Developing a Facility Management Domain Ontology for Storing Facility Management Knowledge in the Field of Buildings' Energy Performance

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Abstract

The implementation of Facility Management (FM) best practice guidelines is crucial in minimizing the energy performance gap in buildings. However, many newly built and renovated facilities continue to consume more energy than initially calculated. To address this complex issue, the present research aims to develop a digital FM domain ontology in a computable form to support the codification and storage of FM knowledge. The research methodology used in this study follows the "Ontology Development 101" strategy, starting with a lightweight form and subsequently modeling it into a heavyweight form using the Protégé ontology editor. The resulting FM domain ontology serves as a classification system to systematically organize and store existing FM best practice guidelines related to buildings' energy performance. Therefore, the ontology provides a semi-legal and computable knowledge base, where FM guidelines are systematically categorized based on different FM-related aspects. The paper concludes by discussing the potential of the proposed FM domain ontology to support design experts and FM practitioners in implementing FM best practices, thus contributing to the reduction of the buildings' energy performance gap.

Keywords:

Buildings' Energy Performance, Knowledge Management, Domain Ontology, Building Design Decision

1. Introduction

The global building sector accounts for over 40% of total final energy consumption and contributes to 36% of greenhouse gas emissions (IEA 2019). However, approximately 70% of the existing buildings still operate with energy inefficiencies (Min et al. 2016). This issue intensifies the urgency to combat climate change, compelling policymakers to address the energy shortage, resulting in the current substantial increase in energy prices.

To address these challenges, policymakers and regulators have been progressively tightening building energy codes, aiming to optimize energy consumption in newly constructed and renovated facilities (Cox 2016). However, current building energy-related standards primarily focus on examining the physical characteristics of buildings, often overlooking their actual usage and operation (Gram-Hanssen 2017). Consequently, newly built, and renovated structures frequently fail to meet initial energy efficiency expectations, resulting in much higher energy consumption during operational stages compared to the original estimations made during the design phase (Cozzi et al. 2020; Hamburg 2019; Min et al. 2016). As highlighted by previous studies, like Zou et al. (2018), closing the gap between the calculated and actual energy consumption of buildings is today a highly investigated research field. Despite existing efforts, only a few studies have investigated the extent to which the domain of Facility Management (FM) can contribute to mitigating the observed energy performance gap in buildings.

Studies by Liang et al (2019) and Min (2016) emphasize the significant role of Facility Managers in setting up long-term energy management strategies for existing buildings. These strategies aim to significantly reduce operational energy consumption and, consequently, achieve the postliminary closure of the buildings' energy performance gap later in operations. A crucial element of these energy management strategies is the post-occupancy evaluation of existing buildings, which allows fine-tuning and optimization of building use-related energy consumption based on data obtained from long-standing energy monitoring (Liang et al. 2019; Frank 2015). As highlight by Frank (2015), Adewunmi (2019) and Adewunmi (2012), this subsequent energy calibration requires the implementation of best practice policies and energy efficiency-related FM guidelines. These documents, while often non-legally binding, describe various technical and operational measures aimed at decreasing, maintaining, or optimizing the operational energy consumption of facilities.

However, Min (2016) argues that to achieve optimal energy performance in buildings, the establishment of FM-related energy management strategies and the implementation of FM best practice policies and guidelines should begin no later than the early design stage. This proactive approach ensures that energy efficiency is integrated into the building's design, ultimately minimizing the energy performance gap in buildings.

To effectively address the energy performance gap in buildings, the central role of FM best practice policies and energy-efficiency-related FM guidelines must extend not only to early building design decisions but also to FM executions, whether in a proactive or postliminary manner. However, it is crucial to acknowledge that an effective protocol procedure has not yet been developed to adequately support design experts or FM practitioners in their daily work regarding the implementation of these written documents.

2. Literature Review

2.1. Main Barriers of Practically Implementing FM Best Practice Guidelines

The practical implementation of written energy-efficient FM best practice guidelines, which are often non-legally binding, can pose significant challenges during both early building design and FM executions.

First, the documentation of FM best practice guidelines is scattered across multiple sources and lack consolidation. This makes locating them challenging during design decisions involving various experts or FM executions by practitioners. Additionally, the continuous updates of these guidelines make accessing the latest versions difficult in practical situations, hindering their dependable identification and re-utilization.

Second, during the initial stages of design decisions, diverse design disciplines often consider multiple FM guidelines with varying degrees of legality. The concurrent adoption of building energy codes and FM best practice guidelines by architects, mechanical engineers, energy consultants, and FM practitioners creates a highly intricate and tumultuous working environment.

Third, sustainable FM standards and policies frequently exhibit a notable degree of ambiguity, making them challenging to directly translate into specific building solutions in day-to-day work (Frank 2015; Støre-Valen and Buser 2019). Design experts and FM practitioners often struggle to accurately interpret the intended meaning of FM guidelines and efficiently incorporate them within the demanding context of design decisions or FM executions.

Last, even when energy-efficiency-related FM guidelines are integrated into design decisions or FM operations, the process of compliance checking remains predominantly manual. This leads to time-consuming and error-prone procedures. While some research initiatives and public projects address compliance checking of building energy codes, there is a notable gap in expediting the code-compliance verification process, especially concerning FM best practice guidelines in the context of building energy performance (Eid and GamaleEddin 2019; Jiang et al. 2018). To the authors' current knowledge, no research initiatives or public projects have specifically addressed this aspect to date.

2.2. Knowledge Management in Facility Management

Numerous initiatives have been undertaken to explore the integration of FM in early building design decisions and the practical implementation of FM guidelines within FM operations. Addressing these challenges requires an interdisciplinary approach that combines theories of communication and organization to effectively manage knowledge, as reported by Rasmussen et al. (2017). Consequently, implementing FM best practice guidelines, whether in early design decisions or FM operations, should be recognized as a comprehensive Knowledge Management endeavor.

Knowledge Management, a relatively new management field (Jensen et al. 2019), has been defined as a deliberate strategy aimed at disseminating the appropriate knowledge to enhance organizational performance at the right moment (O'Dell et al. 1998). Within the domain of Knowledge Management, a paramount objective lies in systematically codifying, organizing, and storing knowledge to achieve the original goals of the knowledge management initiatives, as stated by Maier (2007). These three processes are the codification and storage of FM knowledge, empowering FM practitioners to integrate their requirements during early design decisions and FM operations, as described by Jensen (2008).

The process of knowledge codification and storage, as articulated by Jensen and Chatzilazarou (2017), is an integral part of the refinement process, involving techniques to extract, cleanse, and restructure new knowledge for inclusion in knowledge repositories. The so codified knowledge can then be stored either in digital form, such as knowledge bases, or in document form within these repositories.

2.3. State-of-the-Art FM Knowledge Repositories

The FM industry has a tradition of utilizing Information and Communication-based systems and tools to facilitate the codification, organization, and storage of building-related information and FM knowledge. Jensen et al. (2019) represent a matured research effort in this field, using diverse digital FM knowledge repositories, including intranet solutions and project management tools. However, these repositories are limited to specific buildings and projects and are not designed to accommodate general FM domain knowledge, hindering for flexible adaptation and re-utilization in other building projects.

As a potential generic remedy to address these challenges, researchers, including Jensen et al (2019), have introduced the concept of Building Information Modeling (BIM) as possible FM knowledge repositories. The concept of BIM has indeed transformed the building industry by enabling an integrated, model-based design process, particularly concerning buildings' energy performance. Nonetheless, it's essential to recognize that BIM, as outlined by Ding et al. (2016), primarily encompasses building-specific knowledge and lacks inclusion of general, construction-unspecific knowledge, such as operational processes of buildings.

In conclusion, future digital FM knowledge repositories need to systematically store codified FM domain knowledge, with particular attention to buildings' energy performance contexts. Additionally, these FM knowledge repositories should be seamlessly integrated with BIM Models, offering both building-unspecific and building-specific knowledge independently. Based on this integration, a comprehensive and cohesive knowledge base can be created to address the diverse needs of FM practitioners and design experts alike.

3. Domain Ontologies for Creating Knowledge Repositories

Over the past two decades, the research focus on creating ontologies as a widely accepted research method has gained widespread prominence in the field of computer science, particularly in the context of integrating heterogeneous information sources using the Linked Data approach.

Ontologies are explicit, formal specifications of shared conceptualizations (Gruber 1993) and recent research has led to the development of domain ontologies, specifically tailored to represent knowledge within a particular domain in a formal and logical manner. These domain ontologies furnish vocabularies, establishing relationships among them through fundamental principles, with the primary objective of systematically structuring specific domain knowledge (Gomez-Peres et.al 2004). As posited by Matkar and Parab (2010), the domain ontology created in this manner serves as the core of a knowledge base (i.e. digital knowledge repository), wherein real-world objects, such as written FM best practice guidelines, are categorized under various classes for organization and systematic representation.

Regarding the practical development and utilization of ontologies, two distinct categories can be identified: lightweight and heavyweight ontologies. Lightweight ontologies possess informal characteristics and do not impose formal constraints on their anticipated value (Corcho 2006). Conversely, heavyweight ontologies represent rigorously formal and logically developed ontologies, often constructed using an ontology language in a computable form, such as Web Ontology Language (OWL) offered by the Semantic Web Technology stack. Protégé, an open-source ontology editor (Stanford University 2022), is frequently employed to create and edit domain ontologies using OWL and store them in a standardized format, such as Resource Description Framework.

Over the past decade, substantial research in the building industry has been dedicated to the design of domain ontologies, aimed at codifying, organizing, and store building and building industry-related knowledge (Ding et al. 2016; Liu et al. 2016; El Asri et al. 2021). Concurrently, several scientific research endeavors, exemplified by Ontology Engineering Group (2015a) and (2015b), have specifically undertaken the design of FM domain ontologies. However, these research efforts concentrated on representing knowledge pertinent to the application of smart home systems.

4. Research Methodology

Various scientific methods are currently available for constructing domain ontologies. A comprehensive survey and assessment of existing methods for developing domain ontologies can be found in Sattar (2020). According to this study, the 'Ontology Development 101' strategy, introduced by Noy and McGuinness (2001), stands out as the most widely utilized and cited methodology for designing domain ontologies, by defining seven major development steps: (1) Scope Determination, (2) Consider Reuse, (3) Enumerate Terms, (4) Define Classes, (5) Define Properties, (6) Define Constrains, (7) Create Instances.

Accordingly, the FM domain ontology in question is conceptually designed till the fourth step, firstly modeled in a lightweight format, and subsequently modeled in a heavyweight form using the Protégé tool. This adaptation is essential, as supported by the findings of Chungoora et al. (2010), which established that lightweight ontologies are typically employed for theoretical development. Consequently, the lightweight FM ontology, while highly advantageous as a foundation for creating the heavyweight form of the FM domain ontology, cannot be directly utilized as a digital FM knowledge repository. However, the resulting heavyweight FM domain ontology can indeed function as a digital FM knowledge repository, serving as a knowledge base within a Knowledge Management System.

5. Conceptional Design of the FM Domain Ontology

The principal objective of this paper section is to present an FM domain ontology, conceptualized with the primary intention of serving as a classification system. Through this FM domain ontology, the existing yet frequently overlooked written FM best practice guidelines can be systematically organized and stored, specifically concerning buildings' energy performance.

The primary development process of this FM domain ontology has been thoroughly expounded in Besenyöi (2022), starting with the “(1) Scope Determination” step, which primary aim is to define the main subject area of the domain ontology. This definition was made by establishing a so-called enterprise ontology, presented in Besenyöi (2021), that forms a theoretical but concise guidance for the primary aim of developing the FM domain ontology. Based on this enterprise ontology, within the “(2) Consider Reuse” step, already existing domain ontologies were systematically searched and reviewed in the field of FM and buildings' energy performance. Here, the studies of Jiang et.al (2018) and Tan et.al (2010) have been found adequate for re-using their developed ontologies.

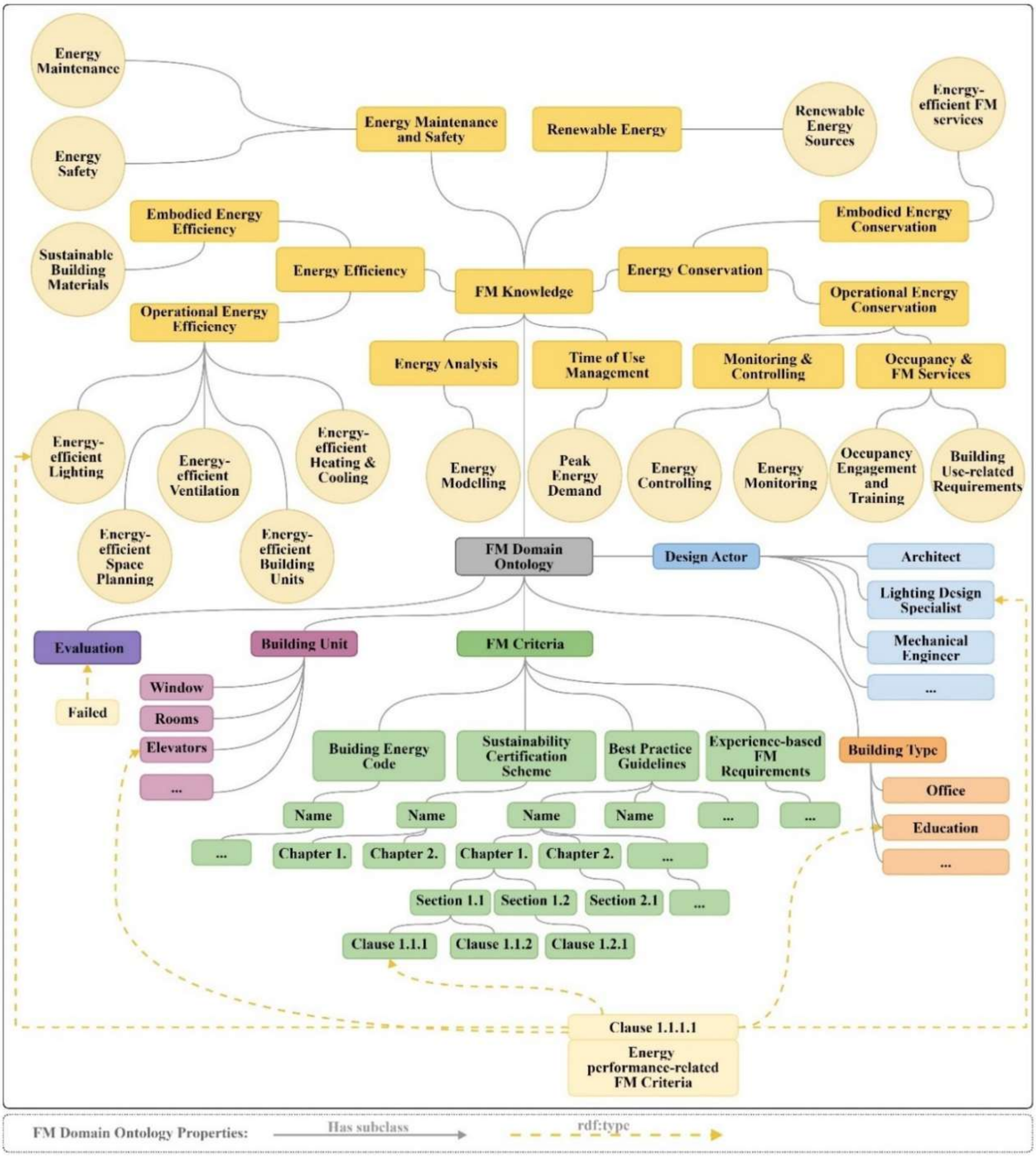

Figure 1. FM Domain Ontology in a Lightweight Form

Based on these two results, as illustrated in Fig. 1 and Fig. 2, within the "(3) Enumerate Terms and "(4) Define Classes" ontology development steps, six primary classes (depicted in boldface fonts) were defined for the FM domain ontology. Among these, the FM Criteria class assumes significant prominence, facilitating the categorization of written FM best practice documents based on their respective levels of legality. This class aids in refining clauses through the implementation of a hierarchical breakdown structure, accomplished through the concept of isomorphism. Ultimately, these clauses delineate energy performance-related FM Criteria that require consideration during early design decisions or FM executions.

Subsequently, the decomposed clauses (i.e. FM criteria) can be further classified based on the Building Type and Building Unit classes. These classes, encompass building types (e.g. office or education buildings) and specific building units (e.g. windows, rooms, or elevators), thereby aiding in the identification of the relevant building type and unit to which the FM criteria must adhere.

Additionally, the Evaluation class plays an instrumental role in determining whether the allocated FM criteria pass or fail during the compliance checking process. Furthermore, the FM criteria can also be allocated based on the Design Actor class, aiming to delineate the design disciplines responsible for implementing the criteria. This class provides clarity regarding the respective responsibilities of Architects, Lighting Design Specialists, or Mechanical Engineers in the implementation process.

Last, the FM criteria can be more comprehensively classified based on the prominent FM Knowledge class, which encompasses six primary subclasses (depicted in italicized fonts). These subclasses were derived using the energy pyramid, as devised by Gulkis (2009), to facilitate a comprehensive comprehension of energy-efficient utilization practices. As per the adaptation of this pyramid, the Energy Efficiency subclass primarily encompasses technical measures aimed at installing energy-efficient equipment. Conversely, the Energy Conservation subclass focuses on operational measures related to the optimal operation of these installed energy-efficient equipment. The Energy Maintenance and Safety subclass outlines technical measures essential for maintaining the achieved energy consumption levels.

Similarly, the Renewable Energy subclass centers on technical measures to maximize the utilization of renewable energy sources, while the Energy Analysis subclass provides rules-of-thumb to enable a more accurate prediction of a building's future energy consumption through energy modeling. Lastly, the Time of Use Management subclass comprises operational measures to shift Peak Energy Demand, leading to operational cost savings. Building upon these subclasses, additional subclasses have been defined to facilitate the systematic categorization of FM criteria.

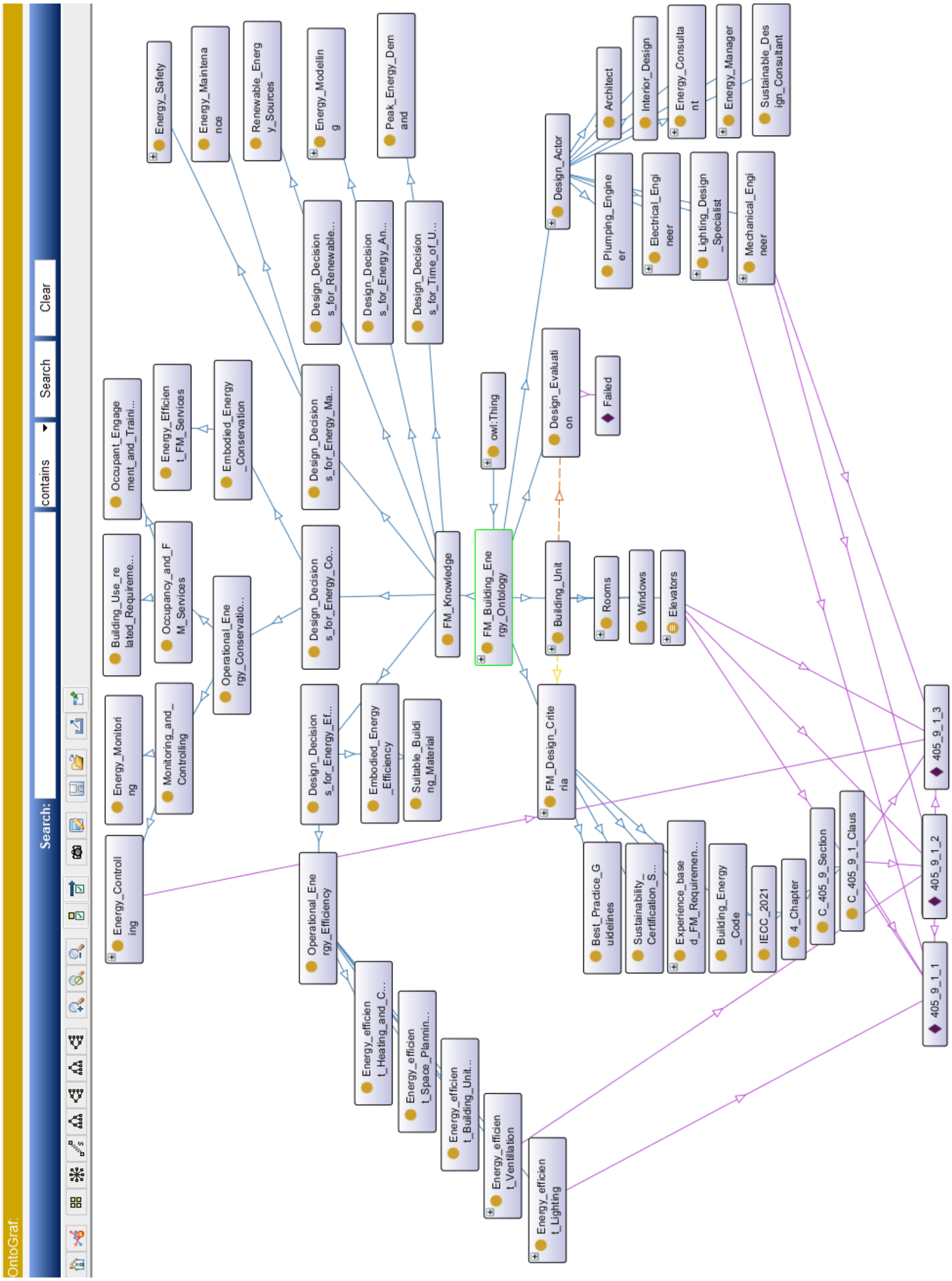

Figure 2. FM Domain Ontology in a Heavyweight Form, visualized by the OntoGraph Ontology Visualisation Tool in Protégé.

6. Discussion and Outlook

The primary objective of this paper section is to explore and elucidate the advantages offered by the proposed FM domain ontology, specifically concerning its role in facilitating the implementation of FM best practice guidelines in buildings' energy performance domain.

Within this discussion, Section 2.1 serves as the central starting point, comprehensively elucidating the principal barriers hindering the effective implementation of FM best practice guidelines. Considering these insights, the authors firmly contend that the utilization of the proposed heavyweight FM domain ontology has the potential to effectively overcome all these barriers in future endeavors.

One of the identified barriers pertains to the vast dispersion of FM best practice guidelines. The proposed heavyweight FM domain ontology can address this challenge by establishing a comprehensive and unified classification system encompassing all types of buildings' energy performance and FM-related guidelines, standards, and legally binding building energy codes. Its foundation on the Semantic Web Technology stack enhances the reliable identification and utilization of the most recent versions of FM guidelines. Consequently, the envisioned heavyweight FM domain ontology could serve as a valuable semi-legal FM knowledge base, open to future integration with the Web, thereby extending its accessibility and utility.

Furthermore, the FM domain ontology effectively tackles the second identified barrier by explicitly defining the diverse levels of legality associated with each document within the FM Criteria class (depicted in green in Fig. 1). It also addresses the involvement of various disciplinary stakeholders through the Design Actor class (depicted in blue in Fig. 1). Due to these classifications, the FM domain ontology streamlines the implementation of FM best practice guidelines by navigating challenges posed by varying levels of legality and diverse disciplinary responsibilities.

In addition to the mentioned benefits, the proposed heavyweight FM domain ontology holds the potential for rule-based reasoning using the Semantic Web Rule Language. This capacity enables the ontology to accommodate logical and computable rules that embody FM criteria categorized within it. As a result, these logically translated FM criteria, stored within the ontology, can play a crucial role in enhancing the accurate interpretation and code-compliance checking of FM guidelines in the future.

As a result, the proposed heavyweight FM domain ontology represents a valuable semi-legal and computable knowledge base that significantly bolsters the efforts of design experts and FM practitioners in implementing FM best practice guidelines for buildings' energy performance. In addition, integrating this ontology with BIM and semantically linking BIM Models to it, a cohesive and comprehensive knowledge repository can be formed. This integrated approach fosters seamless collaboration between specific and general FM knowledge, fortifying the successful adoption of FM best practice guidelines in the context of buildings' energy performance.

7. Conclusion

The effective implementation of energy-efficiency-related FM best practice guidelines is crucial in both early building design decisions and FM executions to address the buildings' energy performance gap. However, currently, incorporating these written documents into the daily work of design experts and FM practitioners remains more of an exception than a standard practice.

To address this persistent challenge, the present research has diligently identified the primary barriers and explored state-of-the-art solutions to facilitate successful implementation. The authors firmly believe that the development and implementation of a specialized FM domain ontology, serving as an advanced approach to codify and store FM domain knowledge, hold the key to overcoming these barriers.

As a solution, this paper introduces an FM domain ontology functioning as a classification system that systematically organizes and stores FM criteria for future use. Initially created in a lightweight form, the ontology was subsequently modeled into a heavyweight version with the aid of the open-source ontology editor tool, Protégé. This envisioned ontology, is poised to evolve into a semi-legal and computable knowledge base, providing substantive information for FM and building design experts concerning diverse, energy performance-related FM criteria. Leveraging the advantages of this advanced knowledge representation, the implementation of FM best practice guidelines can be significantly enhanced, thereby closing the buildings' energy performance gap.

To prove these statements, the practical implementation of the specialized FM domain ontology has been thoroughly demonstrated in Besenyöi (2022), which scientific research should be seen as an extended version of the present paper.

8. References

Adewunmi YA, Alister A, Phooko B and Nokukhanya T. Y.A. 2019 “Energy efficiency practices in facilities management in Johannesburg”. In: Journal of Facilities Management 17.4 pp. 331–343. doi: 10.1108/JFM-11-2018-0067.

Adewunmi YA, Omirin M and Koleoso H 2012 “Developing a sustainable approach to corporate FM in Nigeria”. In: Facilities 30.9 pp. 350–373. doi: 10.1108/02632771211235206.

Besenyöi ZS 2022 Towards a BIM-supported facility management knowledge management system for energy efficient building operations by rule-based code compliance checking. PhD Dissertation, Technical University of Berlin.

Besenyöi ZS, Krämer M 2021 “Towards the Establishment of a BIM-supported FM Knowledge Management System for Energy Efficient Building Operations”. In: Proceedings of the 38th International Conference of CIB W78, Luxembourg. Hg. von CIBW78 – LDAC Conference 2021. Luxembourg: 2021, S. 194-203.

Chungoora N, Canciglieri O and Young RIM 2010 “Towards expressive ontology-based approaches to manufacturing knowledge representation and sharing”. In: International Journal of Computer Integrated Manufacturing 23.12 pp. 1059–1070. doi: 10.1080/0951192X.2010.518976.

Corcho O 2006 “Ontology based document annotation: trends and open research problems”. In: International Journal of Metadata, Semantics and Ontologies 1.1 p. 47. doi: 10.1504/IJMSO.2006.008769.

Cox S 2016 Building Energy Codes: Policy Overview and Good Practices. National Renewable Energy Lab, Golden, CO, United States.

Cozzi L, Gould T, Bouckart S, Crow D, Kim TY, Mcglade C, Olejarnik P, Wanner B, Wetzel D. 2020 World Energy Outlook 2020.

Ding LY, Zhong BT, Wu S and Luo HB 2016 “Construction risk knowledge management in BIM using ontology and semantic web technology”. In: Safety Science 87 pp. 202–213. doi: 10.1016/j.ssci.2016.04.008.

Eid AS and GamaleEddin M 2019 “An Automated BIM-Embedded Approach for Rule-based Checking for Green Building Design in Egypt” In: International Conference on Advances in Structural and Geotechnical Engineering 25-28 March Hurghada, Egypt.

El Asri H, Jebbor F and Benhlima, L 2021 „Building a Domain Ontology for the Construction Industry: Towards Knowledge Sharing” In: Motahhir, S., Bossoufi, B. (eds) Digital Technologies and Applications. ICDTA 2021. Lecture Notes in Networks and Systems, vol 211 Springer, Cham. doi:10.1007/978-3-030-73882-2_97.

Frank OL, Omer SA, Riffat SB and Mempouo B. O.L. 2015 “The indispensability of good operation & maintenance (O&M) manuals in the operation and maintenance of low carbon buildings” In: Sustainable Cities and Society 14 pp. 1–9. doi: 10.1016/j. scs.2014.06.002.

Gomez-Perez A, Fernandez-Lopez M. and Corcho O 2004 Ontological engineering: with examples from the areas of knowledge management Advanced information and knowledge processing. London: Springer-Verlag London, 2004.

Gram-Hanssen K, Georg S, Christiansen ET, Heiselberg PK 2017 "How building regulations ignore the use of buildings, what that means for energy consumption and what to do about it." In: Proc. ECEEE Summer Study. Vol. European Council for an Energy Efficient Economy, pp. 2095–2104.

Gruber TR 1993 "A Translation Approach to Portable Ontology Specifcations" In: Knowledge acquisition 5.2 pp. 199–220. doi: 10.1006/knac.1993.1008

Gulkis A 2009 "The Energy Pyramid: The best path to lasting energy savings" In: Journal of Soil and Water Conservation 64.5 doi: 10.2489/jswc.64.5.143A.

Hamburg A, Kuusk K, Mikola A and Kalamees T 2019 "Realisation of energy performance targets of an old apartment building renovated to nZEB". In: Energy 194 p. 116874. doi: 10.1016/j.energy .2019. 1168 74.

IEA 2019 The Critical Role of Buildings. Tech. rep. url: https://www.iea.org/reports/the-critical-role-of-buildings.

Jensen PA 2008 "Integration of consideration for facilities management in design" In: Design Management in the Architectural Engineering and Construction Sector: CIB W096 Architectural Management & TG49 Architectural Engineering pp. 191–199.

Jensen PA 2009 "Design Integration of Facilities Management: A Challenge of Knowledge Transfer". In: Architectural Engineering and Design Management 5 pp. 124–135.

Jensen PA 2012 "Knowledge transfer from facilities management to building projects: A typology of transfer mechanisms". In: Architectural Engineering and Design Management 8.3 pp. 170–179. doi: 10.1080/17452007.2012.669131.

Jensen PA and Chatzilazarou S 2017 "Knowledge Transfer from Building Oper ation to Construction". In: EuroFM's 16th Research Symposium EFMC 2017. Ed. by S. Balslev Nielsen, P.A. Jensen, and R. Brinkø. Polyteknisk Boghandelog Forlag, 2017, pp. 66–77.

Jensen PA, Rasmussen HL and Chatzilazarou S. 2019 "Knowledge transfer between building operation and building projects". In: Journal of Facilities Management 17.2 pp. 208–219. doi: 10.1108/JFM-05-2018-0030.

Jiang S, Wang N and Wu J 2018 "Combining BIM and Ontology to Facilitate Intelligent Green Building Evaluation" In: Journal of Computing in Civil Engineering 32.5 p. 04018039. doi: 10.1061/(ASCE)CP.1943-5487.0000786.

Liang J, Qiu Y and Hu M. J 2019 "Mind the energy performance gap: Evidence from green commercial buildings". In: Resources, Conservation and Recycling 141 pp. 364–377. doi: 10.1016/j.resconrec.2018.10.021.

Liu X, Li Z and Jiang S. Ontology-based representation and reasoning in building construction cost estimation in China In: Future Internet 3.8 p.39.

Maier R 2007 Knowledge management systems: information and communication technologies for knowledge management. 3rd ed. Berlin: Springer.

Matkar R and Parab A 2010 “Ontology based expert systems – replication of human learning.” In: Thinkquest Ed. by S. J. Pise. New Delhi: Springer India, 2011, pp. 43–47.

Min Z, Morgenstren P and Marjanovic-Halburd L 2016 “Facilities management added value in closing the energy performance gap”. In: International Journal of Sustainable Built Environment 5.2, pp. 197–209. doi: 10.1016/j.ijsbe.2016.06.004.

Noy NF and McGuinnes DL 2001 Ontology Development 101: A Guide to Creating Your First Ontology.

O’Dell C, Grayson CJ and Essaides N 1998 If Only We Knew What We Know: The Transfer of Internal Knowledge and Best Practices. New York. NY, USA: Simon and Schuste.

Ontology Engineering Group 2015a Energy and Resource Information Ontology. http://smartcity.linkeddata.es/ontologies/www.auto.tuwien.ac.atdownloadsthinkhomeontologyEnergyResourceOntology.owl.html.

Ontology Engineering Group 2015b User Behaviour and Building Process Information Ontology http://smartcity.linkeddata.es/ontologies/www.auto.tuwien.ac.atdownloadsthinkhomeontologyProcessOntology.owl.html.

Rasmussen HL, Jensen PA and Gregg JS 2017 “Transferring Knowledge from Building Operation to Design: A literature review”. In: Proc. CIB World Congress 2017. Salford, UK, Sept. 2017, pp. 645–655.

Sattar A 2020 “Comparative Analysis of Methodologies for Domain Ontology Development: A Systematic Review”. In: International Journal of Advanced Computer Science and Applications 11.5 doi: 10.14569 / IJACSA.2020.0110515.

Stanford University Protege 2022. url: https://protege.stanford.edu/.

Støre-Valen M and Buser M 2019 “Implementing sustainable facility management: Challenges and barriers encountered by Scandinavian FM practitioners”. In: Facilities 37.10 pp. 550–570. doi: 10.1108/F-01-2018-0013.

Tan X, Hammad A and Fazio P 2010 “Automated Code Compliance Checking for Building Envelope Design”. In: Journal of Computing in Civil Engineering 24.2 pp. 203–211. doi: 10.1061/(ASCE)0887- 3801(2010)24: 2(203).

Zou PXW, Xu X, Sanjayan J and Wang J. 2018 “Review of 10 years research on building energy performance gap: Life-cycle and stakeholder perspectives” In: Energy and Buildings 178 pp. 165–181. doi: 10.1016/j.enbuild.2018.08.040.