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Article

Development of a Framework to Support Whole-Life-Cycle Net-Zero-Carbon Buildings through Integration of Building Information Modelling and Digital Twins

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Abstract: Decision-making on whole-life-cycle net-zero-carbon buildings is critical for addressing carbon emission and environmental problems. However, there is a lack of a data integration framework and an open international standard approach integrating key decision variables to support scientific computations and decision-making for whole-life-cycle net-zero-carbon buildings. Building information modelling (BIM) is an open international standard representing building information. Digital Twin (DT) can capture and monitor real-time building conditions to facilitate building operation. Integrating information acquired by DT with BIM has considerable potential to enable an open international standard based computational representation of key decision variables throughout the whole-building life cycle process. This paper aims to develop a novel conceptual framework that integrates BIM and DT to support net-zero-carbon buildings. The framework is developed using an open international standard approach and the ontology-based representation method, to define key decision variables using entities, properties, and relationships, and integrates captured data via DT. The research makes significant contributions to enable net-zero-carbon buildings and paves the way for future research on an automated system to support decision-making for the whole-life-cycle net-zero-carbon buildings.

Keywords: whole-life-cycle net-zero-carbon buildings; building information modelling; digital twins; ontology-based representation method

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1. Introduction

Buildings are major sources of greenhouse gas (GHG) emissions and contributors to climate change and global warming. Given the importance of GHG emissions from buildings, efforts to alleviate energy intensity have been made through various initiatives, such as the EU Energy Performance of Buildings Directive and Net-Zero-Carbon Buildings Framework from the UK Green Building Council [1]. The World Green Building Council (WorldGBC) has defined a net-zero-carbon building as a highly energy efficient building with all operational energy demand supplied from on-site and/or off-site renewable energy to achieve net-zero carbon emissions associated with building operations [2]. The WorldGBC has set up carbon emission goals for its whole-life carbon vision, calling for all new buildings to be net zero in operation with at least 40% less embodied carbon from 2030, and all new buildings to be net zero covering both embodied and operational carbon by 2050 [2].

To achieve net-zero carbon emissions targets in buildings from a whole-life-cycle perspective, all stages during the full building lifecycle process need to be considered. However, most existing research focuses on reducing carbon emissions in the design, construction and operational stages, respectively, rather than integrating all stages throughout the whole building life cycle process [3]. For example, the previous literature explored decision-making on energy conservation and emission reduction during the building construction stage through contractor selection and building materials selection [4–7]. The factors influencing building energy and carbon performance in the operational stage include the operation, repair, maintenance and retrofit of energy systems [8–10]. There is a lack of a data integration framework integrating all key decision variables across design, construction, and operational stages in the whole building process to support decision-making for whole-life-cycle net-zero-carbon buildings [11,12].

In addition, an open standard for data is significant to the decision-making for carbon emissions throughout the whole-building life cycle. It improves the consistency and transparency of data and information, which also minimizes errors and reduces time in the decision-making process. However, there is a lack of solutions that develop an open international standard approach to integrate and represent key decision variables and facilitate decision-making for embodied and operational carbon throughout all stages of the building life cycle [13,14].

The integration of Building Information Modelling (BIM) and Digital Twins (DT) technologies has the potential to address these challenges and support the integrated representation of key variables for supporting decision-making in whole-life-cycle net-zero-carbon buildings. BIM provides an object-oriented model to facilitate the exchange and interoperability of building information in a digital format [15]. It can be used to support design analysis, improve design and construction efficiency, facilitate communication between stakeholders, and monitor construction schedules and costs [16–18]. However, there is a limitation to the use of BIM for capturing post-occupancy operational and maintenance information in the operational stage [19,20].

The Industry Foundation Classes (IFC) developed by BuildingSMART, is an open, international, and neutral data exchange schema supporting BIM to enable the exchange of models and information throughout the lifecycle of assets [21]. IFC supports a wide range of geometric representations as well as rich semantic information, which defines building objects, associated attributes and properties, and mutual relationships between those objects, written in EXPRESS specification language [21]. However, the current IFC schema is limited to providing adequate objects, properties, and relationships required for the whole-life-cycle carbon assessment, especially in the operational stage [22,23]. Therefore, it is necessary to extend the current IFC schema to incorporate additional objects, properties, and relationships required for the whole-life-cycle net-zero-carbon assessment.

Digital twin (DT) provides a digital information set that is virtually representative of the static physical attributes, dynamic states, and processes of the built environment [24]. It can create a living model of the physical asset or system, which continually adapts to changes in the environment or operation based on collected real-time sensory data and information [25]. In the Architectural, Engineering and Construction (AEC) sector, DT technologies are mostly applied in the use phase to enhance building operation, such as real-time monitoring and data acquisition, and what-if analyses in building management [20,26]. Data collected via DT can be used to record and evaluate the existing state of the buildings, which informs appropriate decisions on whether the building needs to be repaired, simply maintained, or retrofitted [27,28]. However, there is a lack of research integrating data captured from DT with BIM to enable an integrated computational representation of key decision variables, to support whole-life-cycle net-zero-carbon buildings [20,29,30]. A novel framework is needed, which provides an open international standard based computational representation through the integration of BIM/IFC and DT to integrate key decision variables throughout the whole building process to facilitate decision-making and the automated assessment of whole-life-cycle net-zero-carbon buildings.

To fill this gap, this paper aims to develop a novel conceptual framework that integrates BIM and DT data to tackle the challenges in achieving net-zero-carbon buildings over the whole building lifecycle. Specifically, the research objectives are: (1) to identify the key decision variables that affect net-zero-carbon outcomes of buildings throughout the whole lifecycle of the building process, including design, construction, and operational stages; (2) to identify entities, properties, and relationships in current BIM/IFC schema that represent the identified key decision variables, which will be conducted by mapping the key variables with the existing IFC entities, properties, and relationships; and (3) to develop a novel conceptual framework utilizing the ontology-based representation, which extends the current BIM/IFC schema and integrates data from DT to support decision-making for the whole lifecycle of the building process.

The significance of this paper is creating new opportunities to integrate BIM/IFC and DT technologies to provide a computational representation of key decision variables that make the most significant contribution to gaining net-zero-carbon outcomes of buildings throughout the whole building life cycle. The novel framework will pave the way for future research on an automated system to support decision-making for the whole-life-cycle net-zero-carbon buildings.

2. Research Method

The conceptual framework for supporting the decision-making and automated assessment of the whole-life-cycle net-zero-carbon buildings presented in this paper was developed through four steps, as illustrated in Figure 1. Step 1 is the identification of key decision variables that affect whole-life-cycle net-zero-carbon building outcomes at design, construction, operational stages. Key decision variables are identified through a systematic literature review which are then categorised into three key building stages. Step 2 is to identify existing BIM/IFC entities, properties, and relationships which can represent key decision variables affecting whole-life-cycle net-zero-carbon buildings. This step is conducted through mapping the identified decision variables into the current BIM/IFC schema. Step 3 aims to develop an extension to the current BIM/IFC to incorporate key decision variables affecting the whole-life-cycle carbon-emission outcomes of buildings that are not available in the existing BIM/IFC. Additional entities, properties, and relationships are created at the conceptual level to represent the key decision variables, which are not available in the existing BIM/IFC schema. Step 4 is to integrate the data captured using DT technology at operational stage into the extension described in Step 3. The conceptual framework is developed through utilising the ontology-based representation method to develop an extension to the existing IFC 4X3 schema and integrate DT technology to facilitate decision-making and automated assessment of the whole-life-cycle net-zero-carbon buildings.

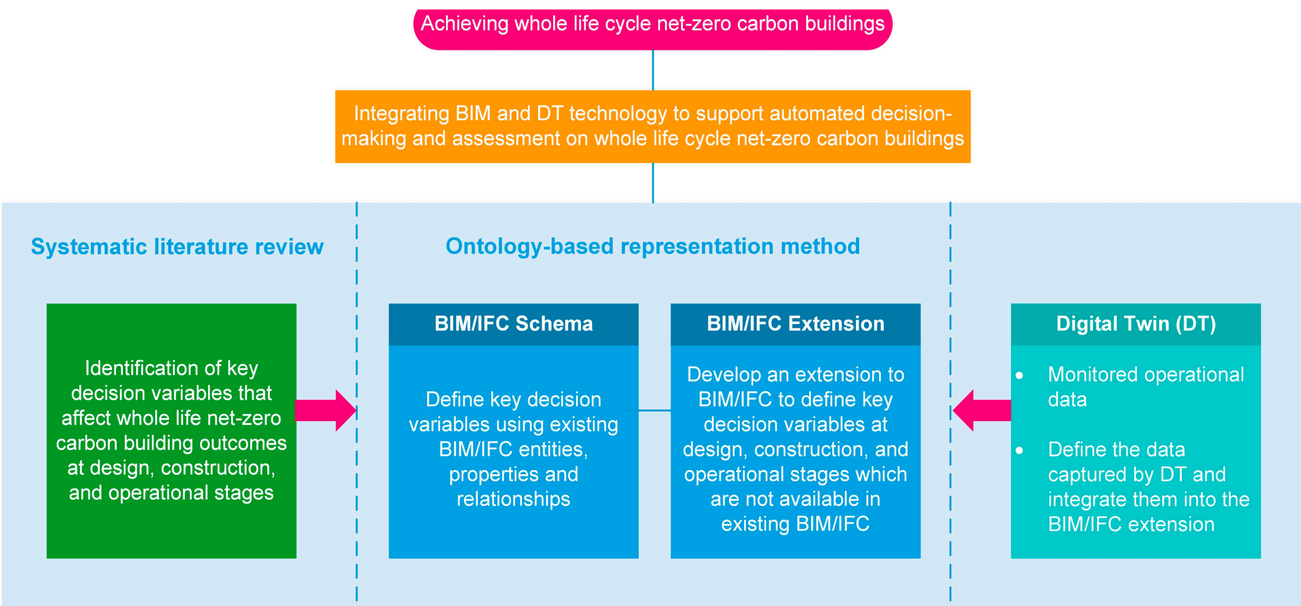

Figure 1. Research design and methodology for the development of the conceptual framework.

2.1. A Systematic Review for the Identification of Key Decision Variables for Whole-Life-Cycle Net-Zero-Carbon Buildings

Systematic review methods were employed in this study to identify key decision variables influencing the carbon emission outcomes of buildings throughout the whole building lifecycle. A rigorous analysis of the literature collected for this review was performed to retrieve a complete, reliable, and up-to-date dataset. The review process is illustrated in Figure 2, including database selection, literature searching and selection, and data classification.

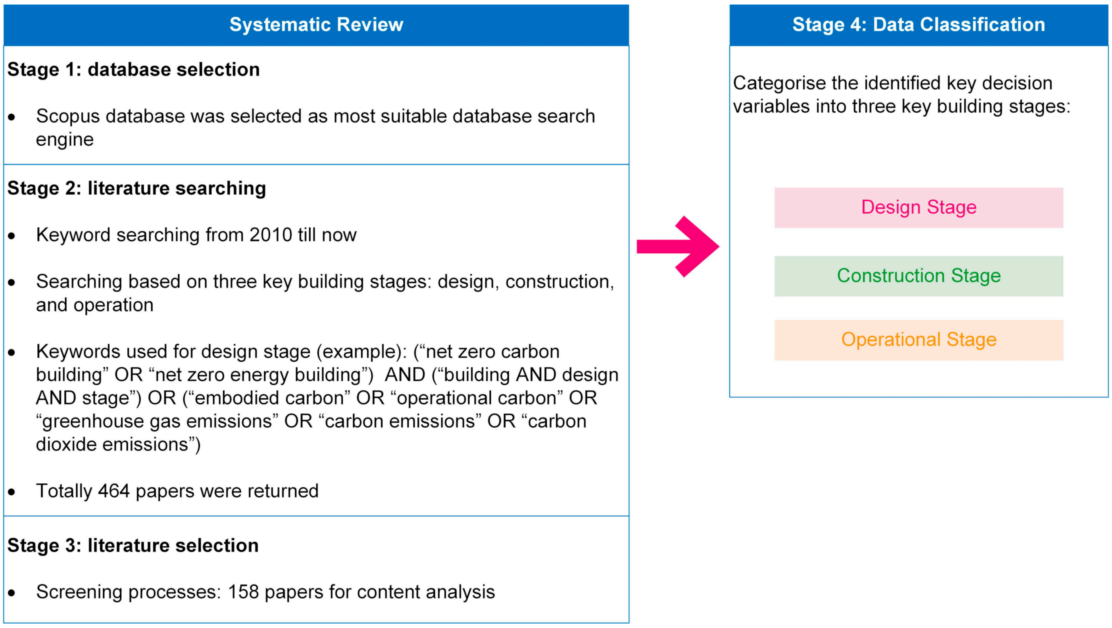

Figure 2. Systematic literature review process for the identification of key decision variables.

Scopus was selected as the literature database in this research because it has relatively broader coverage on journal publications from well-regarded sources, and better suits interdisciplinary research topics compared with other databases, such as Web of Science, Google Scholar, and PubMed, as discussed some of the previous literature [31–35]. Scopus is also a better choice for ensuring the returned literature is relevant to the subject of the review.

The existing literature related to whole-life-cycle net-zero-carbon buildings in Scopus was found utilizing a keyword search. The literature search on key decision variables was carried out on the three stages of building design, construction, and operational stages in a systematic manner. A variety of interchangeable terms are used when referring to the concept of key decision variables affecting net-zero-carbon building throughout the lifecycle building process. For example, the term "energy" is used as an alternative to "carbon" as carbon emissions associated with the initial construction, operation, maintenance, and retrofit of a building, and is calculated based on the total energy consumption for each building stage [36]. Several possible combinations of these terms were utilized for searching within Scopus, and the keyword search strings used in Scopus are given in Table 1. The search timeframe was set at 2010 and more recently. Journals, book chapters, books, dissertations, seminars, lecture posts are considered in the systematic literature review, to eliminate publication bias. The initial search returned 464 academic papers in total.

Table 1. Literature search results for key decision variables affecting whole-life-cycle net-zero-carbon buildings.

Stages	Search Strings	Time Period	Number of Results
Design Stage	("net zero carbon building" OR "net zero energy building") AND (building AND design AND stage) OR ("embodied carbon" OR "operational carbon" OR "greenhouse gas emissions" OR "carbon emissions" OR "carbon dioxide emissions")	After 2010	129
Construction Stage	("net zero carbon building" OR "net zero energy building") AND (building AND construction AND stage) OR ("embodied carbon" OR "operational carbon" OR "greenhouse gas emissions" OR "carbon emissions" OR "carbon dioxide emissions")	After 2010	101
Operational Stage	("net zero carbon building" OR "net zero energy building") AND ("operation" OR "maintenance" OR "retrofit") OR ("embodied carbon" OR "operational carbon" OR "greenhouse gas emissions" OR "carbon emissions" OR "carbon dioxide emissions")	After 2010	234
Total			464

After the literature retrieval, a manual screening process was carried out to select the most relevant papers before the systematic analysis of the targeted literature. The abstract is firstly reviewed, and for some papers, the full texts were read through before deciding whether the paper should be selected. As a result, 158 papers were selected for further content analysis and identification of key decision variables.

The key decision variables identified through systematic review methods are classified into three categories in alignment with design, construction, and operation.

2.2. Mapping the Identified Key Variables with the Existing IFC Entities, Properties and Relationships

After the key decision variables are identified from the literature, a mapping process was carried out to identify the existing entities, properties, and relationships in the current BIM/IFC schema that can represent the key decision variables affecting whole-life-cycle net-zero-carbon buildings.

As illustrated in Figure 3, the first step was to identify whether there are equivalent existing entities in BIM/IFC that can represent the key decision variables. If such entities exist, the key decision variables are mapped to the corresponding entities in the specific IFC subschemas or domains. The second step is to identify whether there are equivalent IFC properties and relationships to define the attributes and properties of these entities that affect the carbon emission outcomes of buildings. If there are equivalent properties and relationships, then no BIM/IFC extension is needed. If a property or relationship is lacking, then an extension is required to define additional properties and relationships. They are then linked to the existing entities to describe the properties of variables. For the key decision variables that are not available in the existing BIM/IFC, an extension to the current BIM/IFC schema is needed to create new entities, properties, and relationships to represent these variables.

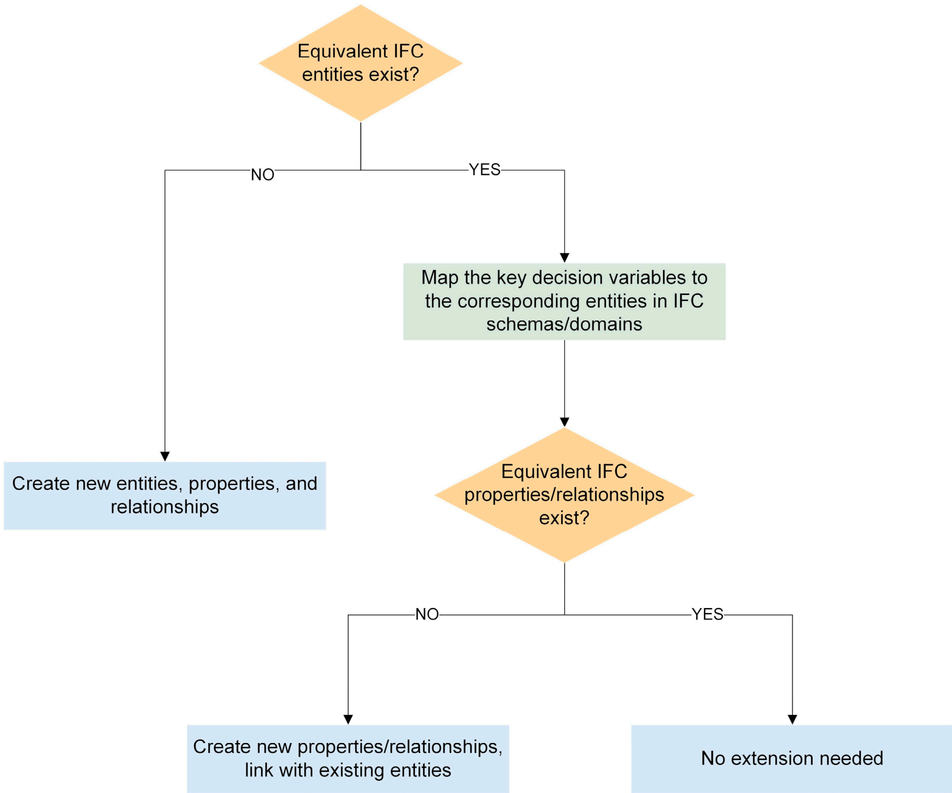

Figure 3. Mapping the identified key decision variables with the existing BIM/IFC schema.

2.3. Ontology-Based Representation Method

This research adopted the ontology-based representation method to develop an extension which incorporates key decision variables affecting the whole-life-cycle net-zero-carbon buildings that are not available in the existing BIM/IFC schema. Data acquired from DT were integrated with the BIM/IFC extension using the ontology-based representation method, to represent key decision variables at the building operational stage. The ontology-based representation method adapted in this research is built upon the ontology-based knowledge representation, which is also consistent with the ontology components in the IFC schema.

Ontology is a term derived from philosophy, which can be defined as "an explicit specification of a conceptualization" [37]. It provides explicit logical assertions about classes, instances, and properties, and provides a way to capture and convert human knowledge into an explicit format that can be understandable by computers [38]. The ontology-based representation method has been widely used by many previous researchers [39–44]. Ontology-based representation can not only describe and connect knowledge but also improve information sharing to a seamless degree among various application platforms.

IFC is an object-oriented open standard developed by buildingSMART and is now a widely used data format for BIM to support platform-independent, open BIM processes [45–47]. The ontology-based representation method adapted in this research is built upon the ontology-based knowledge representation and is also consistent with the ontology components in the IFC schema. IFC supports a wide range of geometric representations as well as rich semantic information in all phases of the life cycle of a building. The IFC schema provides an ontology-based representation of building information; that is, building information is represented with entities, attributes, and properties, as well as relationships to link different elements together. Therefore, the ontology-based representation method was formalized using these three ontology components, entities, properties, and relationships, described as follows:

- Entities: also known as terms or concepts in a domain of discourse [39]. Entities, in this research, represent key decision variables identified at the design, construction, and operational stages. For example, "Renewable Energy System" represents solar panels which captures the energy of sunlight converted into electricity. "Window upgrades" represents the act of modifying existing windows designed for greater energy efficiency during building operational stage.
- Properties: describe various properties, features, attributes, characteristics, or parameters of entities [48]. Properties, in this research, represent attributes of entities that influence whole-life-cycle net-zero-carbon outcomes of buildings. For example, "Efficiency" refers to solar panel efficiency which is a measure of the amount of sunlight falling on the surface of a solar panel and converted into electricity [49], "Temperature set-point" defines the point at which a thermostat is set when operating heating and cooling systems.
- Relationships: define relations between entities or develop the class hierarchy of concepts [39]. Relationships, in this research, represent semantic connections among various entities. For example, "Is determined by" expresses that the decision-making for one entity is determined by another entity; "Is applied to" defines an action or criterion being applied to an existing entity.

3. Results

3.1. Categories and Key Decision Variables Which Affect Net-Zero-Carbon Building Outcomes at Design, Construction and Operational Stages

In this research, the identified key decision variables were categorized into a hierarchy to enable mapping onto the ontology-based representation. The categories of variables identified in this research are suitable for most scenarios but may vary depending on the project and contract type.

3.1.1. Key Decision Variables in the Building Design Stage

Building design stage covers architectural and engineering design. During the architectural design phase, aspects affecting net-zero-carbon building outcomes include the building site, walls, floors and roof systems, shadings, windows, and room spatial layout (Figure 4). Heating and cooling needs can be significantly reduced through passive design strategies such as orientating the building in the best direction [50–54]. Influential factors affecting the design of building envelope in achieving energy efficient buildings include materials, type of construction, and insulation [55–59]. Other energy reduction methods include adjusting the window–wall ratio, utilizing triple glazing and shadings, and changing the location and dimension of internal spaces [57,60–66].

During the engineering design phase, plans for the building's energy systems and services involve key decision variables that can influence building energy performance [67–73]. Typical energy systems include heating, cooling, hot water, electrical lighting, building control systems, home appliances, mechanical ventilation, and renewable energy systems [45,59,74–76]. For each categorized item, the key relevant references are also provided in Figure 4.

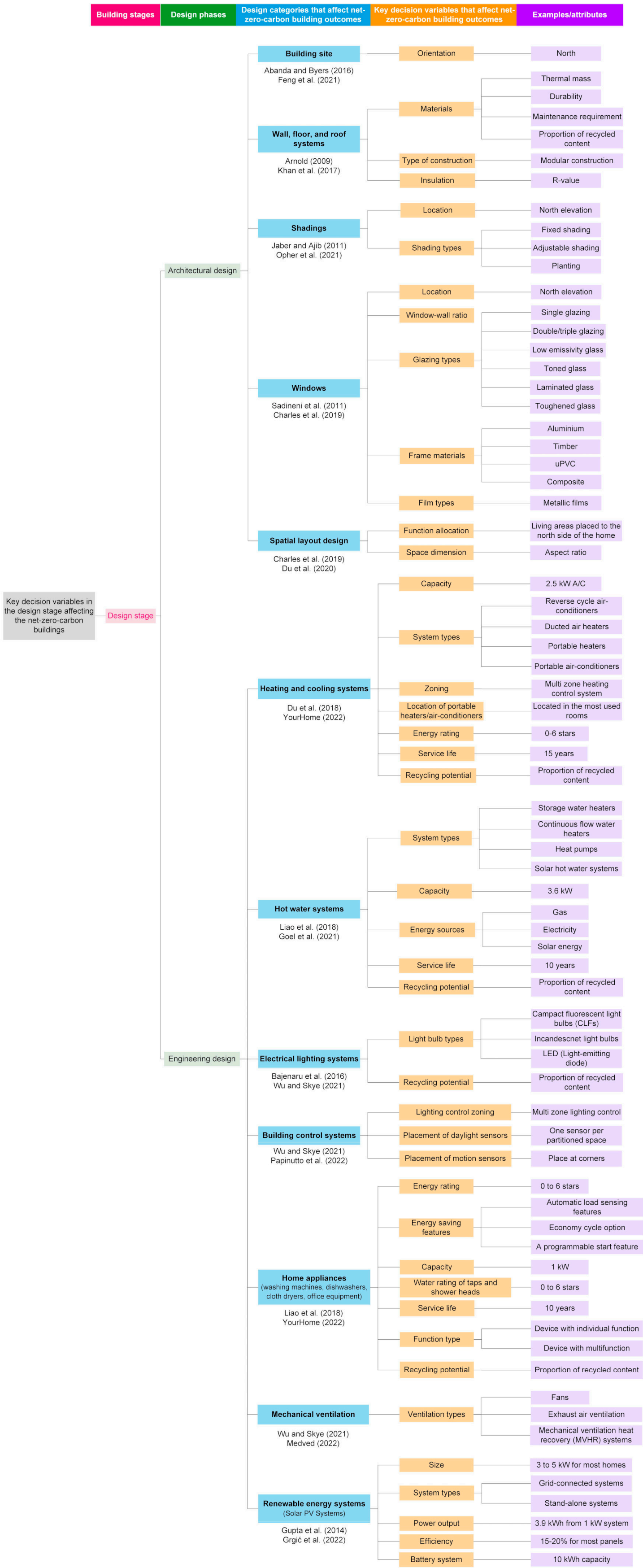

Figure 4. Summary of categories and key decision variables affecting net-zero-carbon building at design stage (key relevant references are provided to each category) [45,50,53,54,56–59,65,66,69–77].

3.1.2. Key Decision Variables in the Building Construction Stage

To deliver a net-zero-carbon building, it is necessary to set up low-carbon performance requirements in contracts and subcontracts, covering materials' and products' selection, and energy-system performance criteria [59,78–81]. Contractor selection is also crucial to the delivery of net-zero-carbon buildings, which depends on experience, past performance, expertise, and resources [82–84]. Selecting environmentally responsible suppliers and sourcing locally made materials through appropriate transportation can significantly reduce embodied carbon [4,59,85–89]. On-site energy and water consumption can be lowered by utilizing renewable energy sources and choosing energy efficient appliances [90–92]. Waste management strategies ensure that as much material as possible is reduced, reused, and recycled [35,93–95]. Construction methods and the operation of equipment and machinery were also proved to be main sources of GHG emissions in building construction in previous research [88,96–101]. These categorized items with key relevant references are given in Figure 5.

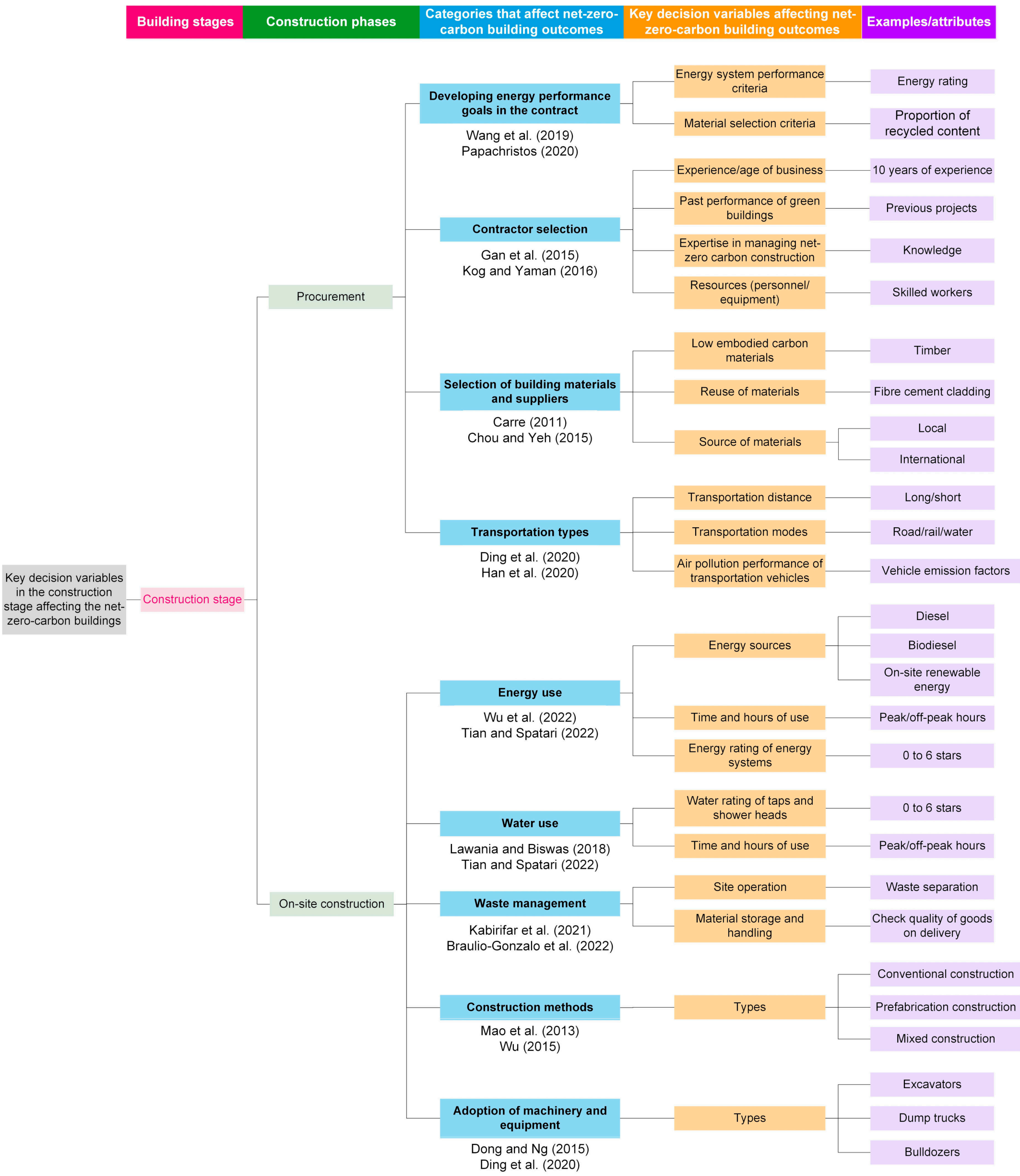

Figure 5. Summary of categories and key decision variables which affect net-zero-carbon building outcomes at construction stage (key relevant references are provided to each category) [35,80,81,83–85,87–89,91,92,95,97,99,100].

3.1.3. Key Decision Variables in the Building Operational Stage

In the operational stage, energy systems operation, building management and maintenance, and building retrofit are three major aspects affecting net-zero-carbon performance, as summarized from the key literature (Figure 6). Various energy saving strategies for operating energy systems such as heating, ventilation, and air conditioning (HVAC), appliances and solar PV systems have been identified in previous studies [9,49,58,102,103]. The regular maintenance and repair of building assets enable potential failures to be identified and addressed early to extend service life and improve energy performance [104–107]. Upgrading building envelope and energy systems is also an efficient solution to reduce energy demand during building operation [68,108–113].

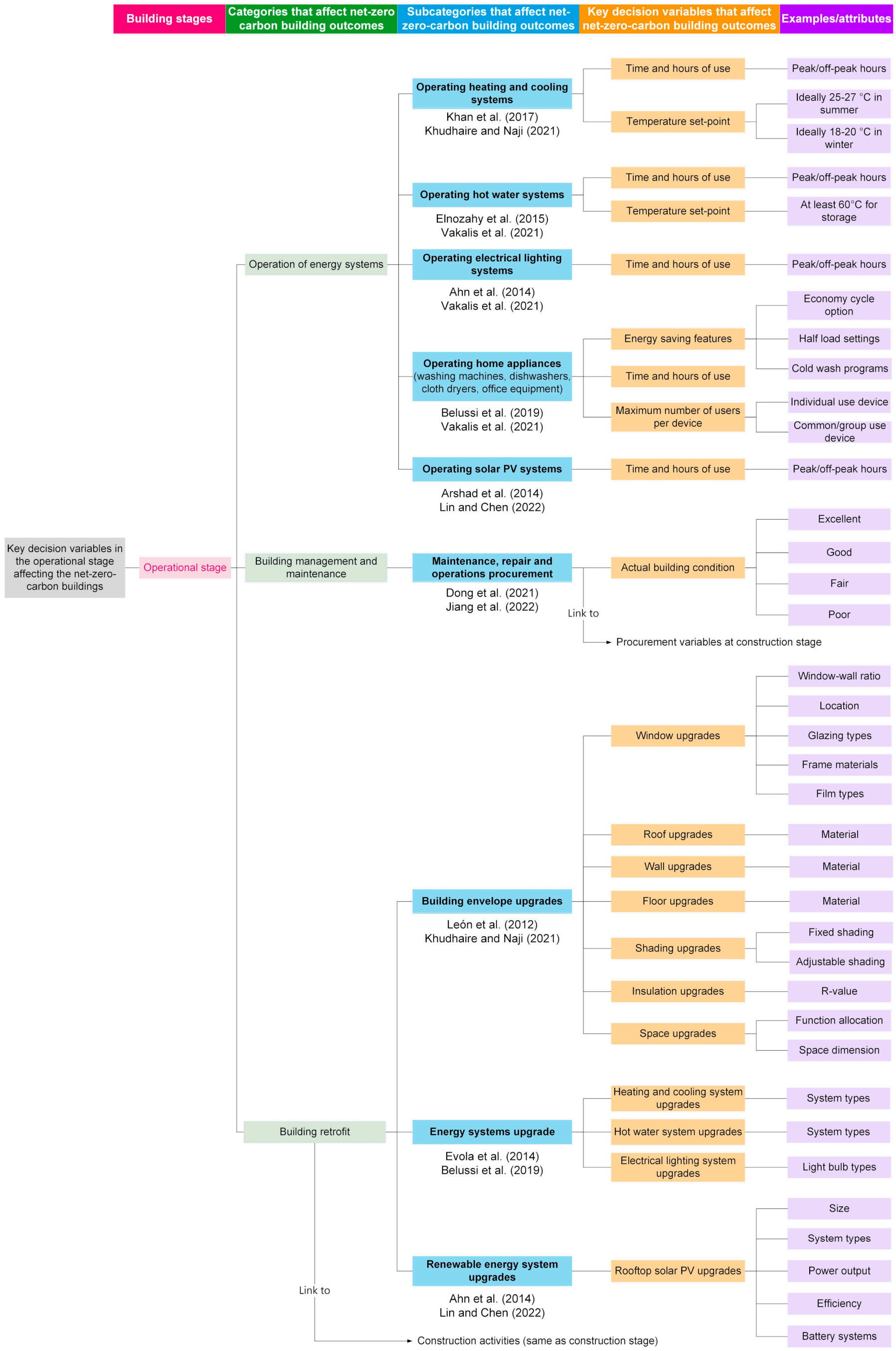

Figure 6. Summary of categories and key decision variables which affect net-zero-carbon building outcomes at operational stage (key relevant references are provided to each category) [9,49,58,102,106–113].

3.2. Existing IFC Schema Which Represent Key Decision Variables That Affect Whole-Life-Cycle Net-Zero-Carbon Buildings

Through conducting the mapping process, an outline of mapping results at the conceptual level is given in Figure 7, which illustrates the correspondence between the categories and key decision variables and subschemas and domains in BIM/IFC.

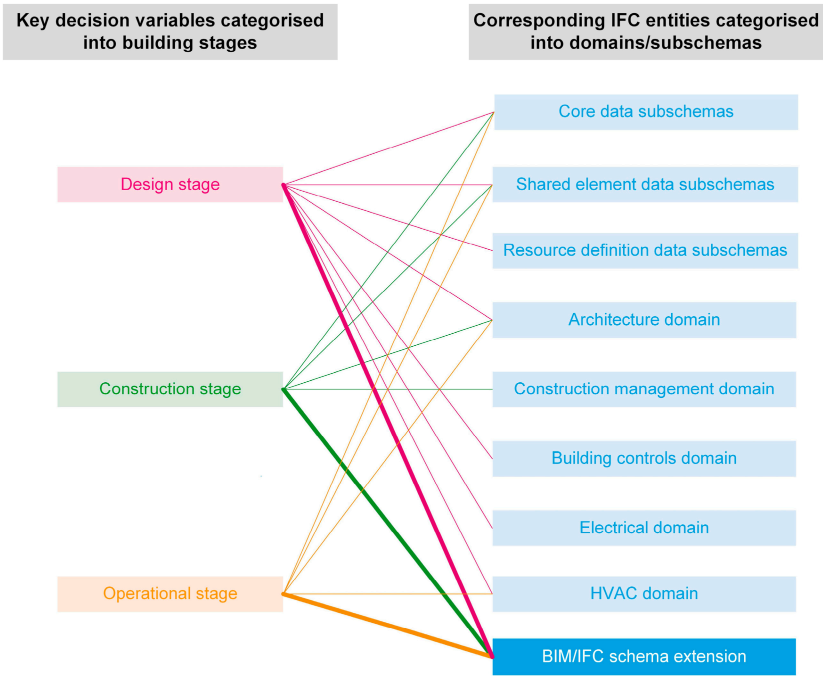

Figure 7. An outline of mapping results between the categories of key decision variables and subschemas and domains in BIM/IFC.

3.2.1. Existing IFC Entities, Properties, and Relationships Which Represent Key Variables at Design Stage

Categories and key decision variables that affect net-zero-carbon buildings at design stage such as the building site, wall, floor, and roof systems, shadings, windows, spatial layout, and energy systems are mapped onto the IFC entities, properties and relationships in the core data subschemas, the shared element data subschemas, the resource definition data subschemas, and the architecture, building controls, electrical, and HVAC domains in the IFC schema. A few key variables that are not available in the current IFC schema will be defined in an extension, which will be described in Section 3.3.1. Most of key variables at the design stage can be adequately defined by the current IFC schema; two examples are given below:

- The orientation of the building site can be defined by IfcSite in the core data subschemas and IfcLocalPlacement in the resource definition data subschemas.
- The wall, floor and roof systems and their construction types can be represented by IfcRoof, IfcWall, IfcCurtainWall, IfcSlab, IfcRoofType, IfcWallType, IfcCurtainWallType, and IfcSlabType. In addition, IfcCovering and IfcCoveringType define the insulation installed into the roof, ceiling, wall, and floor. These entities are all in the shared element data subschemas. Additionally, the material properties of the building envelope, such as thermal mass, durability, maintenance requirements and proportion of recycled content, are described by different IFC property sets, including Pset_MaterialThermal for IfcMaterial, Pset_ServiceLife, Pset_EnvironmentalImpactIndicators, and Pset_EnvironmentalImpactValue for IfcElement.

The diagrams in Figures 8 and 9 illustrate the mapping between existing IFC entities, properties and relationships and corresponding categories and key decision variables at the design stage.

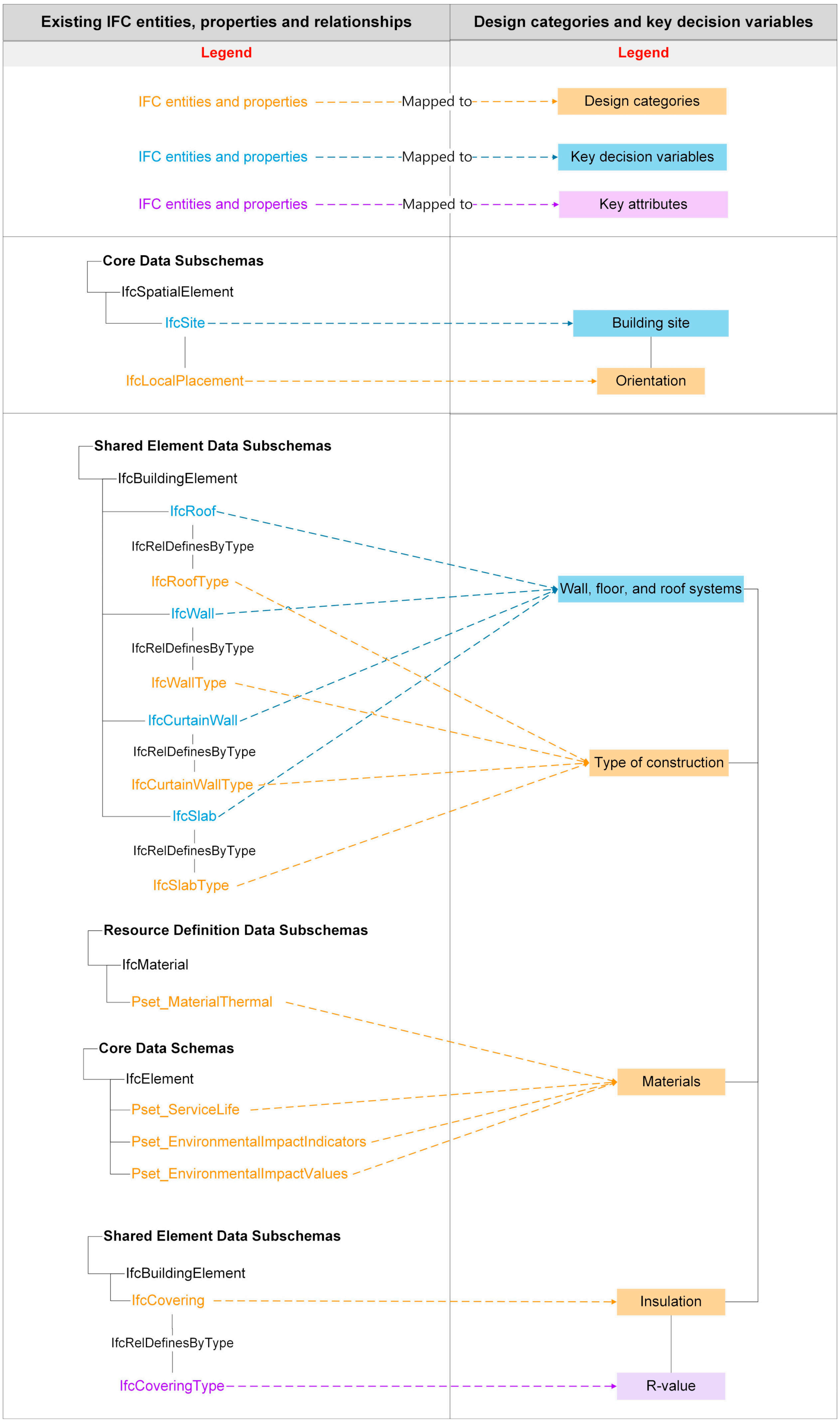

Figure 8. Existing IFC entities, properties, and relationships representing design categories and key decision variables affecting net-zero-carbon building outcomes at design stage.

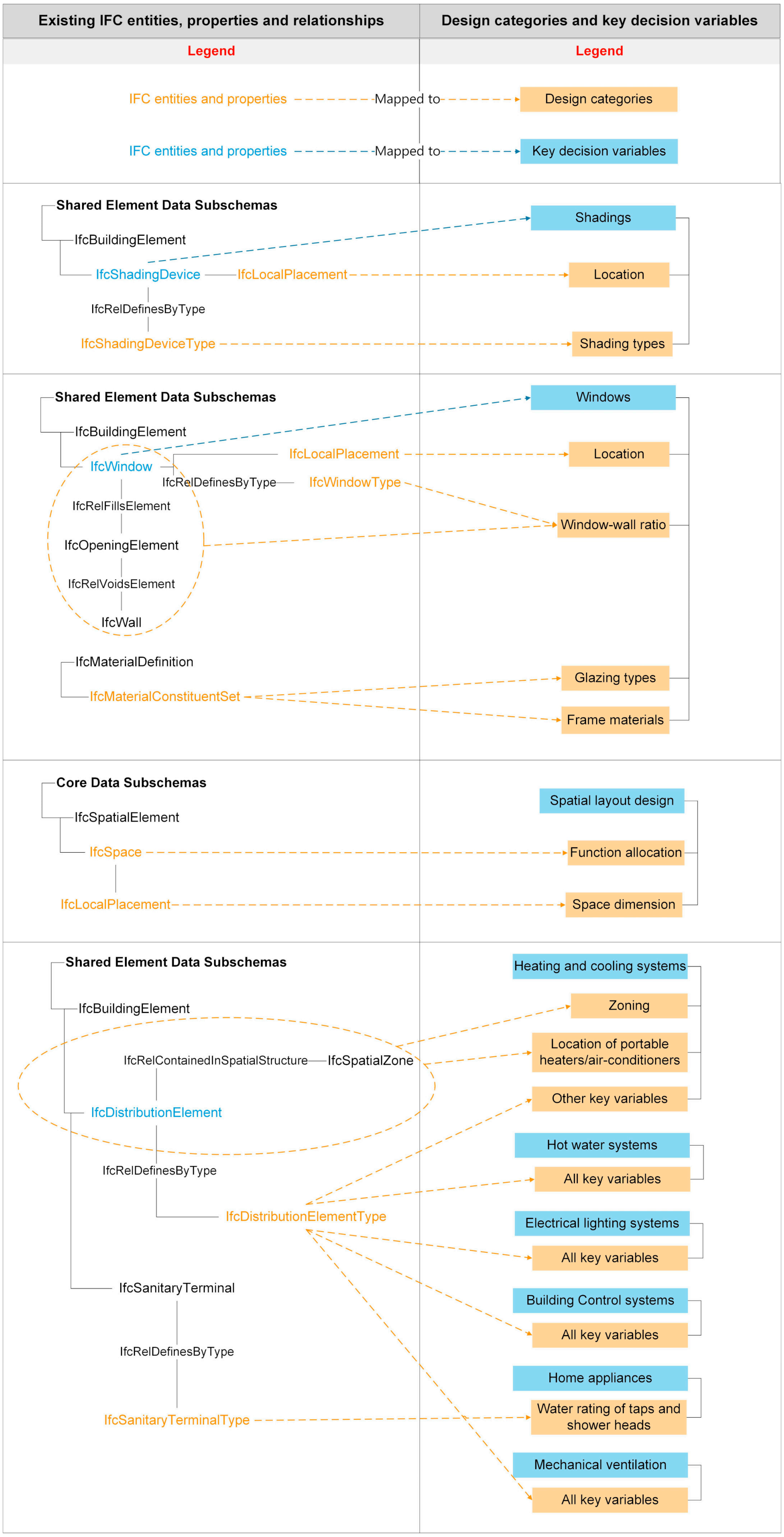

Figure 9. Existing IFC entities, properties, and relationships representing design categories and key decision variables affecting net-zero-carbon building outcomes at design stage (continued).

3.2.2. Existing IFC Entities, Properties, and Relationships Which Represent Key Variables at Construction Stage

Categories and key decision variables affecting net-zero-carbon buildings at construction stage such as the selection of building materials and suppliers, energy use, water use, and adoption of machinery and equipment are mapped to the IFC entities, properties and relationships in the core data subschemas, shared element data subschemas, and the architecture and construction management domains in the IFC schema. Some key variables not available in the current IFC schema will be defined in an extension, which is described in Section 3.3.2. Examples of key variables defined by existing IFC entities, properties and relationships are given below:

- Decision variables in the selection of building materials and suppliers can be defined by several property sets for IfcElement. Pset_EnvironmentalImpactValues and Pset_EnvrionmentalImpactIndicators represent "Low embodied carbon materials" and "Reuse of materials". Pset_ManufacturerTypeInformation represents "Source of materials".
- Energy use on the construction site is usually attributed to the construction equipment and machinery, on-site transportation equipment and vehicles, and energy systems. IfcConstructionEquipmentResource defines construction equipment; IfcTransportElement defines on-site transportation equipment and vehicles; IfcQuantityTime measures time and hours of operating these equipment and vehicles. In addition, IfcDistributionElement defines the use of various energy systems on site, including heating and cooling, electrical lighting, hot water systems, and appliances. The energy rating of energy systems can be defined by IfcDistributionElementType.

The diagram in Figure 10 illustrates the mapping between existing IFC entities, properties and relationships and corresponding categories and key decision variables at the construction stage.

3.2.3. Existing IFC Entities, Properties, and Relationships Which Represent Key Variables at Operational Stage

Categories and key decision variables that affect net-zero-carbon buildings at operational stage such as the operation of energy systems, maintenance, repair, and operations procurement, and upgrading of building envelope, energy systems, and renewable energy systems are mapped to the IFC entities, properties and relationships in the core data subschemas and shared element data subschemas, and the architecture and HVAC domains in the IFC schema. Key variables not covered in the current IFC schema will be defined in an extension, which is described in Section 3.3.3. Examples of key variables defined by existing IFC entities, properties and relationships are below:

- A key variable needs to be considered in the maintenance, repair and operations procurement is whether the actual building condition is excellent, good, fair, or poor. In the existing IFC schema, Pset_Condition is a property set of IfcElement, representing the overall condition of a product based on an assessment considering various criteria, measured on a scale of 1–10, or by assigning names such as good, fair, poor.
- Energy systems such as heating, cooling, hot water, and electrical systems are defined by IfcDitributionElement in the core data subschemas. Building envelope including windows, roof, walls, floor, shadings, and spaces can be represented by various subtypes of IfcBuildingElement in the shared element data subschemas, such as IfcWindow, IfcRoof, IfcCurtainWall, IfcWall, IfcSlab, and IfcShadingDevice, and IfcSpace in the core data subschemas.

The diagram in Figure 11 illustrates the mapping between existing IFC entities, properties and relationships and corresponding categories and key decision variables at operational stages.

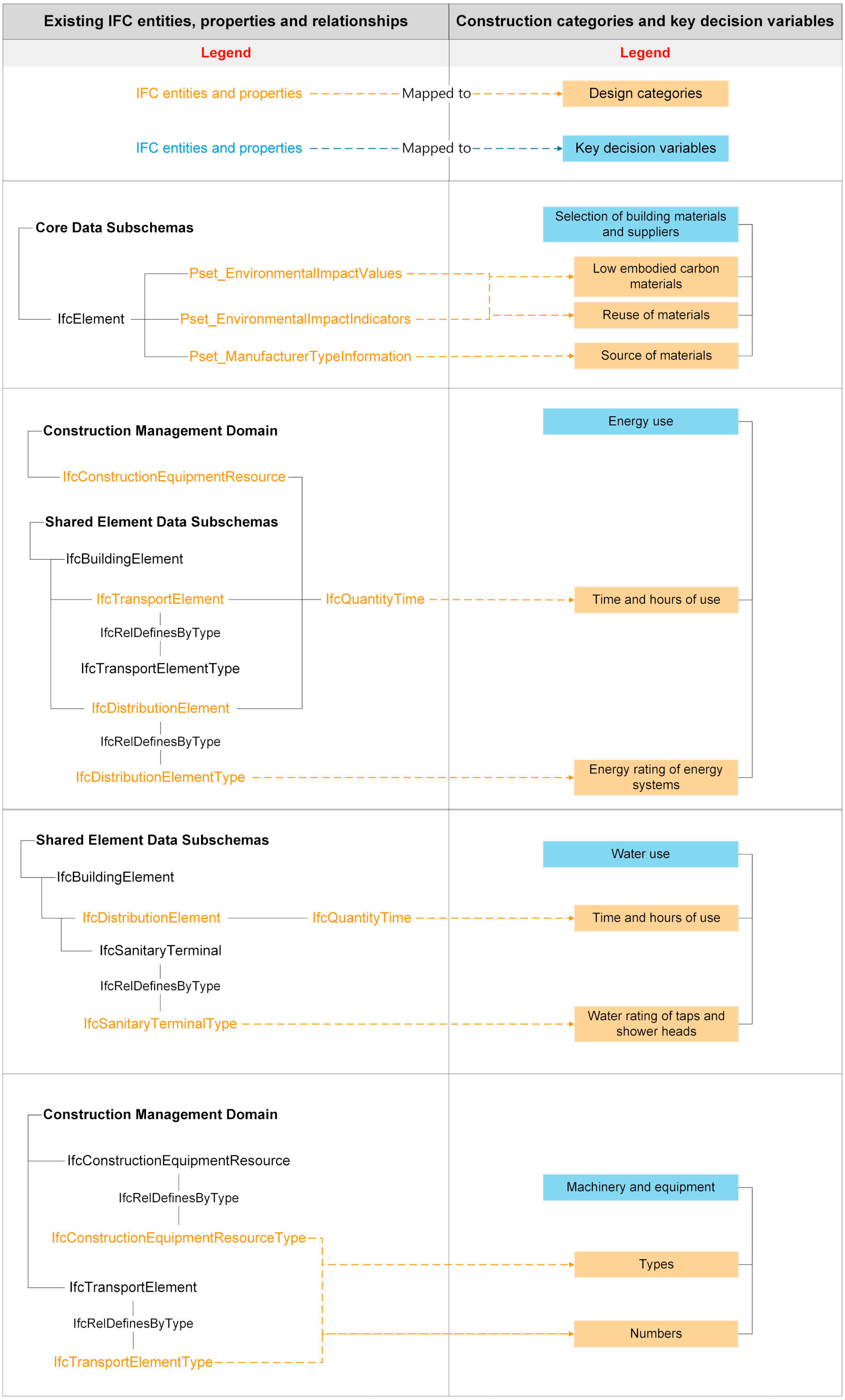

Figure 10. Existing IFC entities, properties, and relationships representing construction categories

and key decision variables affecting net-zero-carbon building outcomes at construction stage.

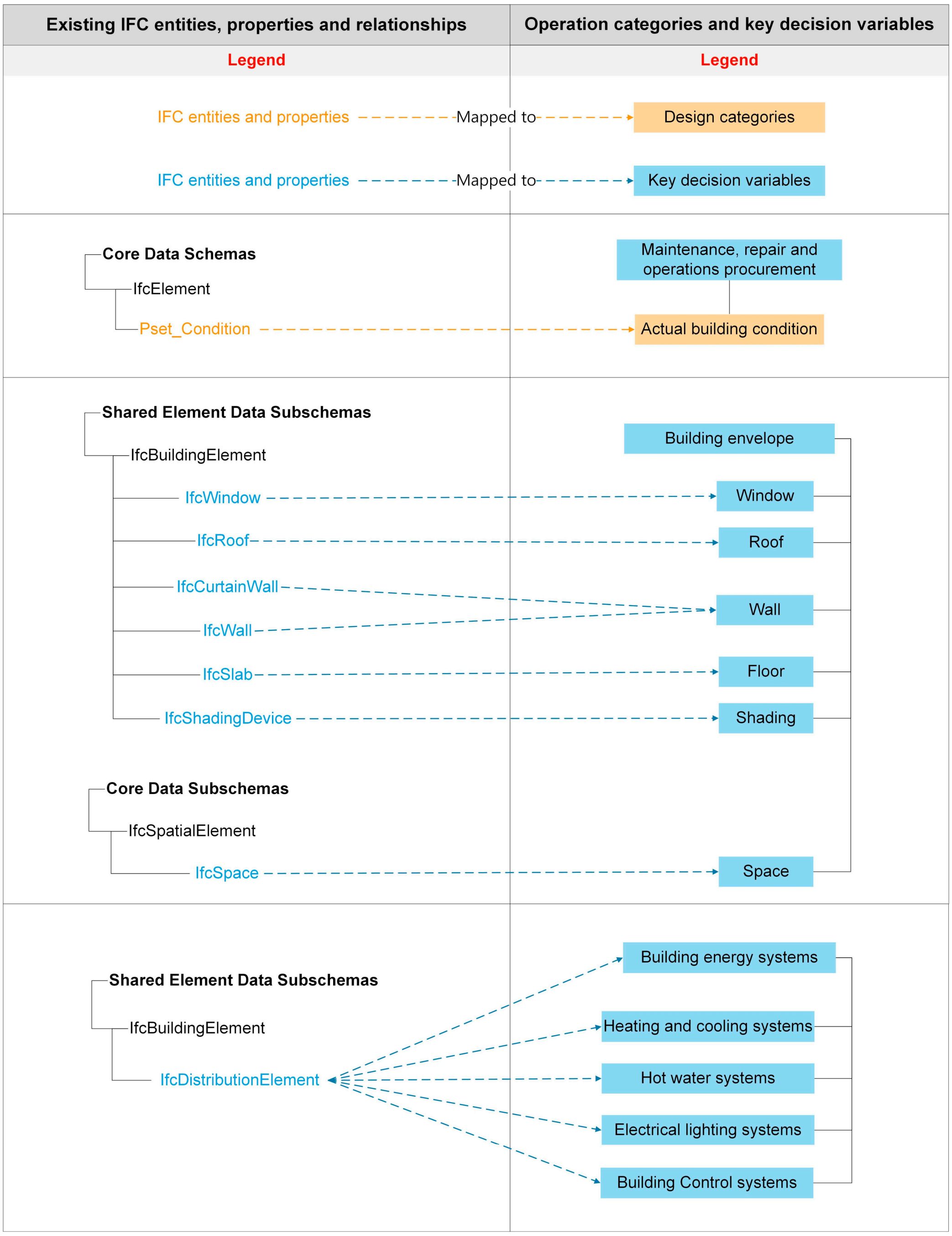

Figure 11. Existing IFC entities, properties, and relationships representing design categories and key decision variables affecting net-zero-carbon building outcomes at operational stage.

3.3. A Conceptual Framework for Integrating BIM and Digital Twins to Support Whole-Life-Cycle Net-Zero-Carbon Buildings

Figure 12 presents the conceptual framework developed in this research, which supports whole-life-cycle net-zero-carbon buildings through the integration of BIM and DT data. The framework is composed of two segments. The first segment consists of the ontology components in the existing BIM/IFC schema, which uses existing IFC entities, properties, and relationships to represent key decision variables affecting net-zero-carbon outcomes of buildings at design, construction, and operational stages.

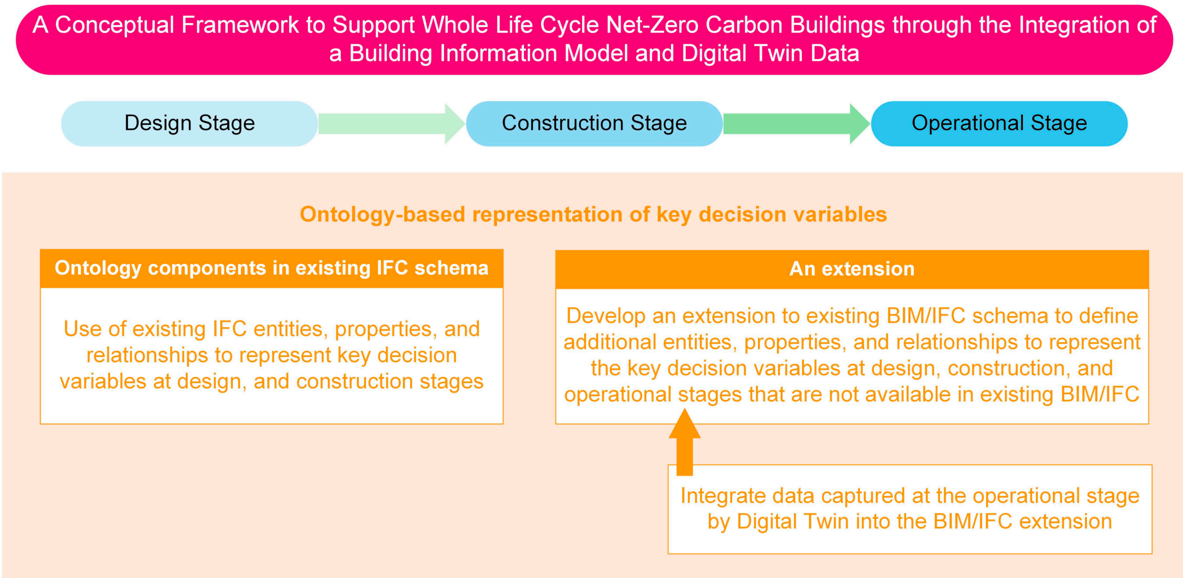

Figure 12. Conceptual framework to support whole-life-cycle net-zero-carbon buildings through the integration of a building information model and digital twin data.

The second segment is the development of an extension to existing BIM/IFC schema to define represent key decision variables that are not available in the existing BIM/IFC schema. By utilizing the ontology-based representation method, additional entities and properties are created to define key variables at each key building stage. Relationships are also defined to present connections between entities within each key stage, and across all stages of the whole-building lifecycle. These newly added entities and properties are then connected with existing IFC entities via defined relationships. Data captured at operational stage via DT are also integrated into the BIM/IFC schema extension.

The following sections explain the newly added entities, properties, and relationships, how an extension is linked to the existing IFC schema, and how DT data are integrated into the extension.

3.3.1. An Extension Representing Key Decision Variables at Design Stage

At the design stage, categories and key decision variables affecting net-zero-carbon buildings that are not available in the current IFC schema include: types of window films, home appliances, and renewable energy systems (solar PV systems). To represent these categories and variables, 4 new entities, 11 new properties, and 1 new relationship were added to the current IFC schema using the ontology-based representation method, illustrated in Figure 13.

There four relationships are presented in Figure 13. "Is installed to" is a new relationship to specify that one entity is installed to another entity. "contains" is an existing relationship capable of expressing a containment relationship between entities. "Is composed of" is an existing relationship that can represent the composition relationship between entities. "Has the property of" is an existing relationship that supports the connection between entities and their properties or attributes.

By using these relationships, the connections among existing and new entities and properties are established:

- "Window film" is a new entity created to represent a thin polymer film containing an absorbing dye or reflective metal layer that can be installed on the interior or exterior of glass surfaces. "Is installed to" is a new relationship, which aims to link "Window film" to existing opening elements. This is established to describe the installation of a film on a window. "Film types" is a new property added to "Window film", connected through "has the property of", which defines different types of window films.

- "Home appliances" is a new entity created to represent domestic appliances including washing machines, dishwashers, cloth dryers, and office equipment. Several new properties are enriched to describe variables relating to home appliances that affect energy consumption, including "Energy rating", "Energy saving features", "Capacity", "Service life", "Function type", and "Recycling potential". They are linked to "Home appliances" via "has the property of".
- "Solar PV systems" is a new entity created to represent solar PV systems. "Battery system" is also a new entity to define stand-alone PV systems that have battery storage. "Is composed of" connects "Battery system" to "Solar PV systems". Four new properties are added to define variables of solar PV systems that affect building energy use, including "size", "system types", "power output", and "efficiency".
- Building elements and energy systems which influence building energy use and carbon emissions are contained in a "Building", involving "Building envelope", "Shadings", "Openings", "Heating and cooling systems", "Hot water systems", "Electrical lighting systems", "Building control systems", "Home appliances", 'Mechanical ventilation", and "Solar PV systems". Building elements and energy systems have a number of attributes and properties to define significant decision variables affecting net-zero-carbon buildings at design stage. "Building" is further composed of "Space", which has the property of "Spatial layout" and can define function allocation and the dimensions of different spaces.

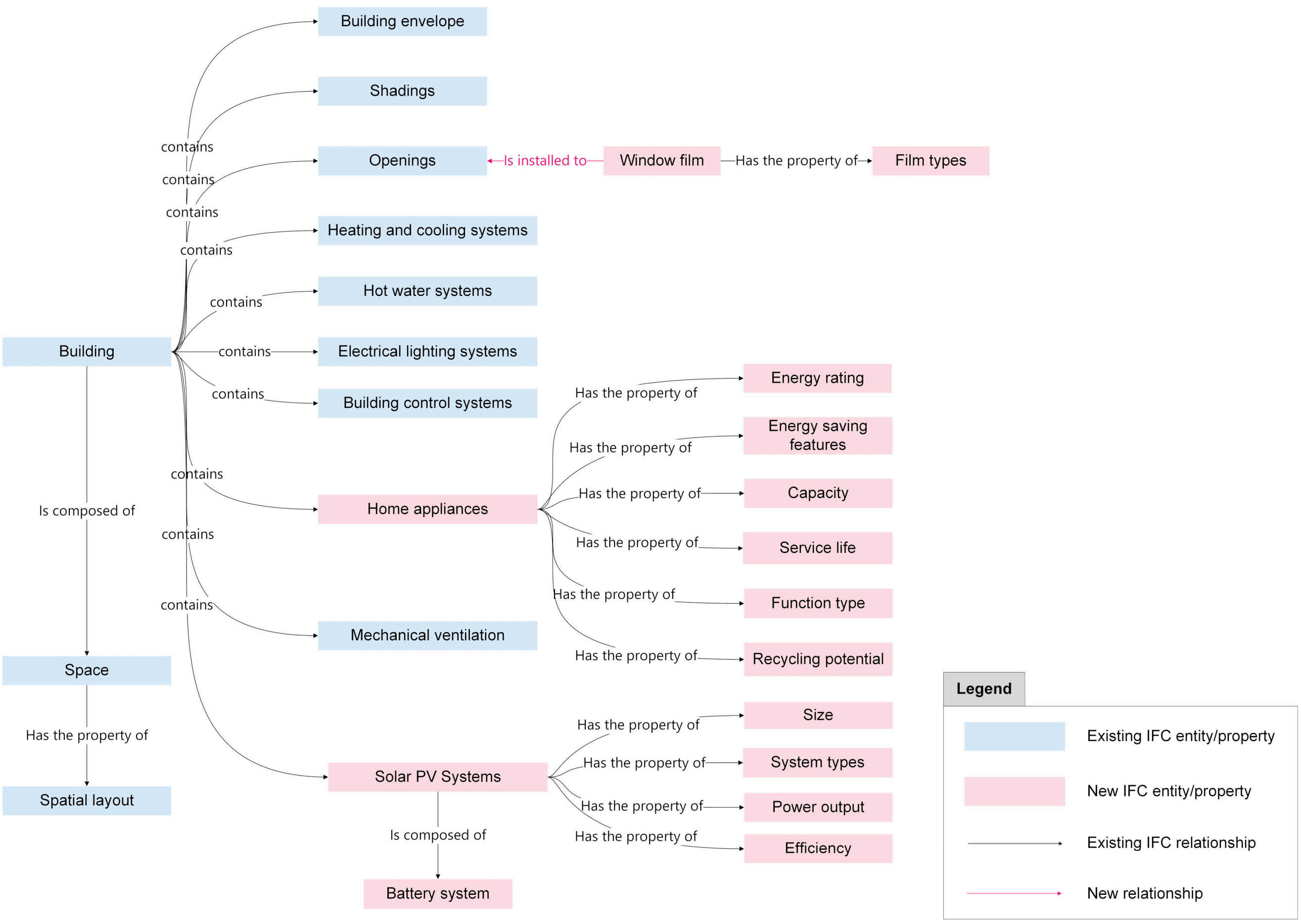

Figure 13. Illustration of an extension of additional entities, properties, and relationships to represent key decision variables affecting net-zero-carbon building outcomes at design stage, and the links to the existing IFC entities.

3.3.2. An Extension Representing Key Decision Variables at Construction Stage

At construction stage, categories and key decision variables affecting net-zero-carbon buildings that are not covered in the current IFC schema include: developing energy performance goals in the contract, contractor selection, transportation types, on-site energy use, waste management, and construction method. In this research, 23 new entities, 8 new properties, and 4 new relationships were used to represent these categories and variables. Figure 14 shows the new entities, properties and relationships and their connections to existing IFC entities through the ontology-based representation method.

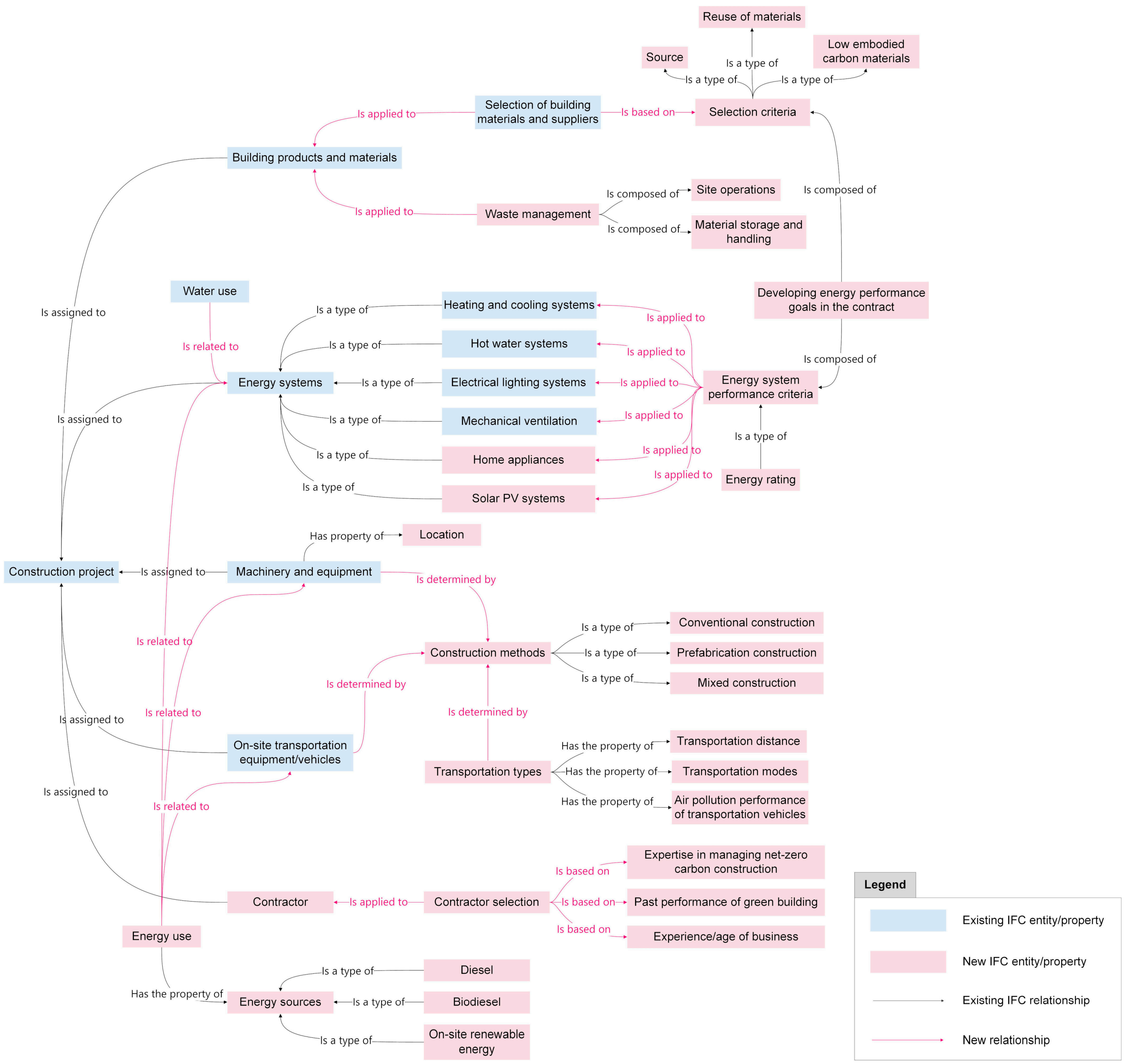

Figure 14. Illustration of an extension of additional entities, properties, and relationships to represent key decision variables affecting net-zero-carbon building outcomes at construction stage, and the links to the existing IFC entities.

The connections between existing and new entities and properties are established via a range of relationships. Three examples are given below:

- "Developing energy performance goals in the contract" is composed of two variables: "Energy system performance criteria" and "Material selection criteria". "Material selection criteria" is what the "Selection of building materials and suppliers" is based on. "Low embodied carbon materials", "Reuse of materials", and "Source" are subclasses of "Material selection criteria", connected via "Is a type of" relationship.
- Three decision-making actions apply to "Building products and materials" affecting energy consumption and carbon emissions, which include "Selection of building materials and suppliers", "Supplier/manufacturer selection", and "Waste management". "Waste management" enables reducing, reusing, and recycling building materials and is further composed of site operations, and material storage and handling.
- "Construction method" is also an important variable at the construction stage, and "Conventional construction", "Prefabrication construction" and "Mixed construction" are three typical types of construction method. The use of "Machinery and equipment", "On-site transportation equipment/vehicles", and the selection of "Transportation types" are determined by "Construction method" in many projects. Three properties are linked to "Transportation types" to define decision variables that affect carbon emissions during transportation, including "Transportation distance", "Transportation modes", and "Air pollution performance of transportation vehicles".

3.3.3. An Extension Representing Key Decision Variables at Operational Stage

At the operational stage, categories and key decision variables affecting net-zero-carbon buildings that are not available in the existing IFC schema include: the operation of energy systems such as heating and cooling systems, hot water systems, electrical lighting systems, home appliances and solar PV systems, and building retrofit such as upgrading of building envelope, energy systems and renewable energy systems. In this research, 19 new entities, 11 new properties, and 1 new relationship were developed, as illustrated in Figure 15, which are connected to the existing IFC schema using the ontology-based representation method.

As shown in Figure 15, there are 5 types of relationships. Existing relationships are "Is composed of", "Has the property of", "Is a type of", and "contains". One new relationship is "Is applied to". Through these relationships, the connections between existing and new entities and properties were established; two examples are given as follows:

- New operation-based actions are created and applied to existing building service systems: "Operating heating and cooling systems" is applied to "Heating and cooling systems"; "Operating hot water systems" is applied to "Hot water systems"; "Operating electrical lighting systems" is applied to "Electrical lighting systems"; "Operating home appliances" is applied to "Home appliances"; "Operating solar PV systems" is applied to "Solar PV systems". A few new properties are established to define the decision variables that affect building carbon emissions in operating energy systems, including "Time and hours of use" and "Temperature set-point". Two types of properties are specifically applied to "Operating home appliances". "Energy saving features" defines features that allow for appliances such as washing machines, dishwashers, and clothes dryers to use less energy. "Maximum number of users per device" defines whether devices such as office equipment are for individual use or common/group use.
- "Repair and maintenance" is a newly added action entity applied to building envelope components and energy systems to describe the repair and maintenance of these elements and systems. "Maintenance schedule" is a new property of "Repair and maintenance" to represent the interval scheduled for maintenance. This action entity is composed of various construction activities and linked to entities at construction stage, since the key decision variables for repair are the same as the construction variables.

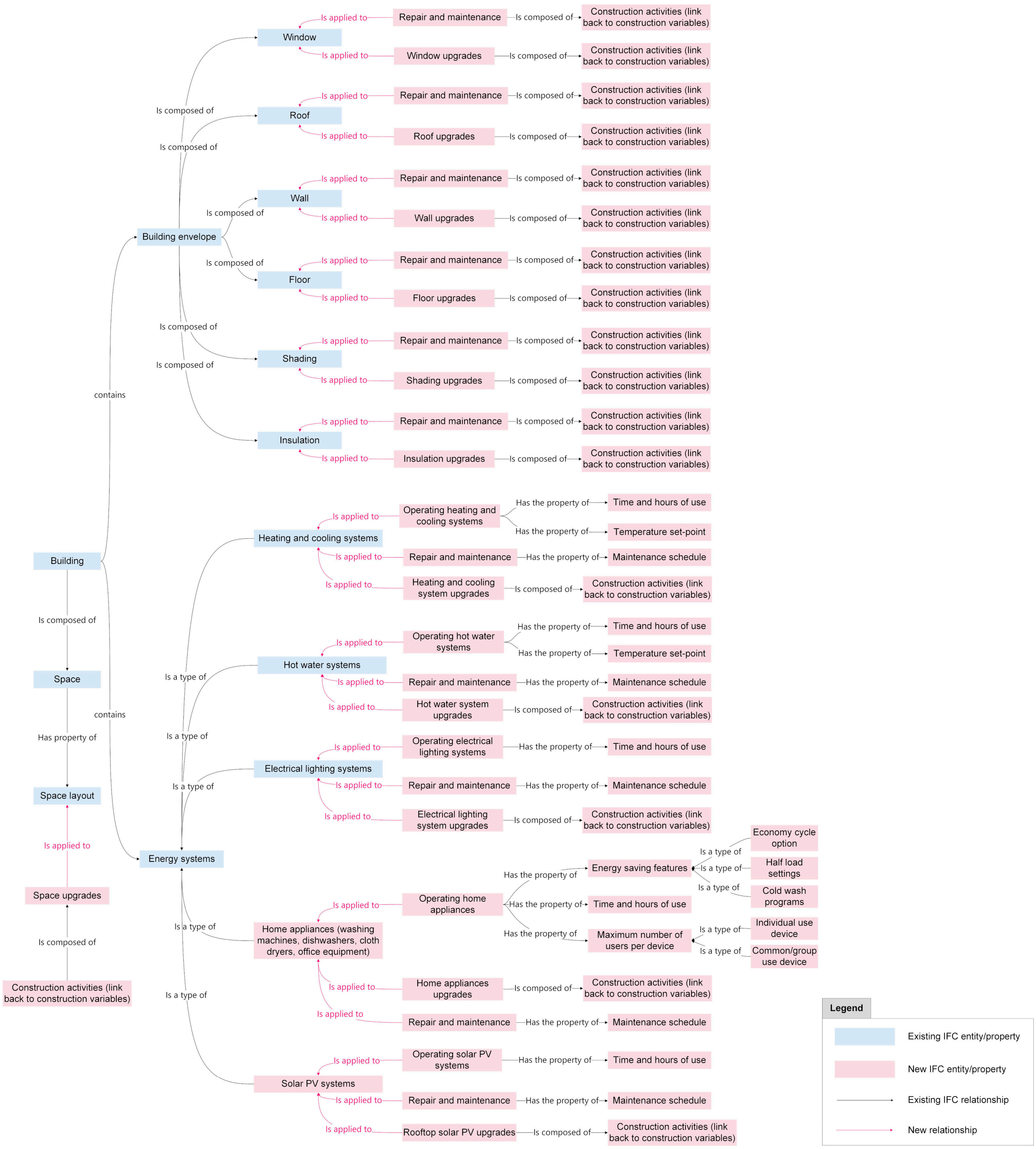

Figure 15. Illustration of an extension of additional IFC entities, properties, and relationships to represent key decision variables affecting net-zero-carbon building outcomes at operational stage, and the links to the existing IFC entities.

3.3.4. An Integrated Conceptual Framework with Connected Entities throughout Design, Construction, and Operational Stages

There are complex relationships between entities across different stages of the whole-building life cycle. Figure 16 presents an example of the integrated conceptual framework developed using an ontology-based representation method, where there are not only relationships between entities within each building stage, but also relationships between entities across design, construction, and operational stages. For example, the entity "Selection of building materials and suppliers" in the construction stage is connected to the entity of "Building envelope" at the design stage, which is composed of "Wall", "Floor", "Roof", "Shading", and "Window". The entity "Operating heating and cooling systems" at the operational stage also has a connection with the entity "Heating and cooling systems" at the design stage. Entities such as "Repair and maintenance", "Wall upgrades", and "Hot water system upgrades" are all composed of "Procurement and on-site construction", which is linked to entities at the construction stage.

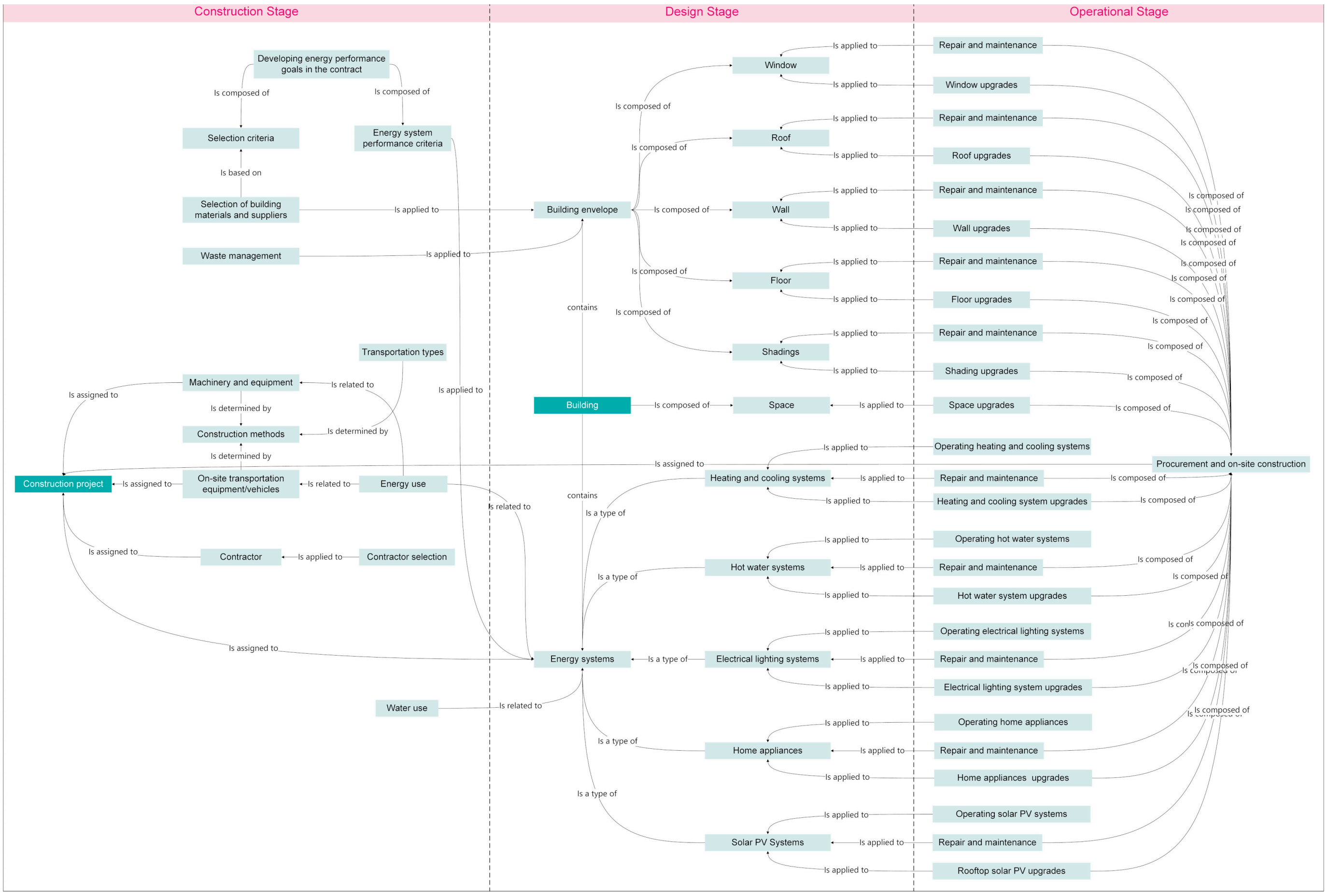

Figure 16. Illustration of examples of connected entities throughout design, construction, and operational stages in the conceptual framework.

3.4. Integrate Data Captured by Digital Twin into an Extension to BIM/IFC Schema

Data acquired from DT can be integrated with BIM/IFC, including both existing and new entities, properties, and relationships to represent key decision variables affecting net-zero-carbon outcomes of buildings. This is achieved through three steps: data acquisition, data processing, and data representation (Figure 17).

The data acquisition mechanism is the foundation of DT, which generally utilizes two approaches: taking snapshots and capturing changes [114]. Various techniques can be used for data collection, including internet of things (IoT) devices and wireless sensor networks such as quick response (QR) codes, and random collection devices such as telephones [115]. In this research, these technologies are used to monitor conditions of buildings (as built) and equipment during the building operation phase, including the building envelope, such as windows, walls, floors, roof, and shadings, and energy systems such as heating, cooling, and hot water systems. Thus, a variety of as-built building information that represents key decision variables affecting embodied and operational carbon at the operational stage is acquired through DT.

The second step is data processing, which includes data storage and data transmission. The captured data are stored and transferred to the next level for integration with BIM. To ensure net-zero-carbon assessment is based on real-time building information; this is essential to achieve low latency in data processing [116]. Communication technologies used for data transmission include short-range coverage access network technologies such as WiFi, near-field communication, mobile-to-mobile, and wider coverage such as 4G, 5G, long-term evolution and low-power wide-area networks [117,118]. WiFi is the most well-known wireless local-area network technology and has been widely utilized to transmit data [115].

After the DT data are acquired and processed, they are integrated with BIM/IFC extension using the ontology-based representation method as described in Section 2.3 (Figure 17). Three ontology components are utilized to represent the identified data, including entities, properties, and relationships. The ontology-based data representation is the core method for integrating BIM/IFC extension and DT data, which is also the focus of this research. The existing IFC schema and extension are developed based on ontologies with rich semantics. Through the ontology-based representation method, DT data can be integrated with newly added entities, properties, and relationships in the IFC extension. In this way, DT data can be linked to the 3D model and semantic information in the IFC extension.

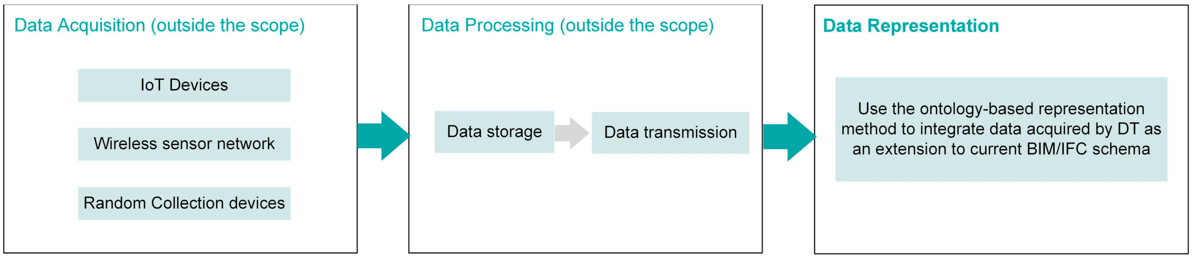

Figure 17. Integration of BIM/IFC and DT data.

A variety of data acquired by DT can be integrated into an extension to represent a subset of key decision variables affecting net-zero-carbon outcomes of buildings at operational stage as presented in Figure 15. As shown in Figure 18, DT can be used to capture the status of the building envelope and energy systems to support building management and maintenance and identify building problems to support building retrofit decision-making. These captured data will inform the corresponding key variables at the operational stage that are presented in an extension to BIM/IFC schema in Section 3.3.3 (Figure 15).

Figure 19 illustrates the process of integrating data captured by DT into an extension involving data acquisition via DT, data processing, and the ontology-based representation of data captured by DT. DT data can be captured through several data acquisition technologies such as IoT devices and wireless sensor networks. After data processing, data captured by DT can be integrated into an extension through the ontology-based data representation, as explained below.

There are two types of data that can be captured by DT, including actual building condition, and the upgrades of the building envelope and energy systems (Figure 18). Existing conditions of building envelope and energy systems can be captured via DT in the operational stage and then be processed and integrated into the extension. These data can reveal the building status and fault location for maintenance and operation, which will affect the operational or embodied carbon at the operation stage. This information can facilitate decision-makers in identifying problems and establishing energy efficiency strategies in maintenance, operation and retrofit for carbon reduction.

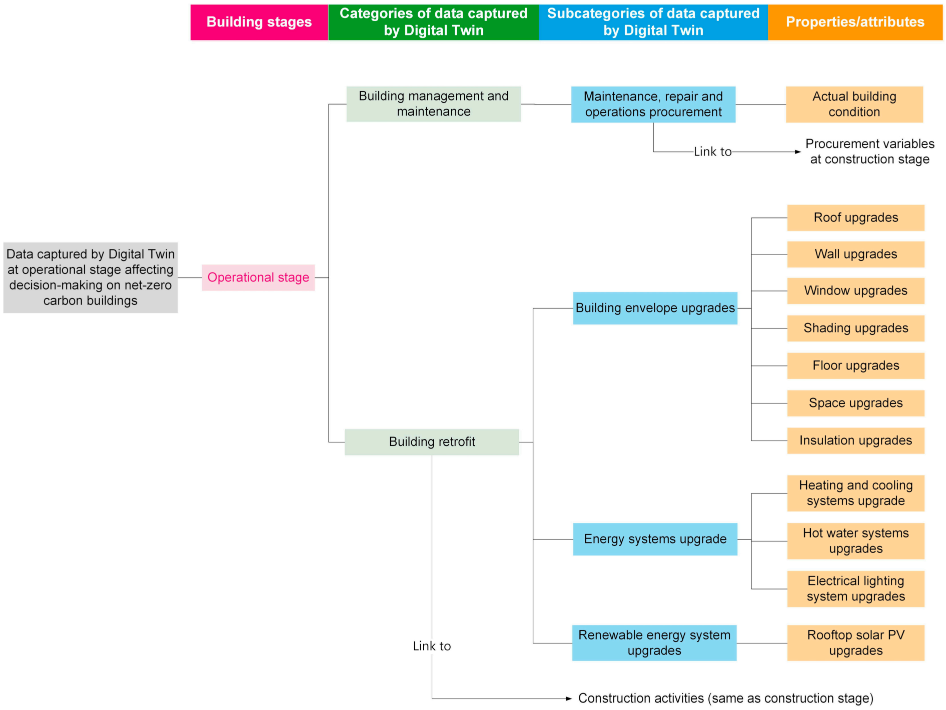

Figure 18. Data captured by DT at operational stage which affect decision-making for net-zero-carbon building.

Upgrades of the building envelope and energy systems can also be acquired from DT which are then processed and integrated into the extension. The information can support retrofitting decision-making based on the as-built condition of building assets, tracking of retrofitting, and updating building status after retrofit, to improve energy efficiency at the building operation stage. Figure 19 presents an example of how these data can be captured by DT and represented using the ontology-based representation method and integrated into an extension at the operational stage. These data are outlined as below:

- "Roof, wall, floor upgrades" informs the upgrades of roof, wall, and floor elements such as upgrading the materials and construction types, replacing insulation and changing finishes.
- "Window upgrades" informs the upgrades of windows such as the location and window–wall ratio.
- "Shading upgrades" informs the upgrades of shadings such as the location, types, and size.
- "Heating and cooling system upgrades" informs the upgrades of heating and cooling systems such as the system types and location of portable heaters and air-conditioners.
- "Hot water systems" informs the upgrades of hot water systems such as the system types. The upgrading of solar hot water system is further linked to "Solar PV system".
- "Electrical lighting systems" informs the upgrades of electrical lighting systems such as the light bulb types and fittings.
- "Home appliances" informs the upgrades of home appliances such as washing machines, dishwashers, cloth dryers and office equipment, particularly their types.
- "Solar PV systems" informs the upgrades of rooftop solar PV panels such as the size and system types.

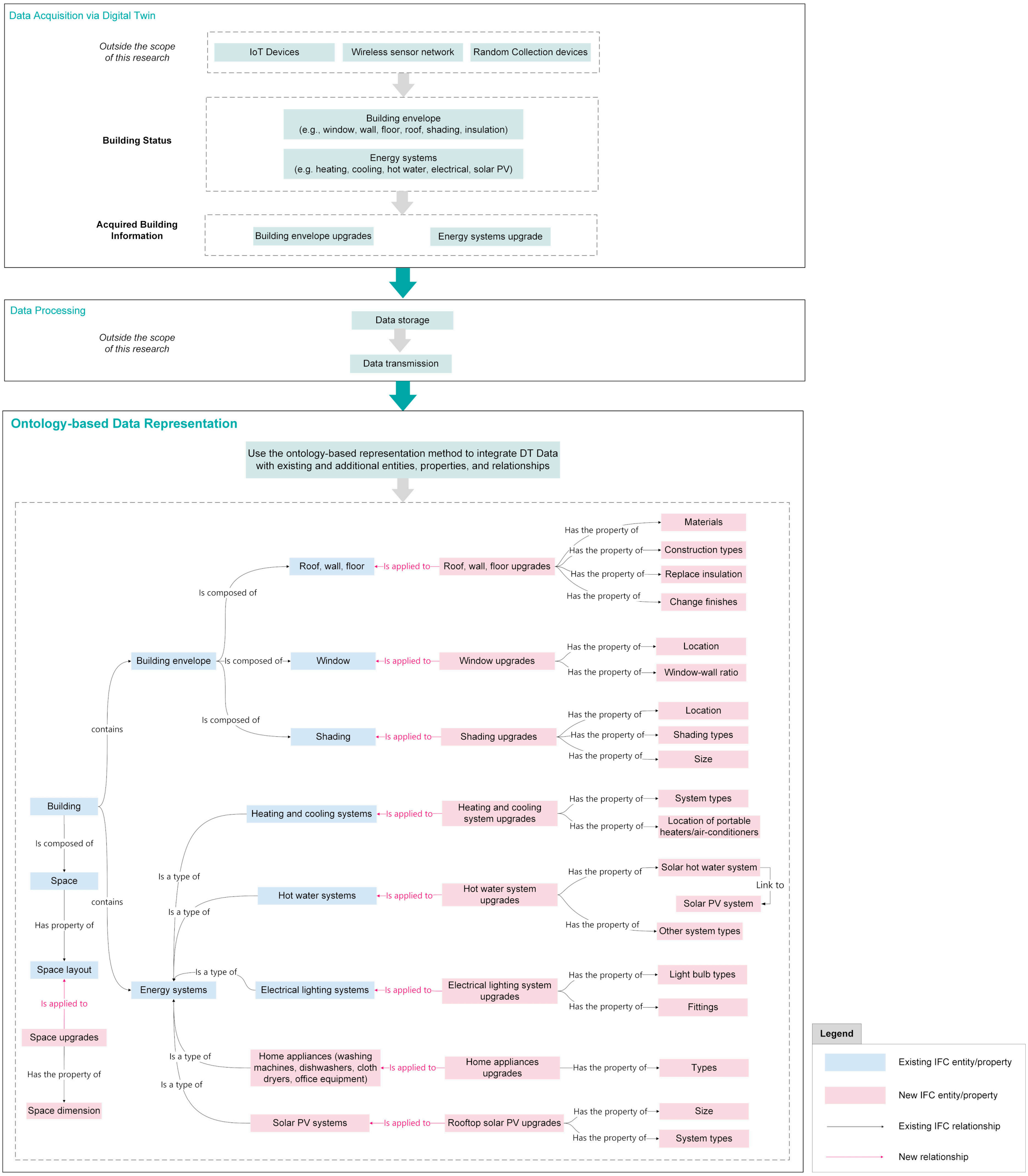

Figure 19. Illustration of DT data integrated into extension using the ontology-based representation method to represent key decision variables at operational stage.

4. Discussions

4.1. Implication of the Framework

Most of the existing research has dealt with decision variables related to carbon emissions in individual stages rather than the whole-building life cycle process. There is a lack of a data integration framework integrating key decision variables to support whole-life-cycle net-zero-carbon buildings. This paper has filled this gap by developing a novel data integration framework to integrate key decision variables throughout the whole-life-cycle building process, including building design, construction, and operational stages, to support decision-making and automated assessment of the whole-life-cycle net-zero-carbon buildings.

Secondly, little of the research has considered an open international standard approach integrating key decision variables affecting carbon emission throughout the whole building life cycle process. BIM/IFC is an open international standard to represent building information, significant to supporting decision-making on the whole-life-cycle net-zero-carbon buildings. However, limited research explored BIM for integration with the building operational stage. DT can capture and monitor real-time building conditions to facilitate the building operational stage. Therefore, this paper contributes to the body of knowledge by integrating DT data into BIM, which provides an integrated computational representation of key decision variables during the whole-building life cycle. Based on that, this paper developed a novel conceptual framework by using an international standard approach, and the ontology-based representation method, which extends the current BIM/IFC schema and integrates data from DT to support the decision-making and automated assessment of the whole-life-cycle net-zero-carbon buildings.

This paper provides general guidance to the built environment industry, and informs practitioners such as architects, designers, suppliers, contractors, subcontractors, and facility managers, of key decision variables that have significant contributions to the net-zero-carbon outcomes of buildings, to facilitate their decision-making process in their specific area, which contributes to the whole-life-cycle net-zero-carbon buildings. The novel conceptual framework can pave the way for future research on an automated system to support well-informed decision-making on the whole-life-cycle net-zero-carbon buildings.

4.2. Research Limitations and Potential Future Works

There are several limitations in this research, which suggest the need for future studies. Firstly, three main building lifecycle stages were considered in this research: the building design, construction, and operational stages. While this research acknowledges that there are a variety of variables influencing the carbon emission outcomes of buildings specific to each project, the focus of this research is on key decision variables that make the most significant contribution to gaining net-zero-carbon outcomes for buildings, rather than providing an exhaustive list of all the decision variables involved. In addition, all identified key variables are classified into different levels and categories using hierarchies. Although the categories of variables are not suitable for every scenario, which may vary depending on the project type and contract type, the aim is to better organize the large number and wide variety of variables that need to be recognized. Future research can extend the scope to cover more building stages, such as the demolition, recycling, and reuse of building materials stages, to promote a more comprehensive approach to achieving net-zero-carbon buildings throughout the whole building life cycle.

Secondly, this research addresses the challenges involved in achieving whole-life-cycle net-zero-carbon emissions and focuses on the reduction in both embodied and operational carbon emissions, without considering the increasing use of solar energy. While this research mainly uses residential buildings for context, the contributions of this research can be applied to all building types.

Furthermore, the novel framework was developed at the conceptual level, based on key decision variables identified through a systematic literature review. All key variables were carefully identified from the published literature, providing findings from previous research in this area, and a rigorous review was carried out to ensure the effectiveness and reliability of the framework. An empirical investigation of gathering feedback on the framework from built-environment practitioners can further improve the conceptual framework. In addition, the dynamic nature of sensor data over time is not considered in this research, which could be further investigated in future research. Finally, as, usually, a conceptual framework is developed as a generic model [119], implementation in any specific software is outside the scope of this paper. The details of software implementation for the integration of BIM and DT can be considered in future work, for example, visual programming such as Dynamo and Grasshopper could potentially be utilized for the integration of real-time sensor data and BIM, which provides a bi-directional link between the design tool and the building performance simulation [120,121].

5. Conclusions

There are many challenges in the achievement of net-zero-carbon buildings over the whole building life cycle. This research tackles the challenge by developing a novel conceptual framework using an open international standard approach and ontology-based representation method, able to define key decision variables affecting the whole-life-cycle net-zero-carbon building outcomes using entities, properties, and relationships, and integrates the captured data via DT.

Firstly, a range of key decision variables that affect net-zero-carbon outcomes of buildings in the design, construction and operational stages were identified through a systematic literature review. Then, existing IFC entities, properties and relationships representing key decision variables were identified through a mapping process. For key variables that were not available in the existing BIM/IFC schema, an extension to the current BIM/IFC was developed to define new entities, properties, and relationships by utilizing an ontology representation method. In addition, building operational data required in the BIM/IFC extension, which can be obtained from DT, were also defined for integration into the extension.

A novel conceptual framework was developed to support whole-life-cycle net-zero-carbon buildings, through integrating BIM and DT. The framework consists of the existing IFC entities, properties, and relationships, and an extension at the conceptual level, which defines the identified key variables and also integrates DT data into the extension. The framework fills the current knowledge gap and creates new opportunities to integrate BIM/IFC and DT technologies to provide a computational representation of key decision variables that make the most significant contribution to gaining net-zero-carbon outcomes for buildings, addressing the challenges involved in achieving whole-life-cycle net-zero-carbon emissions.

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