Developing an ontology-based tool for relating risks to the energy performance gap in buildings

Article

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Abstract

Purpose- Despite extensive research on the underlying reasons for the energy performance gap in buildings, there is a critical need for stakeholders to standardize and facilitate the use of this knowledge and support its broader application by machines. Our research addresses this gap by developing both an ontology and a tool to utilize risk information regarding the performance gap in buildings.

Design/methodology/approach- Research into this topic began with the creation of an energy performance gap-risk ontology for new and existing buildings using the METHONTOLOGY method. This comprised a comprehensive literature review and semi-structured interviews with ten experts concerning six buildings, in order to develop taxonomies and define risk factor interactions. It was followed by a three-stage validation using a mixed-method research methodology. Steps included comparing the ontology with a similar empirical study, gathering expert opinions via interviews and ratings assessments, and finally, interviewing an experienced professional to ascertain whether there were any concepts not covered by the ontology. The taxonomies were modeled in Protégé 5.5, and using the ontology, a spreadsheet tool was developed using Microsoft Visual Basic for Applications in Excel.

Findings- The ontology identified 36 primary risk factors, and a total of 95 when including additional risks linked to certain factors. Factors such as professional liability insurance, stakeholder motivation, effective communication, experience, training, integrated design, simplicity of detailing, building systems or design, and project commissioning can help manage the performance gap in buildings. The tool developed serves as a decision-support system, offering features like project risk checklists to assist stakeholders in addressing the performance gap.

Quality/value-This study is the first to develop an energy performance gap-risk ontology and a tool to help project stakeholders collect, store, and share building risk information.

Keywords

Energy performance gap, ontology, spreadsheet tool, project risks, risk identification

Paper type Research paper

1.Introduction

Buildings are responsible for significant energy consumption and energy-related greenhouse gas emissions (Alam *et al*., 2017). Therefore, it is critical to plan the right policies to improve the energy efficiency of new and existing building stock (Burman *et al*., 2014). To address this problem, governments have upgraded energy and construction standards in buildings and energy performance assessment tools worldwide. These efforts have led to the emergence of a series of low-carbon and low-energy buildings, both newly built and retrofitted (Gupta *et al*., 2020).

Nevertheless, energy estimates at the design stage often differ from actual operational use, and this difference is known as the energy performance gap (Godefroy, 2022). The magnitude of the energy performance gap (EPG) varies widely (Shi *et al*., 2019). In reviewed publications, Mahdavi and Berger (2024) found a median EPG of +30% in residential and +14% in non-residential buildings, while Calì *et al.* (2016) reported that the EPG can be up to 287%.

This phenomenon impacts various aspects of the building industry, including governmental sustainability targets (Ortiz *et al*., 2020), design, economic, technological, well-being, and health benefits (Shrubsole *et al*., 2019). It also affects the credibility of industry professionals, such as policymakers, engineers, and designers (Wang *et al*., 2023). Additionally, energy performance risk has financial implications for energy service companies, which typically guarantee project savings through energy performance contracting (Doylend, 2015).

The EPG of buildings, including green buildings, has been extensively studied for over two decades (Shi *et al*., 2019), with significant efforts being made to identify its causes (Pomponi and Moncaster, 2018) and propose strategies to bridge the gap. However, current research focuses on the technical aspects of building energy performance to reduce EPG, frequently overlooking important social and organizational factors (Zheng *et al*., 2024).

Furthermore, some authors have identified risks contributing to the gap. Risk is characterized as uncertain events impacting project goals (Siraj and Fayek, 2019) and performance (Jayasudha and Vidivelli, 2016). Significant uncertainty persists both throughout the building's life cycle and when replicating actual conditions in energy simulations (Garwood, 2019). Therefore, reducing uncertainties and implementing risk management strategies early in construction increases the likelihood of achieving the project goals (Yousri *et al*., 2023) and effectively mitigates the energy performance gap (Frei *et al*., 2017).

However, relatively few studies examine the EPG issue from a risk perspective (Doylend, 2015; Alam *et al*., 2017; and Topouzi *et al*., 2019). Furthermore, while these studies provide valuable insights into risk factors and their classification, they lack the comprehensive overview necessary to account for the varied risks across different contexts since they focus on one country, and one case study. Additionally, the findings of these studies often overlap with previous research identifying the causes of EPG and exploring it through risk management literature. These studies categorize risks into different classes and this redundancy in terminology and classification hinders the effective communication and practical application of the accumulated knowledge and expertise in current practice to reduce the gap in buildings. Therefore, standardization in the EPG domain, particularly from a risk perspective, is necessary for effective energy performance gap mitigation.

Developing an ontology is often considered the first step towards harmonizing domain knowledge across various information systems (Jiang *et al.*, 2023). Ontologies provide benefits such as semantic modeling, reusability, and the extensibility of information (Schachinger and Kastner, 2017; Han *et al.*, 2015). However, despite the existence of several ontologies in building energy efficiency (Tah and Abanda, 2011; Corry *et al.*, 2015; Zhou and El-Gohary, 2017), a gap remains in the ontological representation linking risks to the performance gap and specifying interrelationships between risk factors across multiple building projects involving different building uses. Moreover, the construction sector needs to work on capturing, storing, sharing, and re-using knowledge due to a lack of mechanisms and processes that encourage the necessary social interaction to shape and formalize it (Shelbourn *et al.*, 2006). Therefore, an environment is needed that can not only standardize these processes in a structured manner, but also serve as a guideline, and transfer risk knowledge to future projects.

Given these research gaps, the primary aim of this study is to develop an ontology to relate risks to EPG. The objectives of the paper are to:

- establish a common vocabulary to eliminate heterogeneity when identifying EPG risks in buildings;
- classify risk factors and define their interrelations;
- develop a tool to assist project stakeholders in gathering, storing, and sharing the risk information of energy-efficient building projects.

Our research contributes to the existing body of knowledge by developing a comprehensive ontology that synthesizes empirical and theoretical knowledge across different building types, certification systems, and contexts. The ontology facilitates knowledge dissemination among project stakeholders and ensures semantic interoperability. By leveraging the ontology into a risk management tool, the research supports the systematic collection of data from buildings and the mitigation of EPG, and contributes to the United Nations' sustainable development goals (SDG). The first section of this paper introduces the study. The second section provides background information, focusing both on the reasons for and risks surrounding the gap and on previous ontology studies. The third section details the research methodology, while the fourth section presents research findings on the ontology and the tool developed. The fifth section offers a discussion, and the final section covers conclusions, research limitations, and future work.

2. Background

2.1. Causes of the energy performance gap

A widely accepted definition describes EPG as the difference between calculated (or simulated) and measured energy use (Bai *et al*., 2024), arising from concurrent factors present throughout a building's life cycle (Hahn *et al*., 2020). Researchers identified EPG factors through various methods, including literature reviews (Van Dronkelaar *et al*., 2016), surveys with facility managers (Liang *et al*., 2019), and detailed analyses of project documentation, thermography, co-heating tests, interviews, occupant surveys, and walkthroughs (Gupta *et al*., 2013).

In the design phase, EPG is influenced by limitations in modeling programs and methods (Menezes *et al*., 2012), misuse of tools (Kampelis *et al*., 2017), unrealistic behavioral assumptions (Gram-Hanssen and Georg, 2018), design complexity, early design choices, and human errors (Godefroy, 2022). Wang *et al*. (2023) highlight the lack of actual data on existing buildings and the disregarding of thermal bridges and insulation gaps during energy modeling. Factors such as post-design changes and construction quality can cause EPG in the construction phase, while unfinished activities and poor-quality handovers contribute to EPG at the commissioning and handover stage (Godefroy, 2022). During operation, occupant-driven factors predominantly cause EPG (Mahdavi & Berger, 2024), including higher operating temperatures, increased air change rates, and discrepancies in plug-loads, lighting usage, and internal heat loads. For this reason, the knowledge and skills of the occupants and energy managers are crucial (Zou *et al*., 2018). Further factors leading to EPG include poor practices, faulty equipment, measurement system limitations, operational instability, maintenance, and facility management issues (Godefroy, 2022).

In addition to the root causes of the gap, strategies for closing it are among the most widely studied areas in current research. Most researchers and practitioners consider technical methods, such as data collection and simulation processes, to be among the best ways to reduce the gap (Zheng *et al*.,2024), as well as transparency in energy performance data reporting and benchmarking (Danish & Senjyu, 2023). However, resolving the EPG also requires soft methods, such as effective communication and management among building stakeholders, and mandatory regulatory strategies (Zheng *et al*., 2024). Therefore, effective stakeholder engagement and collaboration (Madhusanka *et al*., 2022), along with strategies such as designer competence, early involvement of key participants, and an integrated project delivery model, are also critical to bridging the gap (Moradi *et al*., 2024).

2.2. Risks influencing the gap

Risk is often described in terms of uncertain events and their influence on project goals (Siraj and Fayek, 2019). Therefore, early-stage risk identification helps ensure that stakeholders and clients achieve their project goals (Yousri *et al*., 2023). The ISO 31000:2018 standard emphasizes risk assessment—comprising identification, analysis, and evaluation—as central to risk management.

Risk assessment models in green building projects are less comprehensive than in general risk literature (Nguyen and Macchion, 2023). Mills *et al.* (2006) identified five classes of energy-efficient project risks: measurement and verification, economic, operational, technological, and contextual. Qin *et al*. (2016) examined certification, managerial, quality/technological, financial/cost, political, and social risks in the green building life cycle in China, emphasizing their probability and impact. Yang *et al.* (2016) showed that the critical risks for and stakeholders of green buildings differ between countries (Australia and China).

The effective mitigation of EPG requires a well-structured, integrated performance and risk management process (Frei *et al*., 2017). However, studies focusing on risks causing EPG are limited. Doylend (2015) categorized energy performance risks into four groups: design and engineering, management and process, external constraints, and operation and maintenance, while Alam *et al*. (2017) categorized risks into six classes: design input, client-related issues, procurement, construction management, material and equipment, and knowledge and skills. Furthermore, Topouzi *et al*. (2019) identified three main risks: communication, sequence, and assessment, comparing their likelihood in five retrofit approaches, and Thompson *et al*. (2022) identified twenty-two risk factors in an analysis of 49 non-residential buildings.

2.3. An overview of ontology studies

Ontologies, sometimes described as vocabularies, contain a formalized representation of knowledge for a particular domain in the information science field (Pritoni *et al*., 2021). A hierarchy of concepts illustrating entity types, relations among concepts, restrictions on relations, and instances are significant parts of ontologies (Schachinger and Kastner, 2017). Ontologies facilitate knowledge exchange between domains and link shared knowledge, offering advantages like semantic modeling (Schachinger and Kastner, 2017), information reusability, extensibility, and interoperability (Han *et al*., 2015). They are useful in the research areas of artificial intelligence, system integration, the semantic web, and problem-solving methods (Tserng *et al.*, 2009).

Ontology development typically follows an iterative process with various modeling methods (Schachinger and Kastner, 2017). Ontology building uses a customized procedure with no universal method. Among the most common methods used in the construction industry are METHONTOLOGY, SKEM, Uschold & Gruninger's (1996) approach, and NeOn, Grüninger, and Fox's (1995) approach (Zhao *et al.*, 2016). Iqbal *et al.* (2013) conducted a comprehensive review of fifteen ontology engineering methodologies and concluded that, while none of the methodologies are fully mature, METHONTOLOGY stands out by providing detailed descriptions of the techniques and activities employed.

Ontologies related to building energy efficiency serve multiple purposes. Researchers have developed ontologies for selecting photovoltaic systems (Tah and Abanda, 2011), extracting energy requirements from energy conservation codes (Zhou and El-Gohary, 2017), identifying occupants' behavioral adaptation mechanisms (Hong *et al.*, 2015), and representing interactions between smart grids and building energy management systems (Schachinger and Kastner, 2017). Other focuses include thermal comfort and energy efficiency (Esnaola-Gonzalez *et al.*, 2021) and performance assessment via a semantic web-based method (Corry *et al.*, 2015).

2.4. Research contribution

A comprehensive literature review on EPG research revealed the following critical limitations in existing studies:

- Existing research predominantly focuses on the technical aspects of building energy performance to mitigate EPG, often neglecting crucial social and organizational factors.
- Performance gap studies can be categorized into two groups: those with a risk management perspective and those without. Despite using different terms like cause, reason, and risk, the findings overlap significantly between these groups.
- Most studies in the risk management literature use a structured approach with risk classification, something often lacking in EPG studies. Additionally, existing literature on risk identification typically categorizes risks into different classes. The development and application of classifications enhance communication efficiency by revealing patterns and providing a comprehensive overview through the visualization of clusters, densities, and gaps (Kwaśnik, 2019). However, inconsistent terminology and classification between studies complicate the use of previous research insights.

- Existing literature struggles to establish causal relationships between risk factors. Nevertheless, it is essential to consider risk paths, both to prevent significant risks from being disregarded (Alam *et al.*, 2017) and to enhance risk mitigation.
- Additionally, earlier studies on risks affecting building energy performance have been constrained by focusing only on the UK construction sector, renovation methods, literature reviews, and a single case study. However, previous researchers noted that risks affecting building performance vary from one building to another (De Wilde, 2014), and critical risks differ between different stakeholders and countries (Yang *et al.*, 2016).
- Current ontologies address the technical aspects of building energy performance; however, no domain ontology systematically categorizes and defines the relationships between key risks in EPG.
- This study addresses current research limitations by developing an ontology that considers various building types, sustainability standards, and country conditions to provide a comprehensive view of risks affecting EPG. The ontology will standardize risk terminology, classify risks systematically, and establish causal relationships between the risks. Through semi-structured interviews considering the life-cycle stages of different buildings, the study will explore not only technical but also social and organizational factors causing EPG. Later, a tool will be developed to integrate risk management into the project life cycle to reduce the gap in buildings. In this study, risks are defined as uncertain events or situations that can impact building performance either negatively, positively, or both.

3. Research steps and methods

The study includes two main parts: (1) a five-step process for ontology development and (2) the development of a tool based on the ontology. It proposes an ontology rather than a model or conceptual framework, as ontologies represent knowledge, facilitate interoperability, and allow semantic modeling. Although a conceptual framework outlines the current state of knowledge, it is finalized before the study and is rarely modified once data collection begins (Varpio *et al.*, 2020).

Figure 1 illustrates the research steps employed in the study. The ontology was created using the METHONTOLOGY method, as referenced by Zhou *et al.* (2016) and Guyo *et al.* (2023). METHONTOLOGY is well-structured (Fernandez *et al.*,1997), comprehensive, and one of the most frequently used ontology engineering methodologies (Abanda *et al.*, 2017). It enables the creation of an ontology from scratch (Abanda *et al.*, 2017; Khalid *et al.*, 2023), while also permitting the reuse of existing ontologies. Due to the evolving prototype life cycle of this methodology, ontology development is a continuous process, allowing updates at any phase (Khalid *et al*., 2023). The ontology can be employed to create various tools suited to specific requirements. This article provides an illustrative example. Following the ontology development steps, a practical Excel-based tool, EPG-RISK, was created within a spreadsheet environment to help project stakeholders collect, store, and share the risk information of projects.

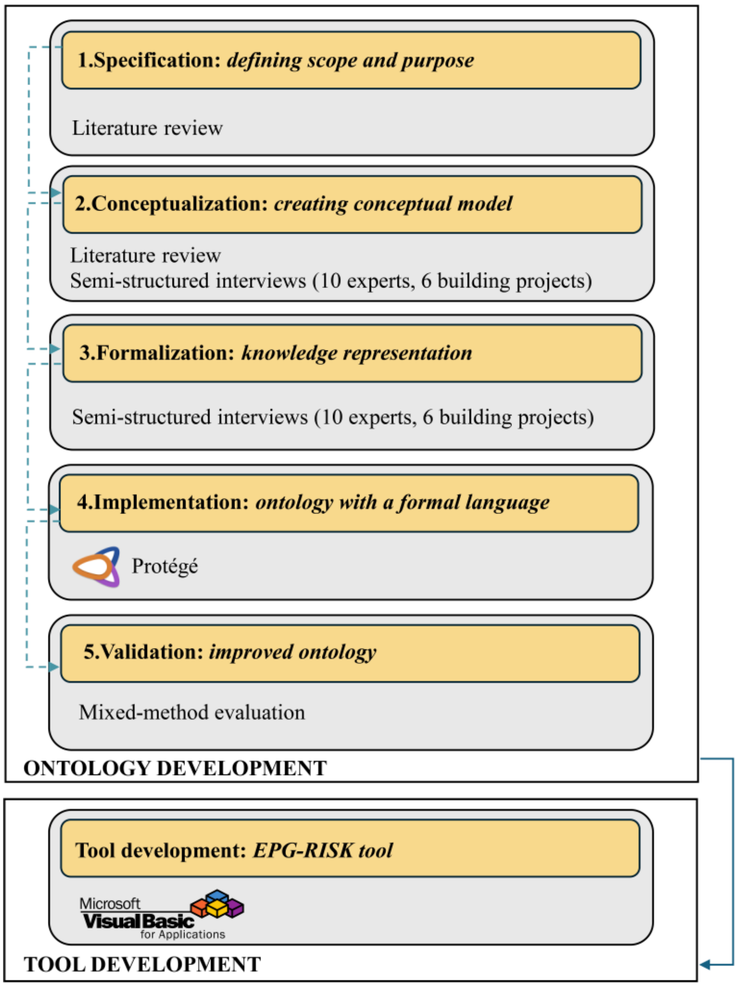


Figure 1. Research steps (Source: Authors own work)

3.1 Ontology development stage

The ontology development process consists of five main steps: specification, conceptualization, formalization, implementation, and validation. The following sections explain each step in detail.

3.1.1 Specification

At a minimum, the specification step should provide the ontology's purpose, level of formality, and scope (Fernandez *et al*., 1997). This ontology aims to explain the energy performance gap in buildings by utilizing project risks. The ontology can then be used by (i) project managers, energy consultants, engineers, and energy service companies involved in developing a specific energy-efficient building project and assessing project risks, or (ii) experts who want to predict the risk of an energy performance gap in a project. Professionals can use the ontology to describe risks influencing EPG in a semi-formal language, considering the design, construction, and operational phases. Additionally, it helps identify relationships between various risk factors.

3.1.2 Conceptualization

The conceptualization process aims to uncover knowledge related to risks contributing to EPG in buildings. Conceptualization, a challenging aspect in ontology design, requires a subjective representation of the world and an understanding of how individuals perceive and categorize their environment (Fidan *et al*., 2011).

This step involved the identification of risks through an extensive review of the existing literature and semi-structured interviews concerning six building projects. Semi-structured interviews are frequently used to understand the ‘what’ and ‘how’, with a particular emphasis on the ‘why’. Additionally, they help us understand the context and analyze relationships between variables (Saunders *et al*., 2019). Several researchers have employed semi-structured interviews (Moradi *et al*., 2024; Alencastro *et al*., 2024; Yousri *et al*., 2023), which was also the preferred method in this study as the aim was to understand the contextual factors for risk and EPG, particularly interrelations.

Initially, critical parameters, such as modeling, software, calculation methodology (De Wilde, 2014; Doylend, 2015; Calì *et al*., 2016), simulation inputs (De Wilde, 2014), and design problems (De Wilde, 2014; Doylend, 2015), were identified via a literature review. Twenty journal articles on EPG in buildings were reviewed, and the most common concepts collected. Later, semi-structured interviews were conducted with domain experts to explore factors affecting risk and EPG, understand their relationships, and develop a conceptual model**.** One criticism of semi-structured interviews is that the data collected may be perceived as “subjective and imprecise.” However, conducting multiple meetings and interviews with the same respondents can enhance data quality and build trust (Albaret and Deas, 2023). Our study addressed these concerns by conducting two rounds of semi-structured interviews. The interviews were held between December 2020 and May 2021, either online or in person, each lasting 60 to 90 minutes. In the first round, interviewees were asked to describe the project phases of an energy-efficient building they had worked on, explaining problems or challenges that might result in an EPG, and stating whether these issues were resolved or led to further problems. In the second round, the identified risk factors and relationships were presented to the interviewees to determine their agreement, gather their feedback, and request suggestions for revisions.

The building project selection process was strategically designed to capture diverse perspectives on EPG in buildings applying the principles of sustainable design, both with and without certification. Projects in Turkey and Germany were selected to provide a comprehensive contextual lens. It is hypothesized that Turkey, offering the perspective of an emerging market in green buildings, and Germany, as a pioneer, particularly in Passive House certification, can both be representative and reflect different but complementary perspectives. The projects that are discussed during the semi-structured interviews included one educational, two residential, and three office buildings, with varying certification levels (Passive House, LEED Platinum, LEED Gold, and non-certified). All buildings were constructed between 2014 and 2020, enabling a comprehensive examination of EPG across different building typologies, sustainability standards, and country conditions (developed and developing). Table 1 demonstrates the building projects and the information about the interviewees.

The interviewees, including project managers, mechanical engineers, and site managers, were selected for their comprehensive knowledge of the buildings, from the design phase to being operational. One participant served as the commissioning agent for two green buildings, one of which was LEED Platinum-certified, with the other being expected to achieve LEED Gold certification. On average, the experts had twelve years of experience in energy-efficient buildings.

Table 1.

Information on buildings and interviewees (Source: Authors own work)

No	Building	Country	Building Type	Construction Year	Area	Interviewee No	Position	Years of experience
I	Passive House I	Germany	Residential	2019	4,009 m²	I1	CEO	34
II	Passive House II	Germany	Residential	2018	15,150 m²	I2	Project manager	21
III	Green Building I (LEED Gold)	Turkey	Headquarters	2020	45,782 m²	I3	Commissioning agent	12
						I4	Quality manager	8
						I5	Electrical technician	10
IV	Green Building II (LEED Platinum)	Turkey	Headquarters	2014	9,538 m²	I6	Project manager	8
						I7	Site manager	8
						I8	Mechanical engineer	8
						I3	Commissioning agent	12
V	Non-certified energy-efficient building I	Turkey	Educational	2017	17,030 m²	I9	Project manager	9
						I10	Mechanical engineer	8
VI	Non-certified energy-efficient building II	Turkey	Headquarters	2019	8,955 m²	I9	Project manager	9
						I10	Mechanical engineer	8

3.1.3 Formalization

In this step, taxonomies and the relationships between the concepts were developed using an iterative development process, as suggested by Fidan *et al.* (2011). Taxonomies represent formal hierarchical relationships between items (Pritoni *et al.*, 2021). Semi-structured interviews provided valuable information that helped us to develop the risk taxonomies and understand how different concepts interrelate. After the initial round of interviews, experts reviewed the identified risk parameters and relationships. In the second round, they evaluated the interrelations, indicated their agreement, or suggested revisions.

3.1.4 Implementation

The implementation step modeled taxonomies and their relationships using an ontology editor tool. Various ontology editors were used, including Protégé, NeOn Toolkit, SWOOP, Vitro, and Anzo for Excel in other studies. Protégé is widely used for modeling domain knowledge (Yuan *et al*., 2018). Tah and Abanda (2011), Esnaola-Gonzalez *et al.* (2021), and Alsanad *et al.* (2019) have all used Protégé to translate their ontologies into a semantic web language. In this study, Protégé 5.5 was selected for its extensive use, free and open-source editing capabilities, stability within the ontology and Semantic Web community, and compatibility with other plug-ins (Abanda, 2011).

3.1.5 Validation

Ontology evaluation focuses on correctness and quality (Hlomani and Stacey, 2014) and is generally undertaken using verification or validation methods. The verification process ensures that the ontology is constructed correctly (Bilgin *et al*., 2014), while validation checks whether it accurately models the real world in its application (Gruninger, 2019). Validation criteria include consistency, completeness, conciseness, expandability, and sensitiveness (Lovrenčić and Čubrilo, 2008).

It is necessary to ensure that the ontology is technically consistent and in compliance with OWL syntax for syntactic verification (Khalid *et al*., 2023). In this study, this was tested using Pellet, an OWL-based reasoner. Later, the validation process was designed as a multi-step process so that the ontology could be tested using different sources of data at each step and enhanced until no further changes were required. A mixed-method research methodology was used to gather and analyze quantitative data, 5-point Likert scale ratings and qualitative data from interviews. Indeed, combining two methods can be more effective than using just one, providing deeper insights into research phenomena that cannot be fully comprehended through either qualitative or quantitative methods alone (Dawadi *et al*., 2021). One aim of employing a mixed-method approach in research is to gather diverse yet complementary data on the same topic, enhancing our understanding of research problems. In this way, data can be collected independently and then integrated before interpreting the results (Dawadi *et al*., 2021). In our study, an article and interviews were used as different data sources to validate the ontology.

In the first stage, an empirical article by Jain *et al.* (2020) was reviewed in detail to evaluate the ontology's completeness and expandability. This particular article was selected because it focused on four building types (apartment block, school, office, and hospital) and used energy model calibration for performance gap assessment.

The second stage comprised the interviewing of six domain experts who were knowledgeable about EPG in buildings. Interviews were conducted online in May 2023, each lasting one hour. The proposed ontology was sent to experts beforehand for review. These experts, mechanical engineers with an average of 25 years of experience (Table 2), were based in the UK (E1, E2) and Turkey (E3, E4, E5, E6). All participants had at least eight years of experience in building energy efficiency and were familiar with EPG issues.

Participants were introduced to the ontology's research aim and definition during the interviews. The suggested classes and concepts of the ontology were presented in an Excel file. Participants were asked to indicate the additions, removals, potential contradictions, and suggestions for future development that they considered necessary. They also reviewed and provided feedback on relationships between classes. At the end of the interviews, experts evaluated the ontology's appropriateness, completeness, consistency, conciseness, and expandability using a 5-point Likert scale. Completeness ensures that the area of interest is suitably covered, while consistency checks for contradictions (Hlomani and Stacey, 2014). Conciseness examines redundant or irrelevant elements (Mishra and Jain, 2020), while expandability means adding new knowledge and definitions without modifying existing groups (Lovrenčić and Čubrilo, 2008).

Table 2.

Profile of the interviewees in the validation stage (Source: Authors own work)

Validation Stage	Expert no	Profession	Country	Experience (number of years)
2nd Stage	E1	Mechanical Engineer	UK	13
	E2			10
	E3		Turkey	23
	E4			33
	E5			35
	E6			35

In the third stage, during a 1.5-hour interview, a mechanical engineer from Turkey with 46 years of experience discussed the reasons for the gap and provided his feedback on the ontology. In this way, different data and information sources were used to evaluate and validate the ontology. This will be explained in detail in section 4.

3.2 Tool development stage

The ontology can be utilized by other researchers to develop tools tailored to specific needs. An illustrative example of such a tool is provided in the article. The tool was developed using Microsoft Excel Version 2406 (2024) and Microsoft Visual Basic for Applications (VBA), an internal programming language used across various Microsoft applications. VBA allows users to create forms with command buttons, option buttons, text boxes, scroll bars, and more, enabling data entry and automated task execution. Using the tool, project stakeholders can not only enter details related to their building stock, including geographical conditions, but also evaluate the magnitude of the risks, and store and share this information with other project stakeholders.

4. Research findings

This section presents the research findings from the ontology development stage, covering the conceptual model, taxonomy, developed ontology, and ontology evaluation. It also introduces the Excel-based tool created.

4.1 Conceptual model

In this study, semi-structured interviews were conducted with ten building experts to validate and/or revise the risks identified in the literature, explore the relationships between the risks, and develop a conceptual model. For example, additional risk factors and their relationships were observed using verbal data from one of the projects, an office building in Turkey, as stated below:

> “Due to flexible work arrangements during the pandemic, fewer occupants worked in offices. When the building was in use, lights were off, but the heating system was still operating. Occupants complained about room temperature, especially in rooms with high ceilings and cafeterias. That year, the weather was unusually severe. To address comfort issues, the heating system was turned on earlier, and occupants were allowed to adjust the room temperature by 2°C. An occupant survey can be conducted to better understand the comfort-related issues and reasons for the gap.”

This building's heating consumption exceeded design projections, while its electricity consumption was lower than anticipated. Unexpected events, such as extreme weather and the Covid-19 pandemic, caused problems or limitations concerning occupant behavior and activities, creating uncertainty in simulation assumptions. The expert suggested post-occupancy evaluations to manage these issues.

Based on a synthesis of literature review findings and interviews about building projects, a conceptual model comprising forty concepts and five classes was created, as shown in Figure 2. The model includes five groups: energy performance gap, design assumptions, problems/limitations, unexpected events and changes, and project management. The design assumption group includes the simulation assumptions made during the design phase, such as the thermal conductivity of materials and occupancy rates. Problems and limitations, including elements like design problems and budget limitations, arise during the different stages of a project’s life cycle, introducing weaknesses to the system. These aspects can cause unexpected events and changes (i.e., changes in project stakeholders), although these may also occur independently. Factors affecting the manageability of these groups are classified under project management, which contains elements like stakeholder experience, communication, and training. According to the model, factors in the first three categories can trigger changes in design assumptions, leading to an energy performance gap.

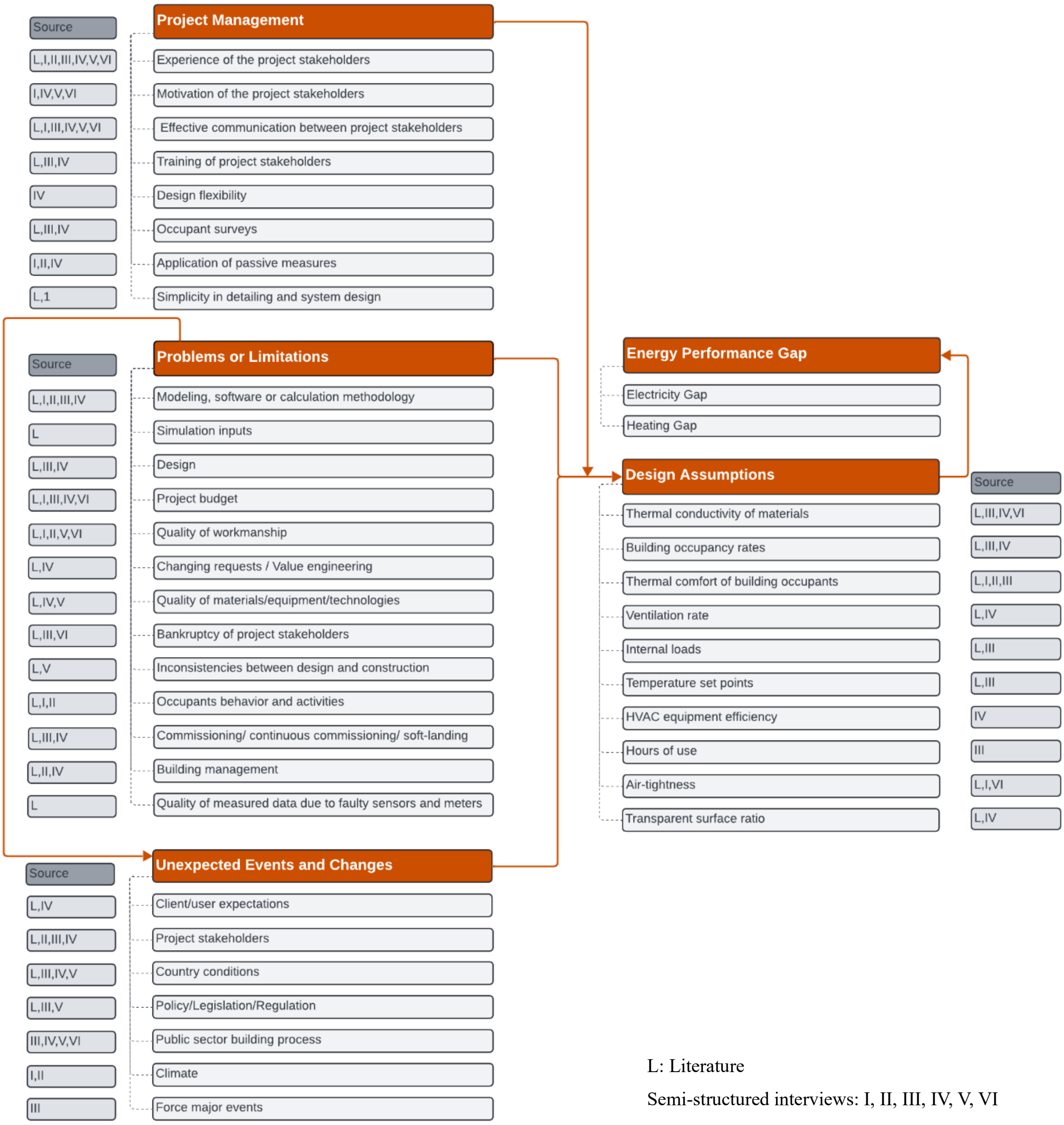


Figure 2. Conceptual model (Source: Authors own work)

4.2. Taxonomy development

A taxonomy organizes elements into a superclass-subclass hierarchy. This structure brings substantial order to the model's elements, categorizes them for human interpretation, and facilitates the reuse and integration of tasks (Fidan *et al.*, 2011). Figure 3 represents the taxonomy classes developed and their relationships in a Unified Modeling Language (UML) diagram. Each box represents a class and consists of three compartments in the UML diagram. The uppermost compartment contains the class name, while the middle one contains class attributes. For instance, the *Building* class has attributes such as building type, construction type, location, and project name. The relationship between the classes is shown using arrows or lines. A straight line indicates an association between classes. Association role labels (e.g., “has,” “results in,” “causes”) on the lines indicate the role of the classes. For example, the Building class “has” an energy performance gap. Unexpected Events and Changes “cause” Problems or Limitations, and vice versa. Multiplicities in UML diagrams indicate the number of instances associated with instances of another class. For instance, multiplicity (1…*) indicates that one or more Unexpected Events and Changes cause one or more Problems or Limitations. While a solid line with a filled arrowhead indicates a directed relationship, a solid line with an unfilled arrowhead shows inheritance between classes. For instance, the Risks class is the super-class of Project Management, Problems or Limitations, and Unexpected Events and Changes.

Figure 3. Data model for risk-energy performance gap ontology (Source: Authors own work)

4.3 The developed ontology

The energy performance gap-risk ontology was developed using Web Ontology Language (OWL) to represent concepts, properties, and relationships. OWL is a standard language for describing ontologies (Delgoshaei *et al.*, 2018). An OWL ontology includes individuals, properties, and classes. Individuals, or instances, represent objects within a specific domain. Classes encompass individuals, and properties are binary relations between individuals (Horridge and Brandt, 2011). OWL has three types of properties: object properties, data properties, and annotation properties. Object properties link individuals, data properties link an individual to an XML Schema Datatype value or an RDF literal, and annotation properties add more information to classes, individuals, and object/data properties (Horridge and Brandt, 2011).

The ontology consists of three main classes: Building, Energy Performance Gap, and Risks. The Risks class contains three subclasses: Project Management, Problems or Limitations, and Unexpected Events and Changes (see Appendix). The following sections explain the classes, properties, and individuals of the ontology.

4.3.1 Building class

The Building class collects general information about building projects to provide a clear understanding of the project's initial conditions. Concepts include Project Name, Building Type, Construction Type, Number of Floors, Heated Floor Area, Certification Status, and whether the building is New or Retrofitted. Object properties like "has," "has-Gap," and "has-Risk-Of" link elements such as Project Name and Problems or Limitations. Data properties, such as "has-Name" and "has-Number-Of-Floors," link objects to specific data types like strings or positive integers. Individuals in this class include residential and non-residential building types, contract types, and wind conditions.

4.3.2 Energy Performance Gap class

The Energy Performance Gap class includes concepts for different types of gaps, such as Carbon Emissions, Electricity, Natural Gas, and Water. These gaps are linked to various risk factors through object properties like "is-due-to" to define their relationships. Studies examine total electricity consumption (Shi *et al.*, 2019) and gas for domestic hot water, fan electricity, pump electricity, lighting electricity, and heating and cooling electricity as energy items in their analyses (Chang *et al.*, 2020).

4.3.3 Risks class

The Risks class comprises Problems or Limitations, Unexpected Events and Changes, and Project Management. Construction projects face numerous risks and uncertainties that can delay completion, result in exceeded budgets, and compromise safety, quality, and operational demands (Öztaş and Ökmen, 2005).

The Problems or Limitations subclass includes seventeen concepts (Figure 4). This category lists risk factors specific to individual project phases, such as design, construction, and operation, which can weaken the system and affect energy performance. For instance, poor workmanship during construction can impact the building’s energy performance during operation. Additionally, risks throughout the project life cycle are characterized by their magnitude, which can be very low, low, medium, high, or very high. The data property “hasMagnitude” links an individual to a string representing this value.

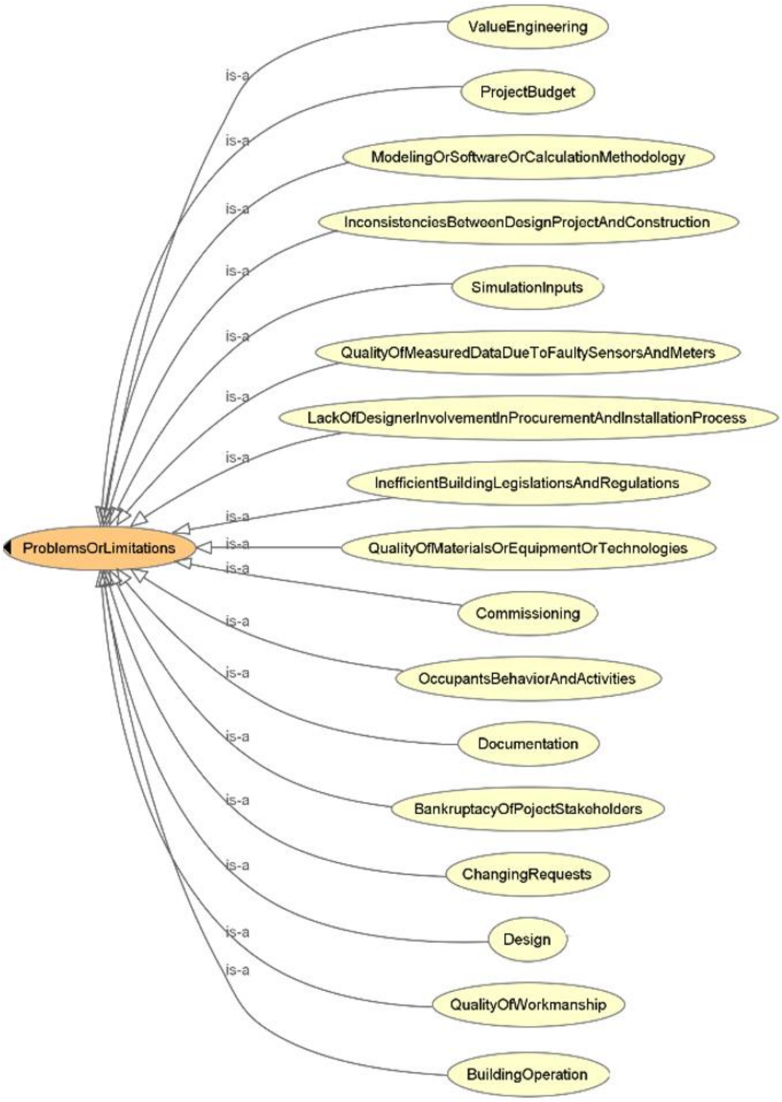


Figure 4. Problems or limitations OWLViz asserted class hierarchy

(Source: Authors own work)

Inaccurate assumptions about simulation inputs during the design phase are a primary cause of the energy performance gap. The Simulation Inputs concept is categorized as a risk under the Problems or Limitations class. Figure 5 lists the assumptions that can cause EPG.

Figure 5. Inaccurate design assumptions OWLViz asserted class hierarchy

(Source: Authors own work)

The Unexpected Events and Changes subclass contains seven concepts, while the Project Management subclass contains twelve. Figure 6 illustrates the asserted class hierarchy of the Unexpected Events and Changes. This subclass includes risks that cause deviations from the project's initial conditions due to sudden changes and events, such as a pandemic, regulatory changes, stakeholder changes, and unavailability of certified equipment. Concepts within this subclass include Country Conditions, Force Majeure Events, and Climate and Geography.

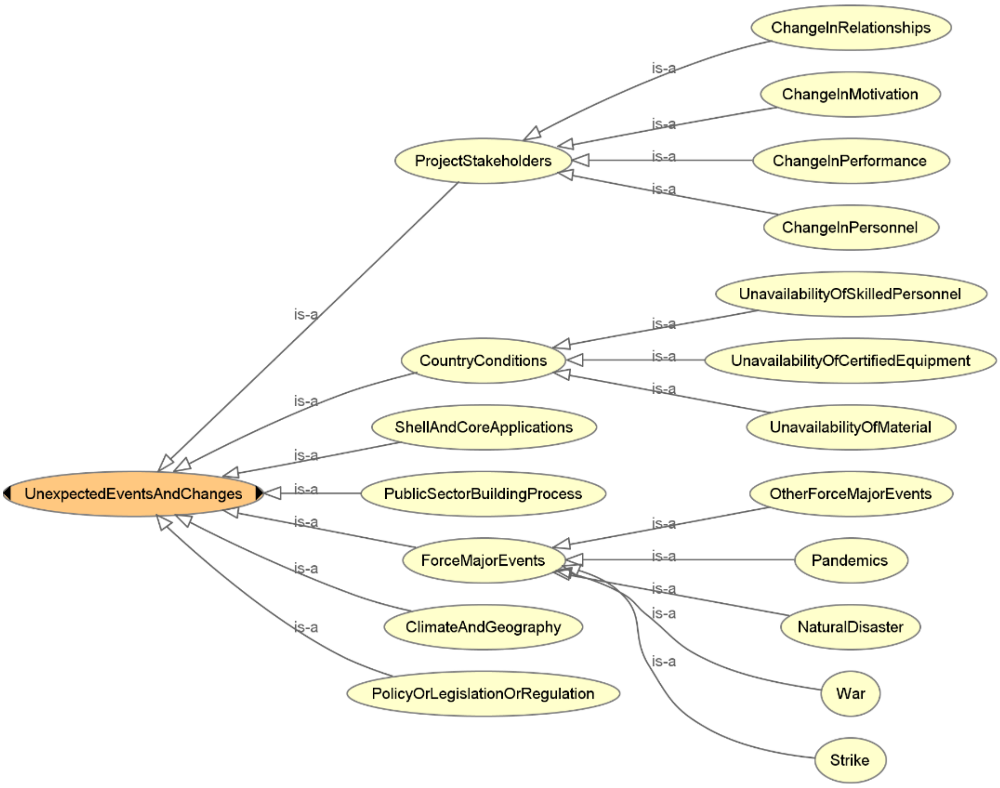


Figure 6. Unexpected events and changes OWLViz asserted class hierarchy (Source: Authors own work)

The Project Management subclass includes risks that influence resilience and affect the manageability of those risks causing the energy performance gap. For example, effective communication between project stakeholders ensures better information flow and collaboration to resolve issues across project phases. This subclass encompasses concepts such as the Experience of Project Stakeholders, Integrated Design, and Design Flexibility.

4.4 Ontology validation

This section presents the results of the evaluation process, which included a three-stage validation process.

In the first stage, an empirical article (Jain *et al.,* 2020) was reviewed to assess the ontology's completeness and expandability. The article included four case studies, and data was manually extracted to compare it with the suggested ontology. New concepts were added to the appropriate class if the article mentioned a gap-causing concept not included in the ontology. For example, Documentation and Poorly Specified Energy Targets were added to the Problems or Limitations class and the concept of Building Management was modified to Building Management and Maintenance.

In the second stage, interviews were conducted with six domain experts. This validation stage resulted in several additions, particularly to the Buildings, Problems or Limitations, and Project Management classes. For instance, Geographical Coordinates, Wind Conditions, and Energy and Exergy Analysis were suggested for the Building class. Mechanical System Design (including Errors in Mechanical Design Assumptions, Overdesign of Mechanical Systems, and Using Incorrect Weather Data) was also recommended for the Problems or Limitations subclass. Moreover, the “Design Assumptions” class, previously shown in the conceptual model (Figure 2), was redefined as an attribute of the “Problems or Limitations” subclass. The importance of concepts such as Integrated Design, Professional Liability Insurance, and Good Interpretation of Design was noted in Project Management.

Moreover, at the end of the interviews, six experts evaluated the ontology's appropriateness, completeness, consistency, conciseness, and expandability using a 5-point Likert scale. Small sample sizes are a common limitation in quantitative studies on risks in green building projects. However, this constraint is understandable given the relatively smaller number of green building practitioners compared to other sectors in the construction industry (Nguyen and Macchion, 2023).

Table 3 presents the participants’ responses using the mean, median, and interquartile ranges (IQR). Descriptive statistics were used by Lee *et al.* (2017) and Alberici *et al.* (2020) despite the sample sizes being small (six and twenty, respectively). Alberici et al. (2020) demonstrated that small sample sizes can be evaluated using the median and interquartile range (IQR). The median and the IQR are commonly used to assess the central tendency and dispersion of a dataset. They are more robust than the mean and standard deviation because they are less affected by outliers. Moreover, the IQR is particularly effective for analyzing skewed distributions (Frost, 2024).

Experts evaluated the ontology’s appropriateness, expandability, and consistency, giving it a median score of 4.00 and an interquartile range (IQR) of 0.00. An IQR of 0.00 means there is no variability among the middle half of the ratings. For completeness and conciseness, the ontology received a median score of 4.00 and an IQR of 1.00, indicating some variability among the middle half of the ratings.

Table 3.

Evaluation of the ontology based on appropriateness, completeness, consistency, conciseness, and expandability (Source: Authors own work)

No.	Questions	P1	P2	P3	P4	P5	P6	Mean	Median	IQR
1	How appropriate do you think the proposed ontology is to identify the risks that cause EPG in buildings?	4	4	4	4	4	3	3.83	4.00	0.00
2	Please evaluate the completeness of the proposed ontology.	4	3	4	4	4	3	3.66	4.00	1.00
3	Please evaluate the consistency of the proposed ontology.	4	4	5	4	4	3	4.00	4.00	0.00
4	Please evaluate the conciseness of the proposed ontology.	4	3	5	4	4	3	3.83	4.00	1.00
5	Please evaluate the expandability of the proposed ontology.	2	4	4	4	4	5	3.83	4.00	0.00

*Answers to each question are given using a 5-point Likert scale.

In the third stage, a mechanical engineer provided insights into the performance gap in buildings. The interview highlighted several critical factors: Involvement of experienced stakeholders, significance of mechanical system design, designer involvement during usage, quality of commissioning, and regular equipment maintenance. This validation stage confirmed that the ontology effectively captured these factors, therefore, no modifications were necessary. Table 4 details the concepts added, the modifications to concept names, and their classification into appropriate classes or subclasses during the validation stages.

Table 4.

Updates to the ontology following the validation stage (Source: Authors own work)

Stage	Type of change	Concept	New Concept Name	Sub-class	Classes					
					C1	C2	C3	C4	C5	C6
I	New additions	Documentation				√				
		Thermal Bridges		Inaccurate Design Assumptions						√
		Water Usage		Inaccurate Design Assumptions						√
		Poorly Specified Energy Targets		Building Design		√				
	Modification of the name	Building Management	Building Management and Maintenance			√				
II	New additions	Certified or not			√					
		Cooled Space Area			√					
		Daily Temperature Difference			√					
		Energy or Exergy Analysis			√					
		Geographical Coordinates			√					
		Heated or Cooled or Both			√					
		Number of Floors			√					
		Occupancy Ratio			√					
		Wind Condition			√					
		Year of Retrofitting			√					
		Carbon Emissions Gap							√	
		Water Gap							√	
		Hot Water Gap							√	
		Inaccurate Determination of Measurement Points		Commissioning		√				
		Incorrect Automation Algorithm		Commissioning		√				
		Building Design		Design		√				
		Mechanical System Design		Design		√				
		Errors in Mechanical Design Assumptions		Mechanical System Design		√				
		Overdesign of Mechanical Systems		Mechanical System Design		√				
		Using Incorrect Weather Data		Mechanical System Design		√				
		Lack of Designer Involvement in Procurement and Installation				√				
		Building Orientation		Simulation Inputs						
		Building Zoning		Simulation Inputs						
		Heat Losses		Simulation Inputs						
		Thermal Transmittance (Floors, Roof, and Walls)		Simulation Inputs						
		Water Usage (Cold and Hot Water)		Simulation Inputs						
		Weather Bin Data		Simulation Inputs						
		Shell and Core Applications					√			
		Integrated Design						√		
		Professional Liability Insurance						√		
		Project Commissioning						√		
		Balancing		Project Commissioning				√		
		Consideration of Occupancy Rate Afterwards		Project Commissioning				√		
		Good Interpretation of Design		Project Commissioning				√		
		Recommissioning When Necessary		Project Commissioning				√		
		Retro-commissioning		Project Commissioning				√		
		Building Maintenance		Building Operation		√				
	Modification of the name	Heating Gap	Natural Gas Gap						√	
		Building Management and Maintenance	Building Operation							
		Climate	Climate and Geography				√			
		Change in Design Assumptions	Inaccurate Design Assumptions	Simulation Inputs						√
		Changing Requests and Value Engineering	Changing Requests			√				
		Changing Requests and Value Engineering	Value Engineering			√				
III		No Changes								

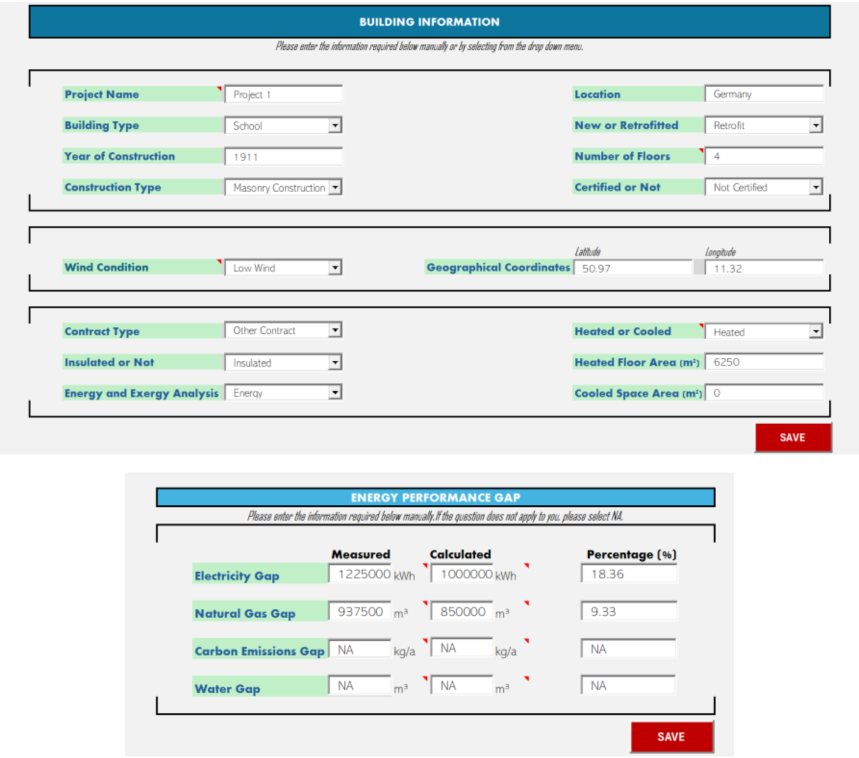
C1: Building, C2: Problems or Limitations, C3: Unexpected Events and Changes, C4: Project Management, C5: Energy Performance Gap, C6: Change in Design Assumptions

4.5 EPG-RISK tool

An EPG-RISK identification tool based on Microsoft Visual Basic for Applications in Excel and Macro was created using the ontology developed to demonstrate its use in practice. The tool comprises seven Excel worksheets.

The first worksheet, ABOUT, provides users with information about the tool. The following five worksheets consider the classes and sub-classes of the ontology.

The second worksheet, BUILDING INFORMATION, collects general data about the project. Users enter energy performance gap information in the third worksheet. Data is entered manually or by selecting from the dropdown menu, as demonstrated in Figure 7.



BUILDING INFORMATION

Please enter the information required below manually or by selecting from the drop down menu.

Project Name	Project 1	Location	Germany
Building Type	School	New or Retrofitted	Retrofit
Year of Construction	1911	Number of Floors	4
Construction Type	Masonry Construction	Certified or Not	Not Certified
Wind Condition	Low Wind	Geographical Coordinates	Latitude 50.97 Longitude 11.32
Contract Type	Other Contract	Heated or Cooled	Heated
Insulated or Not	Insulated	Heated Floor Area (m²)	6250
Energy and Exergy Analysis	Energy	Cooled Space Area (m²)	0

ENERGY PERFORMANCE GAP

Please enter the information required below manually.If the question does not apply to you, please select NA.

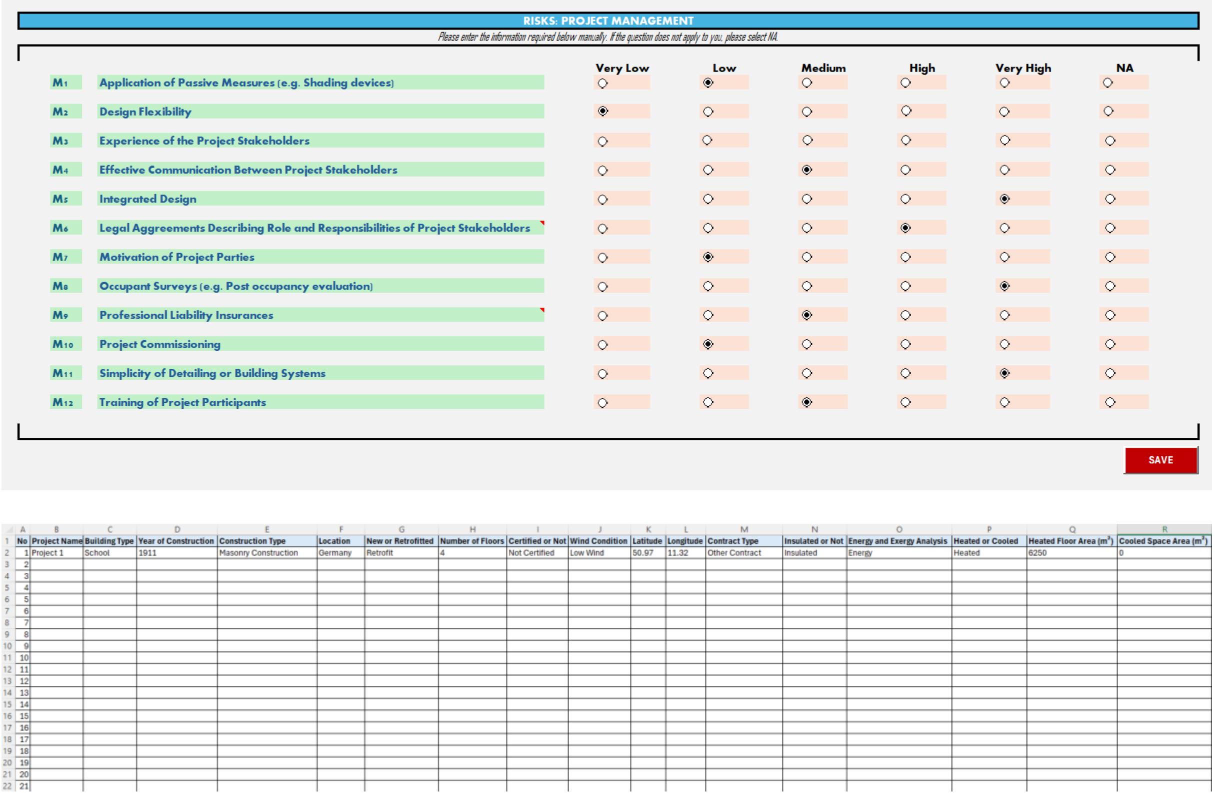
	Measured	Calculated	Percentage (%)
Electricity Gap	1225000 kWh	1000000 kWh	18.36
Natural Gas Gap	937500 m³	850000 m³	9.33
Carbon Emissions Gap	NA kg/a	NA kg/a	NA
Water Gap	NA m³	NA m³	NA

Figure 7. Building information & energy performance gap worksheet (Source: Authors own work)

The fourth worksheet, PROBLEMS OR LIMITATIONS, allows users to evaluate their project based on seventeen criteria, ranging from very low to very high, with an option for "not applicable" (NA) responses using option boxes. This rating system allows users to compare knowledge from various projects and pinpoint the most problematic criteria. Users can conduct a more detailed evaluation by considering sub-criteria, such as identifying which design assumptions (e.g., hours of use, airtightness, building orientation) posed more problems during building energy performance calculations.

The fifth worksheet, UNEXPECTED EVENTS AND CHANGES, allows users to evaluate their project based on seven criteria using option buttons. This section addresses various unexpected conditions, such as force-majeure events like a pandemic.

The sixth worksheet, PROJECT MANAGEMENT, lists twelve criteria that might help to control the magnitude of the gap in the project (Figure 8). Entering data for multiple projects allows users to see project conditions in which a lower or higher EPG was observed. Furthermore, users leverage the tool to inform their project development decisions.



RISKS: PROJECT MANAGEMENT

Please enter the information required below manually. If the question does not apply to you, please select NA.

		Very Low	Low	Medium	High	Very High	NA
M_1	Application of Passive Measures (e.g. Shading devices)	○	●	○	○	○	○
M_2	Design Flexibility	●	○	○	○	○	○
M_3	Experience of the Project Stakeholders	○	○	○	○	○	○
M_4	Effective Communication Between Project Stakeholders	○	○	●	○	○	○
M_5	Integrated Design	○	○	○	○	●	○
M_6	Legal Aggreements Describing Role and Responsibilities of Project Stakeholders	○	○	○	●	○	○
M_7	Motivation of Project Parties	○	●	○	○	○	○
M_8	Occupant Surveys (e.g. Post occupancy evaluation)	○	○	○	○	●	○
M_9	Professional Liability Insurances	○	○	●	○	○	○
M_{10}	Project Commissioning	○	●	○	○	○	○
M_{11}	Simplicity of Detailing or Building Systems	○	○	○	○	●	○
M_{12}	Training of Project Participants	○	○	●	○	○	○

No	Project Name	Building Type	Year of Construction	Construction Type	Location	New or Retrofitted	Number of Floors	Certified or Not	Wind Condition	Latitude	Longitude	Contract Type	Insulated or Not	Energy and Exergy Analysis	Heated or Cooled	Heated Floor Area (m^2)	Cooled Space Area (m^2)
1	Project 1	School	1911	Masonry Construction	Germany	Retrofit	4	Not Certified	Low Wind	50.97	11.32	Other Contract	Insulated	Energy	Heated	6250	0
2																	
3																	
4																	
5																	
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Figure 8. Energy performance gap risk identification tool (Source: Authors own work)

Analyzing the dataset collected in the seventh worksheet (DATA) can identify where the majority of projects face issues. This analysis can provide new directions for both project stakeholders and policymakers to address EPG challenges in both existing and new buildings.

5. Discussion

5.1 Energy performance gap-risk ontology

This research standardizes experience-based and scientific knowledge on EPG in buildings by developing an ontology linking risks with the energy performance gap. The ontology is crucial for (1) providing linguistic unity across scientific literature and industrial practice, (2) facilitating knowledge sharing among project stakeholders, and (3) enabling computer readability and automatic processing in various applications. The ontology can improve industry practices by facilitating risk identification, mitigation, and management.

The ontology developed comprises three main classes: Building, Energy Performance Gap, and Risks. The Risks class is divided into three subclasses: Problems or Limitations, Project Management, and Unexpected Events and Changes. Previous research on risks impeding building energy performance has been limited by reliance on single case studies (Doylend, 2015) or literature reviews (Alam *et al*., 2017), restricting the scope to specific renovation approaches (Topouzi *et al*., 2019) and the UK construction industry (Thompson *et al*., 2022). Since risks vary between buildings (De Wilde, 2024), stakeholders, and countries (Yang *et al*., 2016), it is essential to consider different building types, country conditions, and stakeholders during risk identification. Our study addresses this gap by combining a comprehensive literature review with semi-structured interviews from building projects representing various building types and country-specific conditions (Turkey and Germany). Additionally, interviews with architects, mechanical and civil engineers, a materials manufacturer, and an electrical technician provided a multidisciplinary perspective on the ontology development. The ontology identified 36 main risk factors, and 95 in total, when considering additional risks associated with certain factors.

5.2 Risks influencing the energy performance gap

Despite using different terminologies, the literature on risk management and energy performance gaps in buildings revealed many similarities with the risks identified in the current ontology. Human elements, such as stakeholder communication, experience, motivation, stakeholder responsibilities, occupant behavior, poor workmanship, design changes, and modeling errors are prevalent in EPG. Risks also stem from poor quality materials and technologies, design complexity, regulatory issues, and building maintenance. These findings align with earlier research by Mahdavi & Berger (2024), Godefroy (2022), Thompson *et al*. (2022), Topouzi *et al*. (2019), Gram-Hanssen and Georg (2018), Alam *et al*. (2017), Kampelis *et al*. (2017), and Doylend (2015), due to the common methods used in the research.

The ontology development process identified new risk factors contributing to the energy performance gap. For example, interviewees from two projects in Turkey, a developing country, highlighted construction companies going bankrupt, which harmed construction quality. Additionally, interviewees from four projects noted that the public sector building process posed risks, including difficulties in selecting contractors and challenges associated with using products that enhance energy performance. The lack of local, high-quality mechanical equipment was also a country-specific risk in three out of four buildings in Turkey. These risks affected building energy performance, construction costs, and schedule. Interviewees from both Turkey and Germany expressed concerns about poor workmanship, and modeling, software, and calculation methodologies. The importance of effective communication and stakeholder experience was emphasized in both countries. These results agree with Yang *et al*. (2016), indicating that different stakeholders and countries encounter distinct risks. Consequently, it is crucial to customize risk management strategies that address the specific needs and contexts.

The ontology helps illustrate how different factors interact to contribute to EPG. For instance, project management aspects (e.g., the experience of project stakeholders) can influence problems or limitations (e.g., design issues) and unexpected events and changes (e.g., those related to project stakeholders) during the building life cycle. Unexpected events (e.g., a pandemic) can cause problems or limitations (e.g., simulation inputs). The ontology suggests that factors such as professional liability insurance, stakeholder motivation, effective communication, experience, training, integrated design, simplicity of detailing, building systems or design, and project commissioning can help manage EPG in buildings.

5.3. Excel-based tool for energy performance gap risk identification

Building on the established ontology, a tool was developed in Excel using VBA and Macros to systematically collect, store, and share the risk information relating to building projects. This tool may help stakeholders, such as energy service companies, project managers, energy consultants, and engineers, when addressing EPG. Users can input details related to building stock and geographical factors, such as construction type, number of floors, wind conditions, and EPG of their projects.

Comprehensive project data enables researchers to uncover new insights through various statistical methods. For example, Firth *et al*. (2024) identified correlations between the gap and variables such as property type, floor area, year of construction, latitude, and mean gas consumption. The tool also allows inputs for carbon emissions and water usage gaps, broadening the scope of EPG studies beyond traditional energy performance metrics. Janser *et al*. (2020) criticize the typical definition of EPG for often overlooking several critical aspects of energy performance: greenhouse gas emissions linked to energy demand, embodied energy, and the discrepancy between the optimal and planned energy performance.

Users can assess the magnitude of risks, which are categorized in different sheets, to help prioritize certain risks and take actions to reduce the gap. Listing risks in a structured format enables stakeholders to spot weak points quickly. Project teams can save information for multiple projects, share it with team members, and use it as a reference for future risk management. The tool essentially serves as a project risk checklist, facilitating risk identification and decision support to mitigate EPG. Analyzing the collected data can pinpoint common issues from different projects, offering new directions for stakeholders and policymakers to tackle EPG challenges. Additionally, the collected data can be used in AI and machine-learning models to develop predictive models.

Ultimately, the tool supports multiple stakeholders, such as industry practitioners, policymakers, homeowners, and tenants in reducing the financial burden of the EPG and enhancing stakeholder credibility. Moreover, by supporting more transparent and effective risk management, the tool contributes to the sustainable development goals (SDG). Specifically, it aligns with SDGs 11 (sustainable cities and communities), 12 (responsible consumption and production), 13 (climate action), and 17 (partnerships for the goals).

6. Conclusions

The building life cycle involves numerous risks that complicate accurate performance predictions, making effective risk identification crucial for studying EPG in buildings. Previous studies have examined many factors contributing to EPG, but the disorganized handling of these factors hinders efficient knowledge sharing and comparison.

To address these challenges, this study developed an ontology based on a literature review and semi-structured interviews with industry professionals regarding six buildings in order to structure concepts and factors to interrelate energy performance gap and risk in buildings. The interviews helped identify new risk factors, such as stakeholder bankruptcy, public sector building processes, and a lack of high-quality mechanical equipment, which are particularly relevant to developing countries. Interviewees also highlighted risks related to poor workmanship, modeling, software, and calculation methodologies, and emphasized the importance of effective communication and stakeholder experience.

An Excel-based tool was created using the ontology to collect, store, and share risk data from projects. This tool supports stakeholders by facilitating risk management throughout the project life cycle. The tool can help reduce EPG and its financial burden on different stakeholders, enhance the credibility of designers, engineers, and policymakers, and contribute to the sustainable development goals through effective risk analysis. Analyzing data from multiple projects can identify common issues, providing new directions for policymakers. The tool can also be combined with machine learning to develop prediction models and strategies to minimize EPG.

Although the proposed ontology was validated for its appropriateness, completeness, consistency, conciseness, and expandability, the study has some limitations. These include the limited number of building projects and countries involved in the ontology's development, as well as the small number of experts in the validation phases. Consequently, the ontology and the associated tool are mainly suitable for similar contexts, such as emerging markets in green buildings, and countries with well-developed passive house construction. However, to enhance generalizability, an extensive literature review has been carried out and a mixed-method validation process was followed to capture the global experiences within this domain. Therefore, adjustments may be necessary when using the ontology and the tool in different country and sustainable building contexts. Future research using different building projects and knowledge from different parts of the world may be carried out to test and improve the ontology, if needed. Additionally, future research can leverage the ontology to develop new tools, for example, for quantitative risk analysis, to enhance risk-based decision-making and help establish more realistic energy performance targets.

Declaration of competing interest

The authors declare no conflict of interest.

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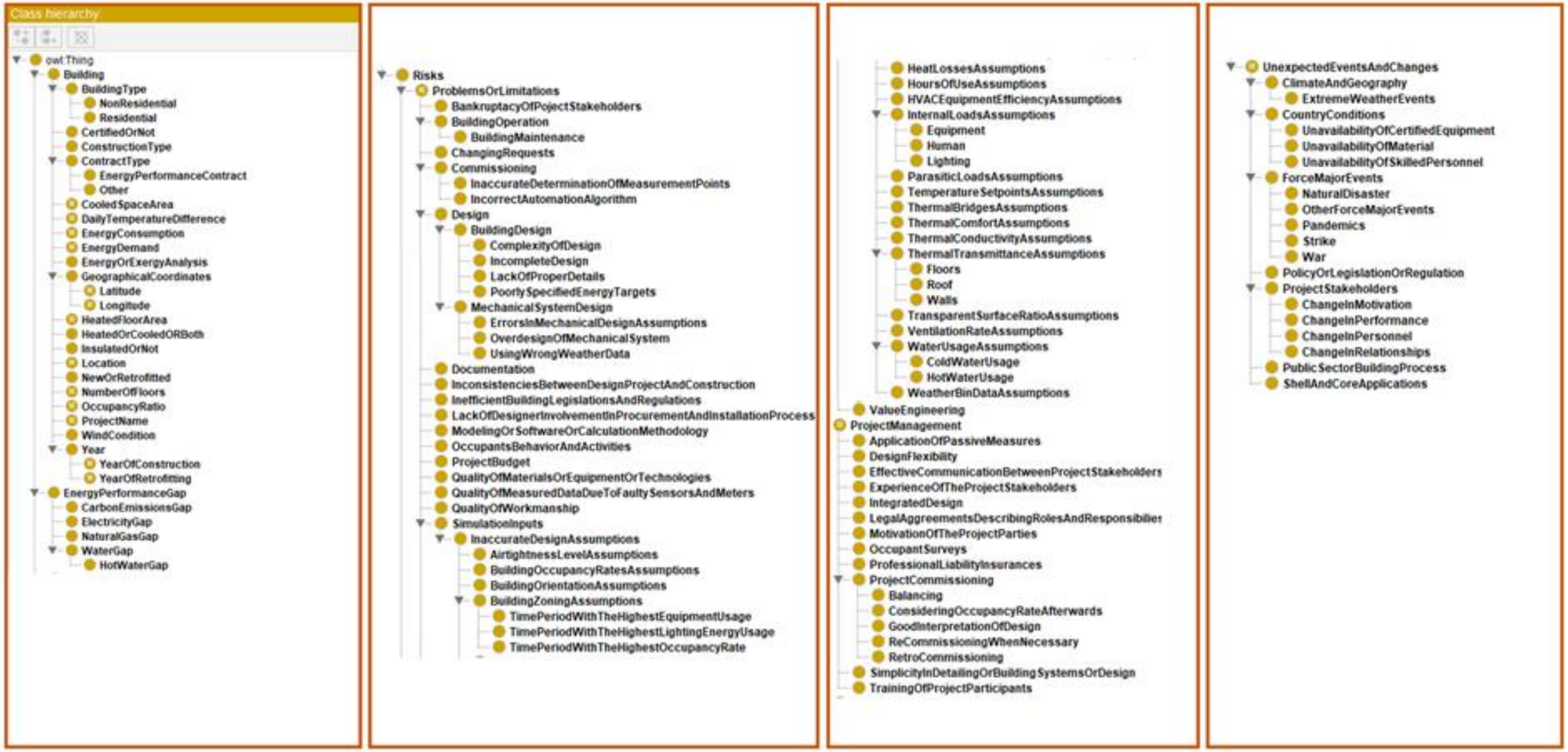
Appendix



Class hierarchy

- owl:Thing
  - Building
    - BuildingType
      - NonResidential
      - Residential
    - CertifiedOrNot
    - ConstructionType
    - ContractType
      - EnergyPerformanceContract
      - Other
    - CooledSpaceArea
    - DailyTemperatureDifference
    - EnergyConsumption
    - EnergyDemand
    - EnergyOrExergyAnalysis
    - GeographicalCoordinates
      - Latitude
      - Longitude
    - HeatedFloorArea
    - HeatedOrCooledORBoth
    - InsulatedOrNot
    - Location
    - NewOrRetrofitted
    - NumberOfFloors
    - OccupancyRatio
    - ProjectName
    - WindCondition
    - Year
      - YearOfConstruction
      - YearOfRetrofitting
  - EnergyPerformanceGap
    - CarbonEmissionsGap
    - ElectricityGap
    - NaturalGasGap
    - WaterGap
      - HotWaterGap

- Risks
  - ProblemsOrLimitations
    - BankruptacyOfPojectStakeholders
    - BuildingOperation
      - BuildingMaintenance
    - ChangingRequests
    - Commissioning
      - InaccurateDeterminationOfMeasurementPoints
      - IncorrectAutomationAlgorithm
    - Design
      - BuildingDesign
        - ComplexityOfDesign
        - IncompleteDesign
        - LackOfProperDetails
        - PoorlySpecifiedEnergyTargets
      - MechanicalSystemDesign
        - ErrorsInMechanicalDesignAssumptions
        - OverdesignOfMechanicalSystem
        - UsingWrongWeatherData
    - Documentation
    - InconsistenciesBetweenDesignProjectAndConstruction
    - InefficientBuildingLegislationsAndRegulations
    - LackOfDesignerInvolvementInProcurementAndInstallationProcess
    - ModelingOrSoftwareOrCalculationMethodology
    - OccupantsBehaviorAndActivities
    - ProjectBudget
    - QualityOfMaterialsOrEquipmentOrTechnologies
    - QualityOfMeasuredDataDueToFaultySensorsAndMeters
    - QualityOfWorkmanship
    - SimulationInputs
      - InaccurateDesignAssumptions
        - AirtightnessLevelAssumptions
        - BuildingOccupancyRatesAssumptions
        - BuildingOrientationAssumptions
        - BuildingZoningAssumptions
          - TimePeriodWithTheHighestEquipmentUsage
          - TimePeriodWithTheHighestLightingEnergyUsage
          - TimePeriodWithTheHighestOccupancyRate
        - HeatLossesAssumptions
        - HoursOfUseAssumptions
        - HVACEquipmentEfficiencyAssumptions
        - InternalLoadsAssumptions
          - Equipment
          - Human
          - Lighting
        - ParasiticLoadsAssumptions
        - TemperatureSetpointsAssumptions
        - ThermalBridgesAssumptions
        - ThermalComfortAssumptions
        - ThermalConductivityAssumptions
        - ThermalTransmittanceAssumptions
          - Floors
          - Roof
          - Walls
        - TransparentSurfaceRatioAssumptions
        - VentilationRateAssumptions
        - WaterUsageAssumptions
          - ColdWaterUsage
          - HotWaterUsage
        - WeatherBinDataAssumptions
    - ValueEngineering
  - ProjectManagement
    - ApplicationOfPassiveMeasures
    - DesignFlexibility
    - EffectiveCommunicationBetweenProjectStakeholders
    - ExperienceOfTheProjectStakeholders
    - IntegratedDesign
    - LegalAggreementsDescribingRolesAndResponsibilies
    - MotivationOfTheProjectParties
    - OccupantSurveys
    - ProfessionalLiabilityInsurances
    - ProjectCommissioning
      - Balancing
      - ConsideringOccupancyRateAfterwards
      - GoodInterpretationOfDesign
      - ReCommissioningWhenNecessary
      - RetroCommissioning
    - SimplicityInDetailingOrBuildingSystemsOrDesign
    - TrainingOfProjectParticipants

- UnexpectedEventsAndChanges
  - ClimateAndGeography
    - ExtremeWeatherEvents
  - CountryConditions
    - UnavailabilityOfCertifiedEquipment
    - UnavailabilityOfMaterial
    - UnavailabilityOfSkilledPersonnel
  - ForceMajorEvents
    - NaturalDisaster
    - OtherForceMajorEvents
    - Pandemics
    - Strike
    - War
  - PolicyOrLegislationOrRegulation
  - ProjectStakeholders
    - ChangeInMotivation
    - ChangeInPerformance
    - ChangeInPersonnel
    - ChangeInRelationships
  - PublicSectorBuildingProcess
  - ShellAndCoreApplications

Figure A1. Classes of the energy performance gap-risk ontology (Source: Authors own work)