design phase of a smart building—is critical for synchronising the different design methodologies adopted by each stakeholder. Stakeholders (designers and modellers) use field-specific design and implementation methodologies from their respective domains at various stages of the design process. As a result, a comprehensive framework defining the criteria for combining data from multiple fields into a single collaborative platform that supports the inter-accessibility of data from all stakeholders involved in designing and modelling a smart building is needed. Such a framework reduces the limitations of disconnected data by creating an ontology-based linked data model for smart building design using semantic web technologies.

1.1 Energy Neutrality in Smart Buildings

Energy Neutrality is a concept dealing with energy payback associated with energy-saving sensing devices such as smart sensor-actuator systems (SSAS) over their lifecycle (Kumar & Mani, 2017b). Often, the energy involved over the lifecycle of an SSAS could be more than the energy-saving it yields, depending on the connected load (Kumar & Mani, 2017a). Smart buildings are those integrated with SSAS aimed at improving the productivity of the building occupants, saving energy, and information management. With smart buildings becoming increasingly complex, energy neutrality computations can provide an insight into the appropriate design and integration of smart sensor-actuator systems. Earlier studies into energy neutrality have revealed that the design of the SSAS in its entirety (electronics, housing, fixtures, wiring) has a significant impact on its total embodied energy (Kumar & Mani, 2017a and 2017b). The SSAS could be viewed as products integrated into buildings, with their lifecycle design influencing their effective integration in buildings, which ultimately affects the sustainability performance of smart buildings.

1.2 Lifecycle Assessment

Lifecycle assessment (LCA) is a method to assess the environmental impacts of a product (such as SSAS) throughout its lifecycle, including extraction, manufacturing, use/operation, and end-of-life stages (ISO, 2006). LCA methodology is one of the industry-accepted and scientific methods to assess the sustainability of a product (Jensen et al., 1997; Röck et al., 2018). It considers the inflow and outflow of mass, energy, and emissions through various product lifecycle stages. ISO 14040-14044 is the international standard that describes the framework and guidelines for conducting an LCA. The different phases according to ISO 14040:2006 are: 'Goal and scope definition', 'Lifecycle inventory analysis (LCI)', 'Lifecycle impact assessment (LCIA)', 'Interpretation phase' and 'Reporting and review phase' (ISO, 2006). The definition of 'system boundary' and 'functional units' are essential steps to conduct an LCA of any product. The databases used are Ecoinvent, GaBi, USDA, ELCD, Agri-footprint, etc. The prominent software used is Gabi, SimaPro, Umberto, openLCA, and so on.

1.3 Building Information Modelling

Widely used in the AECO industry, Building Information Modelling (BIM) is an integrated infrastructural data management process that shares and increases the transparency of building data in its designing, construction, and management (Ghaffarianhoseini et al., 2017; Volk et al., 2014). BIM is a three-dimensional model-ling process for developing a built environment as a digital representation of physical built elements and spaces (Ghaffarianhoseini et al., 2017). Moreover, BIM actively supports design and management decision-making at all phases of the building lifecycle, including planning, design, construction, and management stages, thus providing a collaborative platform for all the stakeholders by enhancing the information flow. The software tools for conducting BIM are Autodesk Revit, ArchiCAD, NavisWorks, Trimble Connect, and VectorWorks Architect.

Table 1 – A brief comparison of LCA, BIM and PLM

	LCA	BIM	PLM
Industry	Sustainability assessment	AECO industry	Manufacturing industry
Goal	Interested in environmental impacts	Building design construction and management	Product lifecycle management
Model & data	Lifecycle model & database	3D virtual models & BIM data	3D Product model & CAD data
Stakeholders	LCA practitioners, compliance authorities, designers & researchers	Shared repository between architects, engineers, and managers	Designers, engineers, manufacturers, researchers

1.4 Product Lifecycle Management

Product Lifecycle Management (PLM) is an extensive data management system for managing the entire life of a product. It is a collaborative activity that integrates product management and stakeholders across its lifecycle (Lämmer & Theiss, 2015). The product's data flows through initial design conception to detailed engineering design, manufacturing, packaging, distribution, usage, service (maintenance), and end-of-life phases. It is critical to centralise a product's information throughout its lifecycle to facilitate cross-domain knowledge exchange. The approach adopted in PLM primarily focuses on improving product efficiency in its design, economic value, environmental impact, and social outreach to promote the decision-making process, especially during early design decisions. Table 1 compares LCA, BIM, and PLM and lays the conceptual foundation for their integration.

1.5 Ontology and Semantics

Ontology is a machine-readable (formal) specification of conceptualisation for representing and organising information in a specific domain to manage complexity, improve understanding, and promote problem-solving ability (W3C, 2004). By converting complex systems into simple processes, ontology creates a shared and collaborative platform in the information sciences, allowing knowledge to be used in widespread cross-domain functionality that can be searched and queried via the internet. It also explicitly manages knowledge bases by systematically organising their specification—in terms of concepts, classes, properties, relations, definition, function, constraints, axiom, rules, and categories—and displaying logical reasoning and web semantics in data description and structural layout (for example, knowledge graph).

The family of ontologies (formal knowledge representation languages) are created in Web Ontology Language (OWL), based on the Semantic Web domain (Antoniou & Van Harmelen, 2004; W3C, 2004). The design of OWL is a build-up version of the Resource Description Framework (RDF). Semantic web technologies (OWL and RDF) promote mapping and analysis of data to create meaningful knowledge-bases and promote information interoperability across domains. In general terms, the primary function of semantic web technologies is the creation of an interlinkage (of language with different formats) that integrates different frameworks adopted from cross-functional fields and data collected from multiple sources in varied (non-standardised) protocols. Hence, ontologies authored in formal languages (such as OWL) are the connecting bridges across multiple data formats to extract common (and unambiguous) meaningful information, characterising the knowledge in class, objects, and their inter-relativity, functions, attributes, and hierarchies. From the semiotic perspective, any language (machine-readable or English) consists of three distinct fields: a) syntactics (objective: the set of rules and grammatical structure), b) semantics (subjective: the arrangement of vocabulary in a structured format to generate its meaning and expression), and c) pragmatics (contextual implicature: inference and implication, context-dependent). Similarly, semantic web technologies have triples for knowledge management and modelling semantic data. The semantic triples consist of three entities which are as follows: (a) subject (entity); (b) predicate (attribute); and (c) object (value-model) to compose a common machine-interpretable statement about the semantic database. Therefore, this makes ontological languages (e.g., OWL) an integration layer to standardise the cross-functional knowledge-base. For the effective design of smart buildings, the integration of LCA, BIM, and PLM is necessitated. The 'smart building design' domain could benefit immensely by leveraging the power of ontology and semantics to integrate SSAS into buildings, thereby making them more sustainable. Hence, Ontology and semantic web technologies provide an appropriate collaborative platform for such a cross-domain integration.

2. Integrated Ontological Framework

An integrated ontological framework is proposed in Fig. 2 to integrate LCA, BIM and PLM at various levels, i.e., L1-data integration layer, L2-data exchange layer, L3-software implementation layer, L4-design implementation layer, L5-stakeholder integration layer, and L6-domain integration layer. An ontological knowledge integration framework across these layers (L1-L6) provides a consolidated framework for the collaborative design of energy-neutral smart buildings. The three vertices of the triangular layers represent the LCA (sustainability domain), the BIM (building domain), and the PLM (product design domain), respectively. In the L1 layer, LCA data is integrated with product and building data. In layer L2, LCA, BIM and PLM exchange formats are consolidated to form a machine-interpretable, formal, and explicit data layer. Then, these data are fed into an integrated software environment that combines the LCA, BIM and PLM capabilities (L3).

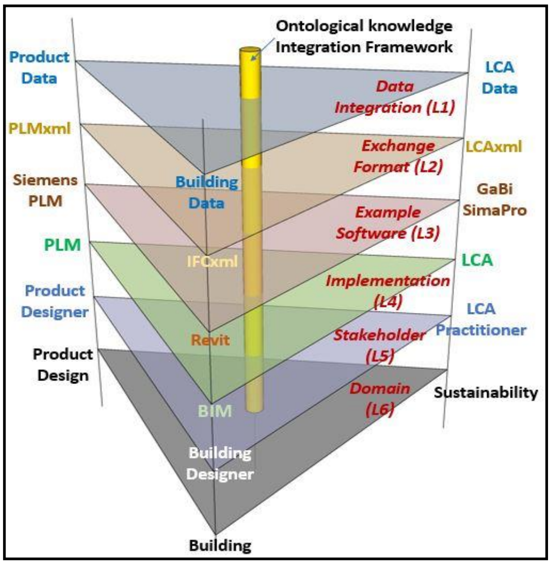


Fig. 2 – A model framework for the ontological integration of BIM, PLM and LCA for the design of energy-neutral smart buildings

After that, a design implementation layer (L4) is envisaged with data processing and knowledge integration capabilities. The L4 layer leads to a collaborative design platform(L5) comprising subject experts, i.e., LCA practitioners, architects and product designers. A single cross-functional design team may replace these designers in the future. Finally, the domain level integration of sustainability, building design, and product design is completed at layer L6, resulting in an inter-disciplinary domain for smart building design.

3. Implementation in Protégé

This preliminary framework for LCA-BIM-PLM integration is modelled on Protégé software using the ontological web language (OWL). The XML version used for the data integration is XML version 1.0. The data modelling vocabulary used is RDFS (Resource Description Framework Schema). The model framework structure comprises: - 'Entity', 'Classes', 'Object properties', 'Annotation properties', 'Data properties' and 'Individual by class'. 'Design_Smart_Buildings' is the main class in 'Owl: Things', and 'LCA', 'BIM', and 'PLM' are subclasses, as shown in Fig. 3.

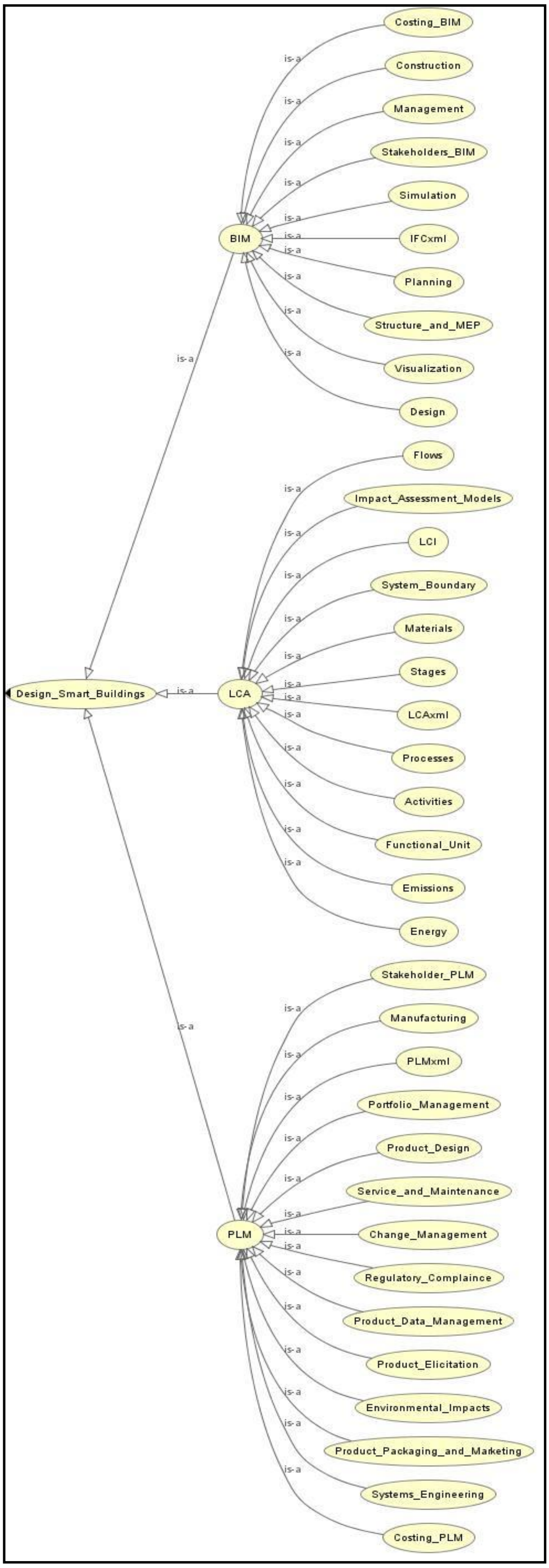


Fig. 3 – Preliminary implementation of the Model LCA-BIM-PLM framework for the design of smart buildings in Protégé Software

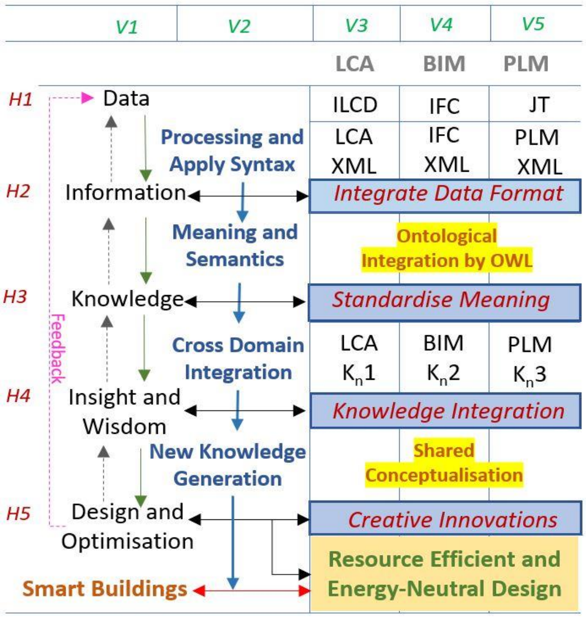
This framework schema can be saved in RDF/XML syntax, Turtle syntax, OWL/XML syntax, OBO syntax, Manchester/OWL syntax, OWL functional syntax, and LaTeX JSON-LD syntax. The 'reasoner' used for querying is ELK 0.4.3. 'OWLviz' is used for visualisation, while 'OntoGraf' is used for creating the graph. DL query and SPARQL 1.1 semantic query languages are used to access, retrieve, and manipulate data in RDFS. A Java code is generated to interface, translate, and bridge the sematic web ontology with the logic programming domain.

Each class/subclass can have their object, data, and annotation properties connected by relationships. Each instance in this framework can be designed as a standalone smart building with all the above-mentioned characteristics. These unique instances of smart buildings could be accessed via the web and would form a smart building database known as the 'Internet of Buildings' (IoB).

4. Discussions

As shown in Table 2, column V1 represents the lifecycle of data through 'data', 'information', 'knowledge', 'insight and wisdom' and 'design and optimisation' stages. The rows represent the integration between LCA, BIM and PLM domains.

Table 2 – OWL-based ontological integration framework for LCA, BIM and PLM to design energy-neutral smart buildings



It should be noted that appropriate transformations are applied to each stage. H1 represents the data processing and application of syntax for data integration. Existing data in the LCA, BIM and PLM industries are fragmented. Recently, work on standardising data formats within the domains has started, e.g., ILCD format in LCA, IFC data format in BIM, and JT format in PLM. The inter-operability of such cross-domain datasets is low due to multiple formats, multiple software platforms and different protocols. The eXtended Markup Language (XML) can solve this problem by applying user-defined specific rule sets (Syntax) to make it machine-interpretable and independent of software and hardware platforms. In this framework, the LCA, BIM and PLM data are converted to XML format, ready to be processed and queried.

Once the cross-domain data is syntactic and formal (machine-interpretable), the question of data semantics (meaning of such data) arises. In the H2 stage, the ontological web language (OWL) is used to semantically integrate this data and reduce ambiguity in its meaning. The processing of cross-functional data with semantic web tools would transform the data into chunks of useful information, which is still far away from a consolidated knowledge stage. In the H3 stage, when these chunks of information are integrated vertically in their respective domain, it becomes knowledge (e.g., Kn1 in LCA, Kn2 in BIM, Kn3 in PLM). In the next stage (H4), these knowledge sets are integrated through an ontological knowledge-integration framework to form a consolidated design knowledge set that provides valuable insights into smart building design and modelling. This acquired wisdom backed by empirical and integrated data, constitutes the breeding ground for 'shared conceptualisation' and 'new' knowledge. The designer (of smart buildings) would use this 'new knowledge' to improve designs, create innovations and provide optimisations for energy-neutrality in the H5 stage. Moreover, the design and optimisation (H5) stage would provide a feedback loop for the data stage (H1), further improving the data requirements, new data collection, data filtering and data integration processes. The capability of the H5 stage to provide a reinforcement feedback loop is not only limited to H1 stage, but it can also give feedback to H2, H3, H4 and H5 stage.

This framework facilitates multi-variate assessment of smart building performance in terms of energy, functionality, and operability before finalising the design by creating a 'design schema' as a transitional framework between the building's physical and digital (geo-spatial and energy-related) information. Additionally, this meta-framework comprehensively characterises a smart built environment integrated with a sensing system, allowing designers (and stakeholders) to evaluate the design using a hybrid simulation platform, and then make necessary early-design decisions regarding building performance, sensor-actuator integration, energy efficiency, and human-building interactions (HBI).

4.1 Design Implications

This ontological integration framework provides for the interactions (and feedback) between various designers, researchers and stakeholders involved in designing energy-neutral smart buildings. A design interaction matrix captures the interactions between buildings (and their functional components), and designers (of building, products, and sustainability) are captured by a design interaction matrix, as shown in Table 3. B(i) and B(j) represent smart buildings. B(i) is the superset containing elements from individual building components to the whole building system. 'Building designer' set D(B) consists of architects, civil engineers, structural engineers, and various consultants involved in the BIM process. Whereas D(P) represents the product designer set of smart sensor-actuator systems and energy-saving appliances.

Table 3 – Design interaction matrix for the ontological integration of BIM, PLM and LCA for energy-neutral smart buildings

$B(i) \rightarrow B(j)$ $\forall B(i) \subseteq B(j)$	**B(j)**	**D(B)**	**D(P)**	**S(L)**
B(j)	B(j) → B(j)	B(j) → D(B)	B(j) → D(P)	B(j) → S(L)
D(B)	D(B) → B(j)	D(B) → D(B)	D(B) → D(P)	D(P) → S(L)
D(P)	D(P) → B(j)	D(P) → D(B)	D(P) → D(P)	D(P) → S(L)
S(L)	S(L) → B(j)	S(L) → D(B)	S(L) → D(P)	S(L) → S(L)

To add the sustainability layer to the smart building design, S(L) indicates the LCA practitioners who perform the sustainability assessment of the system.

The diagonal of this matrix is the self-interactions in the B(j), D(B), D(P) and S(L). The first cell represents the interaction between buildings B(i) and B(j), which opens the possibilities of inter-building communication and smart city integration. This matrix is skew-symmetric, as the D(B)→B(j) interaction is not the same as B(j)→D(B) interaction, but rather is opposite in direction.

The ontological integration framework can assist these interactions between stakeholders in designing better smart buildings. In future, these interactions can be automated, and the D(B), D(P) and S(L) designers can be integrated to form one single set of designers, known as 'Smart Building Designers'. Such cross-platform designers would further improve the design framework, resulting in smart buildings that are both energy- and resource-efficient.

5. Conclusions

Based on the ontological integration of the three participating domains, this LCA-BIM-PLM integrated framework provides a plausible solution for designing an energy-neutral smart building system. A preliminary implementation of this ontological framework is demonstrated in Protégé software with the help of OWL. Furthermore, a design interaction matrix is created between buildings (and their components), building designers, product designers, and lifecycle practitioners, allowing for increased efficiency, optimisation, and sustainability in the building design and simulation process, which is further enhanced by reinforcing feedback loops.

The proposed framework would improve the environmental performance of smart buildings by streamlining the design and simulation process, providing a collaborative platform for cross-field designers. In the future, a robust real-time platform for designing and modelling energy-neutral smart built environments could be developed using this framework as its foundation.

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