Towards the Establishment of a BIM-supported Facility Management Knowledge Management System for Energy Efficient Building Operations

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Abstract
Today in the European Union, approximately three out of four building stocks are operating energy inefficiently. This phenomenon has triggered large-scale building renovation ambitions, aiming to reach significant energy savings. Facility Management has a strong influence on the optimal energy consumption of buildings, although when buildings are re-designed, the consideration of their requirements is often ignored. Due to the last years' research development in BIM, the establishment of a specialized BIM-supported Knowledge Management System could solve this long-existing problem. Accordingly, the presented paper aims to establish a methodological framework based on the systematic alignment of Knowledge Management, Knowledge Engineering, and System Engineering principles, by which the development of such a system could be executed. As a partial validation of this framework, the first system development level is presented, which can be used as a communication base to navigate the detailed system design later.

Keywords: Facility and Operation Management, Knowledge Management, BIM, Ontology-based Knowledge Management Systems, Building Energy Consumption

1 Introduction

Approximately three out of four building stocks are operating energy inefficiently according to the current standards in the European Union today. The renovation of existing buildings has a crucial role to reach significant energy savings, and meantime providing an effective way for the clean energy transition (Filippidou 2019).

Facility Management (FM) is typically considered to be a post-construction service that has a strong influence on the optimal energy consumption of existing buildings (Meng 2013) (Min et al. 2016). They are in charge of analyzing and fine-tuning building user and use-related energy consumption or detecting and changing mal-functioning energy-consumer building units. Consequently, FM possesses a large amount of knowledge about minimizing the operational building energy use, for instance, via small and middle-scale energy retrofitting.

Nevertheless, when buildings are re-designed, or even newly planned, traditionally, the consideration of FM knowledge has often been ignored or stays at a minimum at best (Meng 2013), (Brötchner 2003). It is a long-existing **Knowledge Management (KM)** problem between the domain of FM and the building design sector (Brötchner 2003), that if it is not solved, the so designed buildings may not fulfill their initial expectations, in the form of unforeseeably high operative energy consumption (Min et al. 2016).

KM is a relatively new management field (Jensen et al. 2018) that could be described as a conscious strategy of getting the right knowledge to the right people at the right time to improve organizational performance (O'Dell & Grayson 1998). Consequently, as the building industry is generally characterized by poor communication, numerous studies have attempted to take advantage of the principles of KM and related **Information and Communication Technology-based systems (ICT systems)** to enhance the productivity of the construction sector (Yu & Yang 2018).

2 BIM-supported Knowledge Management Systems

Crosswise the building industry, the concept of **Building Information Modeling (BIM)** represents the consistent use and re-use of digital building information across the entire lifecycle of a built facility (Borrmann et al. 2018). This concept systematically comprises different ICT systems and tools *(i.e., BIM-supported systems and tools)* to aid the overall information management between different construction domains, including FM. Accordingly, in recent years, the number of studies on BIM has been significantly increased in the context of KM (Yu & Yang 2018), where researchers are generally developing so-called **BIM-supported Knowledge Management Systems (BIM-KMS)**.

As presented by (Wang & Meng 2019), research efforts focusing on BIM-KMS are generally building up BIM-supported knowledge bases, tools, or computational systems in the context of specific KM processes *(e.g., knowledge capture, knowledge storage, or knowledge distribution)*. At the same time, other researchers have taken a holistic approach, where the focus point is on the overall KM processes that are aided by BIM-supported systems and tools. In order to provide a good understanding of the differences between the two study types, examples are presented below in the context of the initial FM-Designer problem.

As the main principle of BIM-supported system studies, the **Building Information Model (BIM-Model)** should be seen as the central building knowledge repository, storing knowledge specific to building projects (Wang & Meng 2019). For example, (Wang et al. 2013) show that a building project-specific BIM-Model can systematically store energy-related FM knowledge to aid early design decisions. To address the challenge of project dependency, (Liu & Issa 2016) have presented a BIM-FM knowledge base, by which FM domain knowledge could be independently stored from the BIM-Model. Due to its general content, this FM knowledge base could then be re-used in other building design decisions as well. Similarly (Ding et al. 2016) attempt to establish a separate knowledge base via ontology development to store general construction knowledge linked with the BIM-Model. Other studies, like (Motawa et al. 2014) have focused not only on storing but especially capturing and storing energy-related FM knowledge via an interface linked with the BIM-Model. Behind this interface, a case-based reasoning module was developed that allows the stored knowledge to be retrieved *(i.e., distributed)* by a designer person.

On the contrary to these individual studies, other research works on BIM-KMS are holistically developing KM-based frameworks in the context of BIM. For instance (Deshpande et al. 2014) firstly identifies the main KM processes and accordingly classifies the utilization of diverse BIM-supported systems and tools. Similarly, (Charlesraj 2014) also develops a holistic framework for FM purposes to harness the power of KM and BIM to facilitate FM. This literature work indicates, the utilization of ontologies is highly beneficial to model FM domain knowledge, besides modeling the different KM processes.

3 Methodological Framework to Develop BIM-supported Ontology-based Knowledge Management Systems

According to the presented research works, the concept of BIM-KMS could be identified as the right approach to solve the initial FM-Designer problem. Notwithstanding, there is a significant knowledge gap about how the presented two study types relate to each other regarding developing a BIM-KMS. Consequently, this chapter aims to describe a general methodological framework, where the approaches, addressed in both literature types, are analyzed and integrated into one unified concept. This unification aims to provide a profound way to develop a BIM-KMS, although, for the sake of simplification, firstly without the context of the FM-Designer problem.

3.1 Basic Research Method

As a starting point for the framework development, the main principles of a new and very humble research field should be used, namely Advanced Engineering Informatics. This research field focuses not on the automation of mundane tasks but on developing methods to enhance the existing work environment of engineers (Hartmann & Trappey 2020). Consequently, as a first step, diverse engineering *(and management)* disciplines, and contexts must be thoroughly explored and examined. The main aim of this examination *(and the research field)* is to develop approaches for implementing computer-assisted engineering platforms that apply ontology-based theories and solutions (Hartmann & Trappey 2020). Ontology can be described as an explicit, formal specification of a shared conceptualization (Gruber 1993) that can be primarily used for: *(first purpose)* communications between humans, *(second purpose)* re-use and organization of knowledge, for structuring and organizing libraries, or *(third purpose)* computational inference (Maier 2007).

Consequently, as a first step to establish the required methodological framework, the right approach should be explored to develop a BIM-KMS. This exploration has already been presented in the previous chapter, where the holistic path, on the other hand, the BIM-supported system approach, has been discovered. If the holistic approach is taken, the focus point of the framework development should lay on the determination of necessary KM processes that can be supported by diverse BIM-supported systems and tools. This approach shall be primarily based on **Knowledge Management** principles, as its main aim is to encompass the overall KM initiative. On the contrary, if the BIM-supported system approach is chosen, the emphasis is given to the development of specific computational systems and tools that primary aim is to support a specific KM process *(e.g., knowledge storing)*. This perspective is laying on **Knowledge Engineering (KE)** principles, as they are generally interested in the needed technologies to meet the enterprise's KM demand (Kendal & Creen 2007).

The authors believe that both approaches, and their related disciplines are equally critical to develop a BIM-KMS. Consequently, the unification of the main principles of KM and KE is required under the developed-to-be framework. Furthermore, the three utilization scenarios of ontologies must possess a centralized role within this unification, as both approaches use this knowledge representation technique to ensure the system's success.

In conclusion, the main aim of the framework is to develop a BIM-supported Ontology-based Knowledge Management Systems, henceforward BIM-KMS, that is established on the main principles of KM and KE. However, the correct utilization of ontologies within this system is a complex procedure. For this purpose and to provide a comprehensive overview of the KM and KE-based methodology, the main principles of the **System Engineering (SE)** discipline will be applied for structuring purposes at the end of this chapter. As the result of integrating SE principles, a standardized framework is presented for the KM and KE-based methodology, thus enhancing its utilization in real-life *(research)* projects.

3.2 BIM-supported Ontology-based Knowledge Management Systems

Consequently, to profoundly develop a BIM-KMS, the alignment of KM and KE principles is required. KM is primarily concerned with discovering and leveraging knowledge to the enterprise's benefit by establishing the enterprise-level KM strategy (Kendal & Creen 2007). Meantime KE is generally interested in the needed technologies to meet the enterprise's KM demands (Kendal & Creen 2007). Accordingly, KM and KE activities are inherently interrelated with each other (Liebowitz 2001).

3.2.1 Knowledge Management Approach

Generally, developing KMS requires a KM initiative to be used effectively and efficiently (Maier 2007), which, in the present case, must be adopted to the BIM context. As it can be seen in Figure 1., this

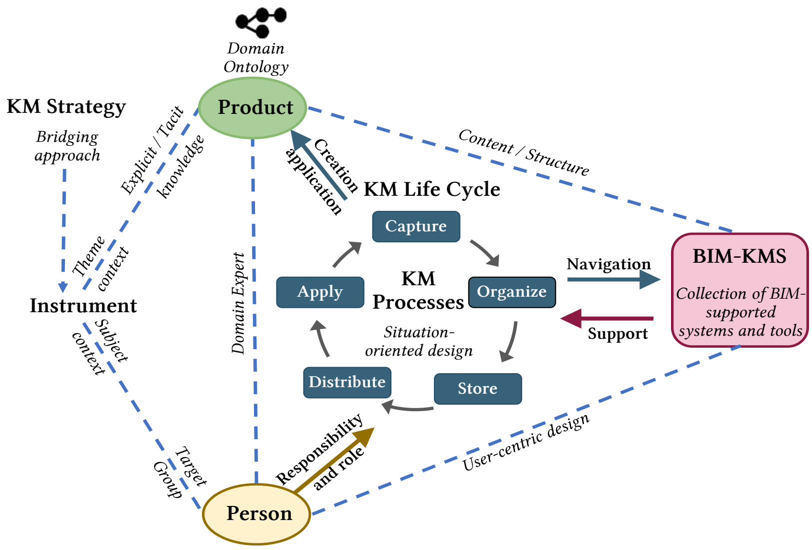

Figure 1. Knowledge Management Approach to Develop BIM-supported Ontology-based Knowledge Management Systems (Adapted from Maier 2007)

adapted initiative includes six main elements, namely the definition of KM strategy, instrument, related KM processes, persons, products, and finally, the BIM-KMS *(i.e., ICT system)*.

According to (Maier 2007), primarily two main strategies can be distinguished in KM. On the one hand, the personalization strategy, which is considered a more human-oriented approach, on the other hand, the codification strategy, that represents a more technology-focused view. Nevertheless, the development of BIM-KMS should not be exclusively based on one of these strategies but instead on a bridging approach. Within this strategy, the emphasis is on the technology-oriented approach although it pays attention to the human side as well (Maier 2007).

In order to successfully develop a KMS, within the instrument element, the KM strategy *(i.e., bridging approach)*, the theme context *(e.g., energy-efficiency building operations*), as well as the matter of subject *(e.g., FM-Designer problem)* should be defined. Thus, the main aim of this instrument specification is to characterize the motivation and achieved-to-be goals of the KM initiative.

Considering the KM processes, their situation-oriented design should be the fundamental focus point of the KM initiative. This design is aided by the classical steps of the KM Life Cycle. This means the KM processes are customized according to the achieved-to-be goals, and meantime further sub-processes are indicated, where the responsibilities and roles of the persons are also identified. This customization is crucial, as the KM processes are aiding the navigation of the planned-to-be BIM-supported systems and tools collectively encompassing the BIM-KMS. In return for this navigation, the so developed BIM-KMS comprehensively supports the KM processes to reach the primary goal of the KM initiative.

The BIM-KMS should be partly or fully consisting of diverse BIM-supported systems and tools, where ultimately, the utilization of the BIM-Model would support the defined KM processes. Accordingly, the user-centric design of these BIM-supported systems and tools is also important, where the design should be based on, on the one hand the supported-to-be KM process, on the other hand, the target group users, who are defined under the person perspective *(e.g., FM person and designer person)*.

Notwithstanding, the KM processes are guiding the creation and application of the product development paraelly. In the case of the present paper, this product is a domain ontology *(second purpose)* that contains experience-based *(i.e., tacit)*, as well as documented *(i.e., explicit)* knowledge simultaneously within the given pre-defined theme. The definition of this domain ontology requires very detailed modeling that is supported by a domain expert. The main aim to develop this ontology is to be used as the base structure of contents within the BIM-supported systems and tools, hence creating a BIM-supported Ontology-based Knowledge Management System.

Within KM, modeling is one of the critical tasks that help to understand and analyze the above described six perspectives of the KM initiative, thus creating a universal communication base for all participants about the KM initiative. This modeling should mainly emphasize the KM process perspective and its relationships with the person, domain ontology, and BIM-KMS elements. Consequently, the so-created model can also aid the detailed design, implementation, and management of the developed to be BIM-supported systems and tools later that are encompassing the BIM-KMS.

Many techniques, methods, and tools have been developed to perform such a complex modeling task (Maier 2007). According to traditional KM studies like (Maier 2007), as well as BIM focused KM studies, like (Charlesraj 2014), ontologies are classically used for this modeling purpose *(first purpose)*, rather than modeling the domain knowledge under the product perspective *(second purpose)*. Accordingly, during the development of a BIM-supported Ontology-based Knowledge Management System, ontologies are not only used to represent the domain knowledge itself in detail but to support the modeling of the whole KM initiative parallelly.

3.2.2 Knowledge Engineering Approach

On the contrary of holistically modeling the previously specified elements in KM, traditionally, KE is taking a classical technology-oriented approach, where the focus point lays on precisely modeling the product *(i.e., domain ontology)* and related ICT systems *(i.e., BIM-supported systems and tools)* (Maier 2007). Accordingly, in the presented paper, the discipline of KE is responsible for developing the structure of content and the computational background of the BIM-KMS.

As it can be seen in Figure 2., this development is navigated by the KE Life Cycle, which processes can be aligned with the KM processes originating from the KM Life Cycle (Liebowitz 2001). For clarification, within this alignment, the KM processes are aiding the holistic development of the BIM-KMS; meanwhile the KE processes are focusing on the computational system development running behind the BIM-KMS. This system is a **Knowledge-based System (KBS)**, more specifically, an Ontology-based Expert System in the context of BIM.

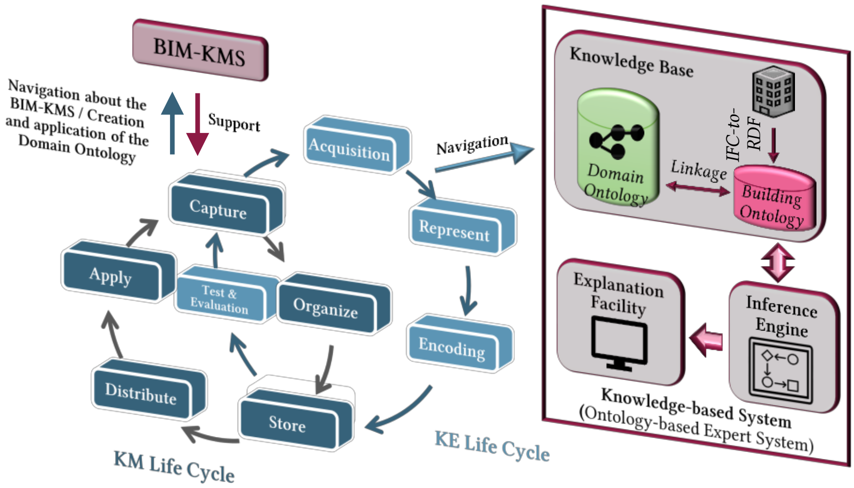

Figure 2. Knowledge Engineering Approach to Develop BIM-supported Ontology-based Knowledge Management Systems (Adapted from Liebowitz 2001, Grasic & Podgorelec 2011)

This type of expert system, as it can be seen in (Grasic and Podgorelec 2011) and (Liebowitz 2001), is usually composed of a knowledge base, an inference engine, and an explanation facility. Especially in the context of BIM, this knowledge base, as (Ding et al. 2016) has proposed, should consist of a domain *(e.g., construction)* ontology that can be linked together with the BIM-Model. This domain ontology is equivalent to the domain ontology navigated by the KM approach. This connection could enable the knowledge base to parallelly contain, on the one hand, general *(e.g., FM)* knowledge stored in the domain ontology, on the other hand, building project-specific knowledge, represented by the BIM-Model. This linking could be reached by converting the BIM-Model, stored in an IFC format, into an RDF form by an IFC-to-RDF converter (Bondule et al. 2018), (Krämer & Besenyöi 2018).

As mentioned in the KM approach, the domain ontology requires very detailed modeling, which occurs by the methods of Ontological Engineering, which is the predecessor of KE. Within these existing methods, like Unified Process for Ontology Building (De Nicole et al. 2005), generally, two main participants are involved, the domain expert and the ontological *(i.e., knowledge)* engineer. The domain expert is responsible for delivering the content of the ontology under the given theme, meanwhile, the ontological engineer focuses on modeling the domain knowledge logically. In this sense, ontologies are used to create, structure, or organize libraries or repositories *(second purpose)*. Once the domain ontology development is ready, it can be linked together with the BIM-Model, thus collectively implemented as a knowledge base in a KBS.

Once this implementation is established, the knowledge base can be used for computational inference *(third purpose)* for analyzing the internal structures of the implemented system in theoretical and conceptual terms (Maier 2007). Consequently, in this sense, ontologies would have a third role within a BIM-KMS, where the newly derived facts encountered by the expert system provide new knowledge at the end.

3.3 Adapting System Engineering Principles for Developing BIM-supported Ontology-based Knowledge Management Systems

As it has been presented in the previous sub-chapters, the main principles of KM and KE systematically can be aligned, on the one hand via the similarities of the KM and KE Life Cycle, on the other hand via the main KM product, namely the domain ontology. The main aim of this unification was to profoundly develop a BIM-supported Ontology-based Knowledge Management System. However, these two disciplines represent different views and different levels of abstractions on the system development, where ontologies are used not only in one but three different aspects. To solve this issue, hence providing a systematic overview for the system development, the authors believe that the main principles of the SE discipline should be considered.

SE is an interdisciplinary approach to enable the realization of successful systems or concepts, where a pyramid of system hierarchy is used to decompose the development progress into successive levels of details (Kossaikof et al. 2020). Furthermore, the utilization of ontologies in SE projects is not new. For instance (Chourabi et al. 2008) has presented a complex knowledge modeling framework for SE projects, where ontologies are used in a multi-layered perspective. Consequently, as it can be seen in Figure 3., the pyramid of system hierarchy can be used to provide the base structure for the methodological framework to develop a BIM-supported Ontology-based Knowledge Management System.

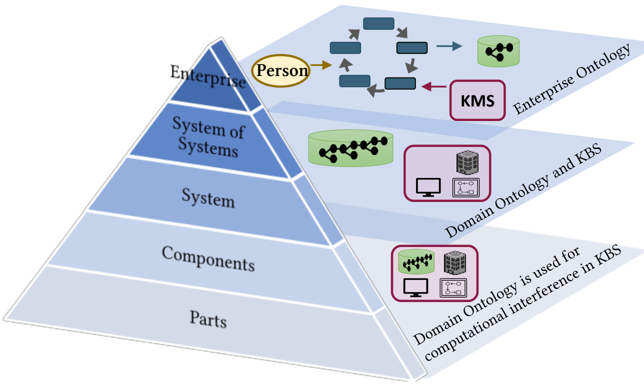

Figure 3. Methodological Framework to Develop BIM-supported Ontology-based Knowledge Management Systems

Considering the first level, an enterprise can be anything that consists of people, processes, technology, and systems, where enterprise SE refers to applying SE principles to engineering a system that part of an enterprise (Kossaikof et al. 2020). Parallel, general KMS usually gets the adjective of enterprise in traditional KM approaches to stress that these systems attempt to create a platform for a business or organization (Maier 2007). Accordingly, a BIM-KMS in KM view *(presented in Section 3.2.1)* could be seen as the enterprise-level building block in SE. This concept is enforced by (Chourabi et al. 2008), as the first layer of the system development should be based on the main principles of KM, where the primary aim is to describe a super concept. With the help of a particular ontology, this super concept enables communication about the targeted processes, tools, and products, e.g., for exploring domain knowledge. The authors believe that establishing this super concept is equivalent to modeling the KM initiative with the help of ontologies. Accordingly, this ontology at the enterprise level is created to represent the overall KM initiative *(first purpose)*; hence it would be a so-called knowledge-ontology (Liebowitz 2001), or enterprise-ontology (Gómez-Pérez et al. 2004).

As the decomposition of the previous level is getting more detailed, in the third *(system)* level, the development of the domain ontology *(second purpose)* and the KBS shall occur. Accordingly, a BIM-KMS in the KE view *(presented in Section 3.2.2)* could be seen as the system-level building block in SE. This concept is also supported by (Chourabi et al. 2008), as in the multi-layered ontology-based knowledge modeling framework, a domain ontology is developed according to the directions of the enterprise ontology to specify a concept for a specific engineering domain.

Consequently, in the fourth level, the components of the KBS *(e.g., explanation facility, inference engine, knowledge base)* are customized individually. This shall also be the level where the ready domain ontology *(second purpose)* is implemented in the KBS as a knowledge base. Meantime the connection between the domain ontology and the ontologically represented BIM-Model is established. Finally, in the last level, the different parts of the individual KBS components can be established, where for instance, the so-created ontology is used for computational inference purposes.

4 Validation

According to the presented methodological framework, the successful realization of an all-embracing BIM-KMS shall be possible. Nevertheless, considering the initial goal of this paper, this methodology was primarily established to solve the current KM problem between the domain of FM and the building design section regarding energy efficient building operations.

Consequently, this chapter aims to apply the above-presented methodology to reach this original goal, meantime to serve as a validation for the methodology itself. This validation shall be started with the top, enterprise-level of the presented SE-based framework, and accordingly, the deeper levels *(system, components, and parts)* could be further developed later.

Respectively, as the first crucial step to reach the original goal, the enterprise level of an Ontology-based BIM-supported FM Knowledge Management System is presented. Accordingly, the main focus point of this chapter is to adjust the presented KM initiative, which can be seen in Figure 1., to the context of the original FM-Designer KM problem, regarding energy efficient building operations. This adjustment is represented by modeling the main perspectives in KM in the form of a lightweight ontology. As the result of this modeling, an enterprise ontology is established that can be used as a super concept to enable the communication between humans about the targeted processes, products *(i.e., FM domain ontology)*, and the related BIM-supported systems *(i.e., KBS)* later on.

4.1 The Knowledge Management Instrument

In the presented paper, the main goal of implementing KM is to improve the application of FM knowledge within energy-efficiency-related renovative design decisions, hence enhancing the performance of the building design. FM knowledge can be inherently divided into tacit and explicit knowledge, but as Facility Managers possess a significant amount of tacit knowledge (Lê & Brønn, 2007), the current research only focuses on this category. Accordingly, the KM initiative should focus on how to get the correct experience-based FM requirements to the right designer people at the right time to improve the energy-efficiency-related building design decisions.

The KM strategy bases on a bridging approach, where technology, namely the BIM-KMS, should systematically aid the collection, organized compilation, storage and distribution of FM requirements. If this distribution process is successful, the application of FM requirements within renovative design decisions can be enhanced. Nevertheless, only those FM requirements should be considered within the BIM-KMS, which specially target building design-related decisions *(subject context)*, affecting the operative building energy consumption *(theme context)*.

To reach this presented goal, the more detailed design of the KM processes must be established in relation to the planned-to-be BIM-KMS, the diverse responsibilities of the involved persons, and the developed to be the product, namely the FM domain ontology.

4.2 Enterprise Ontology of a BIM-supported FM Knowledge Management System for Energy-Efficient Building Operations

As shown in Figure 4, the KM processes start with Knowledge Generation, which is an instantaneous human process, as in the mind of every people, tacit knowledge is generated by thinking or gaining experiences (Babu et al. 2008). In the context of the presented research, this process is performed by an FM person, who is responsible for generating energy-efficiency-related requirements, that must be considered during the renovation procedure of a building. The authors believe that this process can be aided by a particular BIM-supported system, composed of the BIM-Model of the building, connected to the building's **Building Management System (BMS)** and **Computer Aided Facility Management System (CAFM)**. By looking at the FM user interface of this composition, FM person could graphically visualize, for instance, which rooms have unusually high energy consumption, originating from the usage of the air conditioning system. Accordingly, by experience, the FM person could realize that the existing air conditioning units in specific rooms are undersized, as their operation hours are unusually high, while the room temperatures do not reflect the thermostat settings.

As a second step, Knowledge Capture refers to a process where tacit knowledge resides within people's minds, is retrieved, and converted into an explicit form, such as words or concepts (Becerra-Fernandez & Sabherwal 2015). According to the author's opinion, in the presented study, this process could be aided by specializing the FM user interface connected to the BIM-Model. This interface should enable the FM person to select a specific building object *(e.g., air conditioning unit)*, and record the deduced requirement in the form of natural language annotations. This capturing method enables the organization of FM tacit requirements via specific building objects. Inspired by (Motawa et al. 2014) and (Felten et al. 2009), the recording procedure should be established by the phases of a critical issue

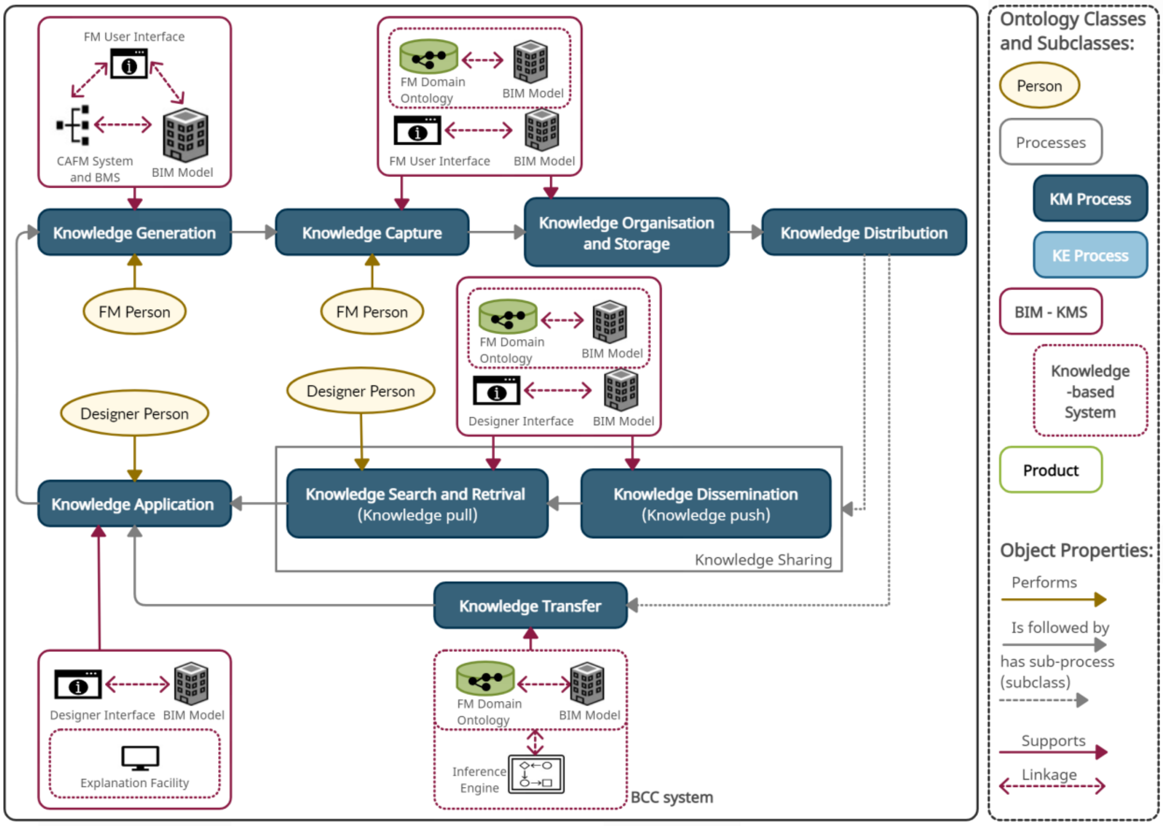

Figure 4. Enterprise Ontology of a BIM-supported Facility Management Knowledge Management System for Energy Efficient Building Operations

(e.g., undersized air conditioning unit), consequence *(e.g., high energy consumption)*, requirement *(e.g., replace to larger unit)*, and specification *(e.g., detailed specification about the new air conditioning unit)*. After the capturing process is finished, the knowledge base *(i.e., the domain ontology)* behind the FM user interface connected to the BIM-Model, could be seen as an FM tacit knowledge storage containing organized building-specific energy-efficiency-related requirements that are ready to be distributed.

In the following step, distributing the stored knowledge could be primarily distinguished by two categories, **Knowledge Sharing (KS)** and **Knowledge Transfer (KT)**, even though these three terms are frequently used interchangeably. In this paper, KS is considered as a process where the stored knowledge can be disseminated by the sender *(knowledge push)*, and the so shared knowledge can be manually searched and retrieved *(knowledge pull)* by the receiver (Jensen et al. 2018). Meantime, KT could be seen as a process where the sender is certain that the receiver will interpret the stored knowledge correctly while reconstructing and using this knowledge in a way that the sender intends (Maier 2007). The authors believe that FM requirements should go through either the process of KS or KT to ensure, one way or another, their consideration within renovative design decisions.

Considering the process of KS, the FM tacit knowledge storage could be handed over *(i.e., disseminated)* and connected to the designer's user interface, linked with the BIM-Model. As the FM requirements are systematically stored by building objects, the designer person could, although manually, search and retrieve recorded FM requirements via the designer interface *(e.g., detailed specification of new building unit)*, including the reasoning behind them *(e.g., undersized air conditioning unit)*. As a result of this search, the designer could systematically visualize via the BIM-Model, which building objects should be replaced or renovated in which manner, and accordingly manually apply *(or deny)* the FM knowledge within the design decisions.

On the contrary of KS, the process of KT should be responsible for ensuring the correct interpretation, reconstruction, and utilization of the stored knowledge, in a way that the sender intends. The authors believe that this process can only be achieved, if the FM requirements are translated into computable rules, and the defined rules are validated without human interaction. Accordingly, the concept of **BIM-based Code Compliance Checking Systems (BCC system)** could support this process, as it could be regarded as an element of a Knowledge *(Management)* System, which is responsible for the processing of embedded knowledge into computable solutions for automatic processing (Hjelseth 2016). Thus, by using a BCC system as a KT tool, the FM requirements, stored in the knowledge base behind the FM interface, could be translated into computable rules and automatically checked against the BIM-Model. As a result of KT, the designer within the Knowledge Application procedure could instantly realize via the designer interface which building objects *(e.g., air conditioning unit)* are not compliant against the pre-defined FM requirements *(e.g., detailed specification about the new air conditioning unit).* Parallel, the designer could also understand the reason behind the non-compliance *(e.g., undersized air conditioning unit).* Accordingly, the designer could change the design in accordance with the FM requirement.

Lastly, when the Knowledge Application is finished, and further design changes have occurred, the designer could hand over the BIM-Model for further FM Knowledge Generation purposes, thus restarting the KM Life Cycle.

In conclusion, based on the first level of the methodological framework *(presented in Section 3.3)*, an enterprise ontology can be developed that aids the navigation of a BIM-KMS in the context of the initial FM-Designer problem.

5 Conclusion

The renovation of existing buildings has a high potential to reach significant energy savings, however, when buildings are re-designed, usually the consideration of FM requirements is often ignored. The utilization of a BIM-supported Facility Management Knowledge Management System has high potential to solve this long-existing issue, nevertheless, the development of such a system is still unclarified today. Accordingly, the main aim of the presented paper was to establish a methodological framework by which the profound establishment of such a system is made possible.

This framework is combining Knowledge Management, Knowledge Engineering, and System Engineering principles to develop at first hand a general BIM-supported Ontology-based Knowledge Management System. This system is utilizing ontologies in not one but three different ways. According to the framework, firstly, an enterprise ontology must be established that provides a communication base for humans about the developed processes, domain ontology, and related BIM-supported systems. This enterprise ontology forms the backbone of the system development. Secondly, a domain ontology must be designed, that provides the core functionality of the system, by structuring and organizing libraries, thus forming a part of the knowledge base in the system. Lastly, this domain ontology-based knowledge base can be used for computational inference purposes, e.g., to check if FM requirements regarding energy-efficiency are compliant against a given building design or not.

As a partial validation of this framework, the first system level is adjusted to the initial FM-Designer problem, thus creating an enterprise ontology. One of the core processes of the enterprise ontology focuses on the knowledge distribution task, where BIM-based Code Compliance Checking Systems are used to ensure the correct interpretation and validation of FM requirements within renovative design decisions. Consequently, the presented paper can be considered as a groundwork to provide an expanded understanding of BIM-based Code Compliance Checking Systems as knowledge transfer tools in the view of Knowledge Management Systems.

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