Semantic Web Technology for Building Information Model

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Abstract: Smart building is a trend towards the Buildings Automation paradigm. Smart building aims to autonomously control devices and systems in given environment. These devices and systems are nevertheless supervised by facility management. The facility management normally is aided by heterogeneous systems and applications. Due to multifarious data of the systems, applications, and missing semantics in building automation, the data is manually handed by facility management, for analysis and decision making. Therefore, such a system is required to integrate such multi-form data of various systems and applications. Hence, Semantic Web technology is proposed in this paper for the data integration. The paper explains development of Semantic Web Model for BIM systems, used at Masaryk University. The model links various systems, which are used for facility management, and is applicable in different environments. The model not only provide base for analysis and decision making for facility management, but also facilitate developers to focus on front-end of application. Hence, the aim is to structure the data for simplifying the queering mechanism used for analysis.

1 INTRODUCTION

Necessity of each organization is to ensure various aspects of its operation that are not directly involved in primary goal, i.e. providing service to customers or selling products. Facility management (FM) covers the aspects, such as space management, help desk & service desk, maintenance or energy monitoring. International Facility Management Association (IFMA) defines FM as a profession that encompasses multiple disciplines to ensure functionality of the built environment by integrating people, place, process and technology.

FM distinguishes several systems and data sources that support and simplify tasks of FM. Widely used Computer Aided Facility Management (CAFM) systems cover most areas of FM. CAFM software serves as repository and user interface for operational data, for example assigning employees to rooms, log of maintenance plans, requests & tasks, energy consumption data, etc. CAFM software is used for analyzing and evaluating a building performance in perspective of FM (Paul et al., 2012). CAFM systems offer advanced analytical tools for evaluating efficiency and performance of operation based on economic (energy consumption), spatial (occupancy planning) and technical data (maintenance). The Building Information Model (BIM) is a data source that contains spatial information about building constructions (materials, dimensions), locations (sites, buildings floors, rooms) and devices installed in them (valves, pumps, plumbing, lights, power lines, etc). Data from the BIM database serve as an input for CAFM systems. Spatial data are imported into the CAFM system as a "background data" for space management, occupancy planning, maintenance management and other tasks. Finally, the task of FM is tightly connected to modern "intelligent buildings". These facilities incorporate wide scale of automated systems for example security system, access control system, fire alarm system or building automation system that controls Heating, Ventilation, Air Conditioning (HVAC) devices. The system consists of various sensors and controllable devices. Building Management System (BMS) facilitates remote monitoring and controlling the building operations. BMS also provides additional services such as archiving historical data and event notification.

Currently the integration of BMS data with CAFM and BIM is simplified to a simple structure that cannot be effectively queried because the integration part is completely missing. The integration is impossible because BMS data structure is determined by the network topology, not by the semantic structure. The semantic structure is required because the advanced analytical

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features of CAFM software are currently unavailable for BMS data. This does not affect the small installations, where data retrieval and analysis can be easily performed manually. However, for large sites (hundreds of devices, thousands of sensors), the amount of data prevents effective gathering of required information. Despite of this, BMS contains large amount of accurate, up-to-date and detailed data which are valuable for building operation analysis that cannot be obtained by any other way.

BMS has two types of users - one group is facility managers who know which data they need for analysis, economic context, but are unable to get the data from BMS. The other group is building operators who have capabilities to gather the data from BMS. They don't have enough knowledge, competence or authority to fully evaluate the building operation to make long-term decisions based on the results.

The work flow for BMS data analysis is complex for flexible data analysis. With currently available systems, when the building operators are requested to get the required data in provided format, they gather the addresses of respective data points according to request. Then, the data is extracted subsequently to required format. This process is not automated and repeated every time, when the report is required. Therefore, a user interface is required, that will help facility managers to gather data from various databases accordingly. Using the architecture and Semantic Web approach, front end applications will hide low-end aspects of data gathering and allow facility managers to query BMS directly.

Then, a facility manager should be able to query the system, for example:

- Show me which rooms on the second floor of "A11" building had active AC units during last 8 weekends.
- I want to receive a report after 24 hours, about electricity consumption in 5 minute intervals of specified 4 buildings during this night.
- I want to know which devices influence temperature in the office of Mr./Mrs. XY.

This paper proposes possible solutions to the problem by defining systems architecture and introducing ontology that facilitates BMS data queering for analysis. Therefore, a platform is developed to integrate the data. The paper explains related work in section 2 and general architecture of overall FM integration platform is explained in section 3. Overview of Semantic based Smart Building and Ontological Model is explained in detail in section 4. Section 5 and 6 explains use case scenarios and provided solutions to scenarios using Ontology model, respectively.

2 RELATED WORK

Information technology plays an important role in intelligent building, as an increasingly sophisticated demand (Andrew et al., 1998; Kroner, 1997), from decades for comfort living and requirement for increased occupant control. Indeed, much of the work in regard to building automated systems was done, but still communication is lacking, between several heterogeneous data for analysis. Recently, some of the work to analyze building data is published. The work mainly focus on the concepts and relations between various entities of the building taxonomy. Much of the research focus on intelligent building technology development, performance evaluation and investment evaluation techniques (Wong et al., 2005).

Various devices communicate and interact, without direct human intervention. Coordination between devices act as supervisors, these devices are devoted to manage available resources to meet defined requirements. Building management and automation systems are still far from this vision (Michele et al., 2014). Scenarios are defined during implementation but no dynamic changes are occurred. Currently, automatic information management systems (i.e. performance monitoring system and systems for interacting end-users, devices, and services in a defined environment) are quite limited.

Ontology or taxonomy engineering is a primary concern for defining concepts and relation between them. Therefore, main entities of building, according to requirements, are used as concepts to design ontology model. Hence, relations between concepts facilitate reasoning, which ultimately contributes in analysis. For designing self configuration and self management system, *Ambient Intelligent (AmI) system* (De Paola, 2014) is an example, which uses ontology for interacting with given environment and exploiting knowledge for cognitive processes and autonomously managing its own functions. Likewise Wireless Sensor Network (WSN) is also used in *Open Framework Middleware* (Rob et al., 2009) for management in smart buildings. *Open Framework Middleware* diagnosis faults in sensor networks. Therefore rule base knowledge management model is designed. This model facilitates FM applications, such as in energy monitoring, security, water flow control, etc. Additionally, *Home and Building Automation (HBA)* (Michele et al., 2014) is another flexible multi-agent system. This system applies knowledge base representation and automated reasoning for resource discovery in building automation. Analysis, based on the reasoning, is used to reduce cost of energy and monitor performance of various applications.

In smart building automation, wireless pervasive computing is introduced to enhance life comfort, and importantly reduce maintenance and consumption cost. The smart building automation integrates mobile technology to facilitate maintenance, which deals with monitoring and life safety plans in case of emergency. An ontological model is proposed (Dekdouk, 2013) to switch-off lights when no one is in room, scheduling water valves & pumps accordingly and switching to photovoltaic installation if bright shining sun rises. Besides this, an approach for embedded systems of sensors is used to detect activities of visitors and occupants (Paul et al., 2009), while interacting with smart building. The focus is to support FM tasks, such as building management, maintenance, inspection and emergency response. Therefore, ontology model is used for analysis to match currently received data with the data subscribed by FM applications.

Industry Factory Classes (IFC) are extensively used in construction of BIM in smart buildings. These classes are extracted from IFC and imported into a Semantic Web Model, where the requirements are analyzed by facility manger according to feasibility of a building construction, using SPARQL. Similarly, the Semantic Model is also used to view the 3D building models to visualize data. Therefore, an approach (Nicolle and Cruz, 2011), based on both semantic architecture (named as CDMF) and IFC 2x3 is used for 3D geometries of a building. The approach, i.e. *SystemGraph*, facilitates data maintenance during the building life cycle. In project *DRUM/PRE* (Seppo, 2013), IFC classes are used for data maintenance & connections, and are linked through Semantic Web Technology to allow required queries. The IFC classes are also used to define policies for Energy-Efficient smart buildings, i.e. in *Think Home* project (Mario and Wolfgang, 2010). Therefore, Green Building XML schema is used with IFC to construct Semantic Web Model. Various policies are defined in *Think Home* project, in form of rules and restrictions. These policies facilitates facility managers in querying thermal measured units and thermal material properties for the construction of a building model. The explained polices in the project are similarly used in (Massimiliano and Giuseppe, 2013).

Another aspect of smart building systems is to reduce information load on end-users (i.e. building operators). Aim of *Smart Home and Social Services* (Yulia et al., 2013) is to construct user friendly system and filter out irrelevant data according to end-user requirements. Therefore, for future decision making in smart buildings, the communication between end-users and heterogeneous systems is important. Hence, a comprehensive communication among systems is provided (Christian et al., 2008). This system enhances possibilities in making analysis and decision on stored knowledge.

The approach explained in this paper is used for BMS in MU, which covers several aspects of operational analysis in smart building. Main emphasis of the BIM Ontology Model at MU is to communicate various heterogeneous systems. BIM at MU deals with location and device information in a building. Knowledge domain of the Model facilitates in monitoring & automatic controlling various devices, provide instant response to concerned end-users, and reasoning & analysis for future decision making. The Model will reduce cost and time consumption during analysis and future decision making.

3 DATA OPERATION ANALYSIS: GENERAL ARCHITECTURE

Various data sources are related to FM and building automation. There are three basic categories of data sources i.e. CAFM, BIM and BMS. The proposed architecture, as shown in figure 1, supports seamless integration among these systems. The architecture will support development of analytical tools. These analytical tools will be used for BMS, as used in CAFM systems. Therefore, the architecture is essential for efficient large scale building operation analysis. The architecture facilitates the ontology repository that provides meaning to BMS data. The ontology repository helps analytical and monitoring developers, to focus on front-end user interface and analytical features. Facility managers will be able to do analysis, using Ontology repository, without requiring data from building operators. This will solve the gap for facility managers between economic knowledge and technical BMS data.

The architecture introduces additional elements to CAFM, BMS and BIM systems. These elements include Technology data mart, Business Intelligence applications, Complex Event Processing Engines and Ontology repository. Technology data mart is OLAP data source that provides operational data for further analysis. The operational data is received from BMS OLTP archive server. Ontology repository enables the applications to explore relations between elements, which are stored in different systems. These relations between elements will link BMS data point with the source device in the BIM. The architecture will be used either to develop new analytical applications or to add new functionality to existing systems, e.g. CAFM. Business Intelligent Applications and Complex Event Processing Engines are the examples of new analytical

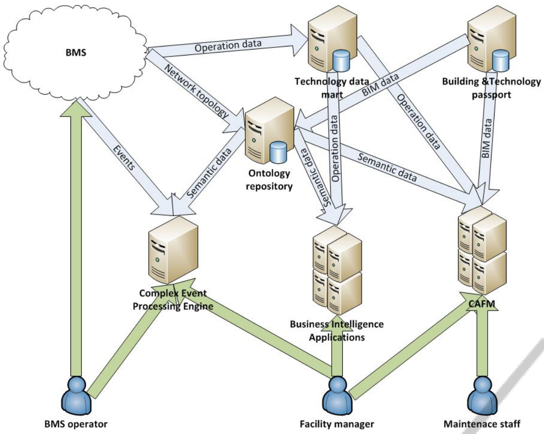

Figure 1: BMS at Masaryk University.

applications. The Ontology repository describes relations between BMS and BIM. The BIM is integrated with CAFM in current environment. Integration between BMS and CAFM is achieved by transitive relations between the three systems.

The proposal uses the complete FM environment of Masaryk University (MU). The MU uses all the core systems i.e. BIM, BMS and CAFM. These three systems are distributed over 200 buildings at 40 distinct sites in Brno, Czech Republic. The BMS connects 40 buildings; all together contain 1000 devices and hundreds of thousands of data points. BACnet communication protocol is used for integrating devices in BMS. These devices are of various vendors and are used for different functions. Those buildings which are integrated in BMS also has BIM database. The BIM database is an in-house developed database. The BIM uses GIS based on ESRI ArcGIS server.

4 SEMANTIC BASED SMART BUILDING

While analyzing building operation (e.g. BIM, BMS and CAFM), several concepts are gathered from different systems. Table 1, provides overview of semantics concepts required for BMS, which are organized by their source systems. For example, temperature in a particular room is a Measured Variable, in Environment column, and is explained as;

- Meaning (physical quantity - room temperature)
- Source (data from BIM database – Location Information and Device Information)
- Available data (BMS network addresses for real-time data, historic data and event triggers)
- Relations (which variable is influenced by & what is influenced by a variable)

Detailed description of BIM is explained below. The Ontology Model is based on practical experience and requirements required for the MU's BMS systems. The Model is generalized on the abstract concepts that are common for each of the building's operation, monitoring and FM systems. Currently, development of Ontology is in progress, therefore concepts describing BIM domain and its integration is discussed here.

Location Information in BIM – Location Information is stored in spatial database named as "building passport". Location is described by its location code. These location codes serve as primary keys in spatial database. Usually, room is represented as a location in a building. In spatial database location code is a string defining location data as Site Code, Building Number, Floor and Room information; figure 2 elaborates building passport.

Device Information in BIM–Device Information is stored in spatial database named as "technology passport". In spatial database Device Information describes location of the device, its purpose and its connection to a particular system in building. For example the systems could be Building automation system, security system, CCTV, water supply, power lines, etc. In spatial database, technology code is a string consisting of System, Sub-System, Device type and Device Index; as described in figure 2. The Device Index is used to distinguish similar devices in a room. The "building passport (BP)" is integrated with "technology passport (TP)" to define a complete code for a device, its connections and its location in a building.

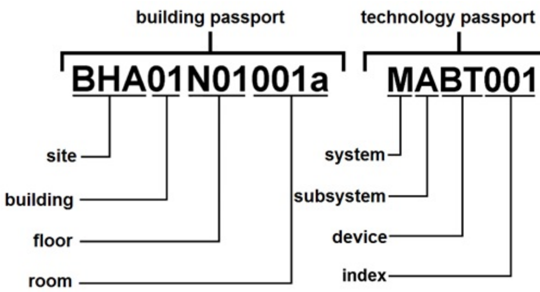

Figure 2: BP and TP (Unique ID of BIM).

4.1 Semantic Web and Complex Data

The data is analyzed for achieving the aim, to design Ontological Model, for complex data of BIM used at MU. As explained before, similar Device Types could have same or different Index Numbers, which could be connected with same System and Sub-System. Similar data for similar device types postulate the idea to

Table 1: Elements of Building Operation Semantics.

Environment	BMS	BIM
Measured Variable	Device	Location Information
	Object (Data Point)	Device Information
	Object Purpose List	
	Physical Quantity List	

select common System, Sub-System, Device Types and Index Number. The case of complete room data, also predict that common information from room data should be selected, which is categorized according to Site Code, Building Number, Floor and Room information.

Categorizing common data facilitates to simplify the complex data. This complex data is managed to distinguish between various devices and rooms in different buildings. The common data provides a complete view of various devices used in all buildings and also contributes in grouping variety of Systems and Sub-Systems, for analysis.

4.2 Main Concepts and Relationships

Common data is extracted from actual data of room and devices used in BIM system. The common data is then analyzed to construct concepts for Ontological Model. Based on concepts of BIM system, it is decided to keep building taxonomy, i.e. BP, as domain knowledge of the Ontological Model. Therefore, building taxonomy includes Site Code, Building Number and information of Floor and Room is kept as concepts under the domain knowledge.

Common data of devices are named as TP. An instance of TP is a self explanatory entity that informs building operators about Device Type, its connection with a System and Sub-System. Therefore, instance of TP is considered as separate concept in Ontological Model, described as taxonomy of device. The taxonomy of device further explains sub-concepts, which includes System, Sub-System, Device Type and Index Number.

The challenging step of BIM system is to deal with repetitive index numbers of device instances in TP and repetitive room number at each floor in a building, used in BP. Initially, it was decided to make relationship between Room and Floor information with Index Numbers and Device Type. But after analyzing and considering the actual data, Ontological Model provided results that don't exist in actual data. In second step, relationships were taken into consideration to connect the instances of TP and BP tightly. Most of non existing data issues were solved but the problem come-up with repetitive BIM data. The same data which connects TP with BP was displayed several times. Finally, it was decided to keep the TP data uniquely and then connect with BP data. Therefore, a new concept was introduced named as "Identifier", which identify each of the instances of devices that are installed in a room, as shown in figure 3.

Analyzing common data and defining concepts provides an overview of Ontological Model, as shown in figure 3. These concepts, i.e. classes and sub-classes, facilitates in populating the Ontological Model. Hence, the common data extracted from actual data of BIM system is used to populate the Ontology. The concept, i.e. "Identifier", is populated according to total number of devices installed in a building.

Relationships between the concepts are defined according to logical association of entities in BIM. These relationships, i.e. predicates, are conceptual relationships that are used by building operators at MU. Consequently, definition of relationship is keenly considered in reference to technical aspect of BIM.

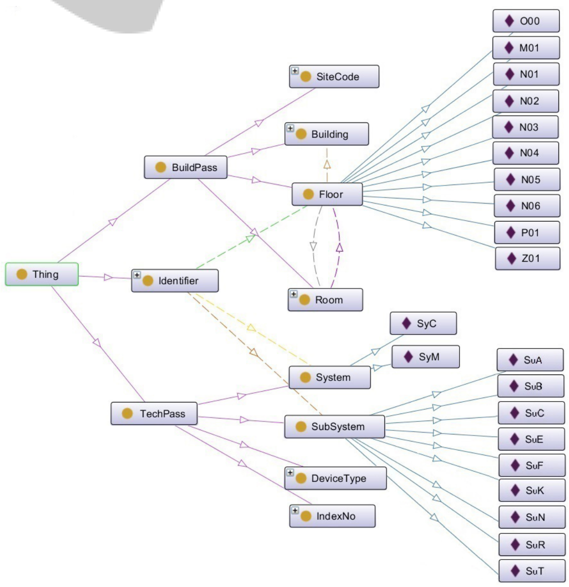

Figure 3: BMS root Ontological Model.

4.2.1 Second Level of Ontological Model

Defining concepts and relationships in Ontological Model, facilitates in improving final results according to requirements. Major issues related to repetitive results and non existing actual data are solved for a building in a site. After populating the Ontology for a second building in same site, again generates repetitive results, this is because of similar alpha-numeric numbers assigned to floors in different buildings.

For avoiding recursive results, due to floor numbers in different buildings, the Ontology Model is extended to second level. The common data from building taxonomy and devices taxonomy is populated at root level of Ontology, but the relations between instances are defined at second level. Therefore, for each building at MU, an extended Ontology is used, for keeping the uniqueness of information. Hierarchical level of the Ontology Model is depicted in figure 4. The hierarchy is used for the Ontology Model, depends on analysis of relevant concepts in terms of entities and linking data of BIM (i.e. building and device taxonomy) (Zarrad et al., 2012). In taxonomic relations, links are established on canonical structure of concepts and lexico-syntactic patterns (Carmen and Desislava, 2011) are used to construct BIM unique ID. These similar relations are also used in (Asfand-e yar et al., 2009).

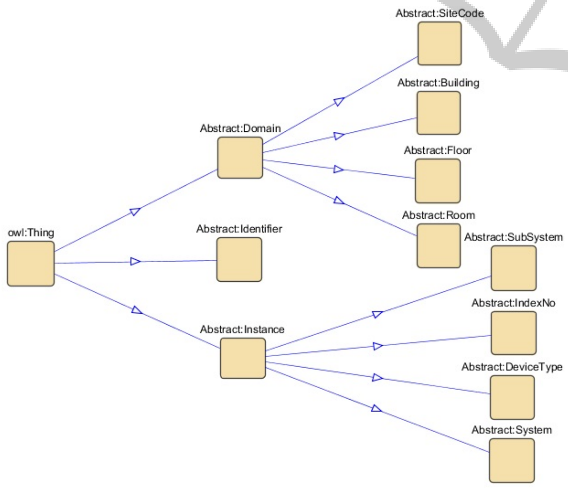

Figure 4: BMS Second Level Ontology Model.

5 SCENARIO

The use cases elaborate requirements of facility managers in MU's buildings. List of devices are installed in each building, such as various sensors, network sockets, electrical fuse, water flow meters, various electrical devices and much more. These devices further connected with CCTV, security systems, fire alarm systems, time multiplexers, structured and unstructured cables, etc.

Facility managers perform analysis on basis of readings generated by active devices. The efficient and complicated systems connect devices and reports administrator about various kind of readings received from active devices. Hence, to search for a list of active devices in room, a list of active devices should be provided as a result by the Ontology Model to building operators. Same as, if complete fact about a room is queried then complete fact about a room should be forwarded by the Ontology Model to building operator. In some cases, it is required to get information about a specific device, which is installed in a building. Therefore, the Ontology Model should compile a list of rooms and sent to building operator, where that specific device is operative.

Such queries facilitate not only building operators but also higher authorities in a FM for performing various analysis concerning active devices in several buildings of MU.

6 INFORMATION FILTERING

Capability of the model is to filter relevant requirements to facilitate user according to her queries. The Ontology Model captures available information connecting certain devices with Systems and Sub-Systems and also room information where devices are actively functioning. A pictorial illustration of the developed Ontology is represented in figure 3.

As discussed before, three types of cases facilitates end-user's requirements. First case is to filter all those devices with connecting System, Sub-System, Device Type and Index No. Therefore, complete room information should be provided, which identifies the room its location in building and site. For filtering required information, following logic is used to create a query with required information of a room at a floor in a building and site.

Identifier (?ID) ∧ *hasSpecific (?ID, ?Room)* ∧ *hasPerticular (?ID, ? Floor)* ∧ *isLocatedIn (?Room, ?Building)* ∧ *isSitutatedAt (?Building, ?SiteCode)* ∧ *isDistinguishedBy (?ID, ?Index)* ∧ *isEquipedWith(?Room, ?Devices)* → *isAssignedTo (?ID, ?Devices)*

In this scenario the concept Identifier filters required room in a building at a specific floor, accordingly. After filtering the room from complete knowledge of building, then the "Identifier" selects list of those devices which are installed in that room.

In second scenario, described below, an Identifier of required device is selected by filtering it according to required System, Sub-System and Device Type. After filtering identifier according to device information, a list of rooms is selected from domain knowledge of Ontology, in which location of installed particular device is provided.

Identifier (?ID) ∧ hasDefined (?ID, ? DeviceType) ∧ isEquipedWith(?Room, ?DeviceType) ∧ hasDefined (?DeviceType, ? SystemAndSubSystem) ∧ isDistinguishedBy (?ID, ?Index) → isInstalledIn(?ID, ?Room)

Selecting list of rooms, in third scenario, has same procedure, as in first scenario. Only, selection of Identifier is done by providing required information about device i.e. System, Sub-System and Device Type. The Index Number is not provided to filter the Identifier, because similar Device Types, connected with similar System and Sub-System have different Index Number. When appropriate Identifier is identified using filtering procedure, a list of room is selected from domain knowledge of Ontology.

Identifier (?ID) ∧ hasDefined (?ID, ? DeviceType) ∧ isReferredTo(?ID, ?SubsystemAndSystem) ∧ isConnectedWith (?DeviceType, ? SystemAndSubSystem) ∧ isInstalledIn (?DeviceType, ?Room) → isAssignedTo (?ID, ?Room)

According to the third scenario; for example, a building operator search for a list of room that has Device Type "SK" connected with System "C" and Sub-System "F". Therefore, she has to provide the device information in SPARQL query, as shown below. Initially the query selects all those identifiers who has Device Type "SK", System "C" and Sub-System "F", therefore a long list of identifiers is selected. In second step pattern matching process is performed. Therefore, initially, the identifiers of Device Type "SK" having Sub-System "F" are filtered. Then the resultant identifiers from Device Type "SK" and Sub-System "F" are filtered according to System "C". The identifiers other than System "C" are removed from filtered list. At this point, all those identifiers are listed, whose System is "C", Sub-System is "F" and Device Type is "SK". Finally, according to the filtered list of identifiers, complete information of Room is selected according to Site Code, Building Number, Floor and Room information.

```
Select ?Sc ?B ?F ?R
  Where { ?id1 Abstract:hasSpecific
  ?R. ?id1 Abstract: hasParticular ?F.
  ?R Abstract:isLocatedIn ?B.
  ?B Abstract:isSituatedAt ?Sc.
    {Select ?id1 Where {
    ?id1 Abstract:hasConnection Abstract:SyC.
    ?id2 Abstract:hasReferred Abstract:SuF.
    ?id3 Abstract:hasAssigned Abstract:DtSK.
    FILTER (?id1 = ?id2)
    FILTER (?id2 = ?id3)}
  } }
```

Results

Sc	B	F	R
Abstract:BBA	Abstract:B01	Abstract:N01	Abstract:R000
Abstract:BBA	Abstract:B01	Abstract:N01	Abstract:R001d
Abstract:BBA	Abstract:B01	Abstract:N01	Abstract:R001d
Abstract:BBA	Abstract:B01	Abstract:N01	Abstract:R035

Figure 5: Results of SPARQL query.

Figure 5, describes results of above defined query. The query is applied on Semantic Model of one building i.e. "BBA". The results explains that the queried device, which is connected to System "C" and Sub-System "F", and is actively functioning at three rooms of the building. The results also describes that two of the devices are installed in one room, i.e. the room "R001d", shown in figure 5, is at Floor "N01", Building "01" and Site Code "BBA". The complete location address of the room is "BBA01N01001d", this address is understandable by end-users at MU.

The Ontology Model is developed according to explained structure of BIM. SPARQL queries are applied, subsequently to requirements of building operators and facility managers. The Ontology Model personalizes the information related to BIM and reduce information load by filtering irrelevant data considering users requirements.

7 CONCLUSION

This article is about FM and explains the integration of BIM and BMS systems. The proposed approach addresses the missing semantic information of BMS. Therefore, facility managers can perform operation analysis in large-scale environments. The designed ontology covers the concepts of BIM, used for Location Information and Device Information. Queries are applied on the Ontology Model for reasoning the Location Information and Device Information based on hierarchical structure used in BIM.

Ontology Model helps the developers in BMS to focus on user interface and analytical methods rather than on data integration. Therefore, facility managers will be able to perform analysis and decision making for future planning. This is the significant improvement in current analysis work flow.

The research in several areas of large-scale BMS data analysis is possible by introducing "Semantic smart building ontology". Initially, advanced analytical tools should be developed. Additional research is also required in the field of user interfaces, both for the query definition and results presentation.

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REFERENCES

Andrew, H., Eric, L., and James, R. (1998). *Intelligent Buildings in South East Asia*. Publisher E & FN SPON, London, Chaper 1.

Asfand-e yar, M., Anjomshoaa, A., Weippl, E., and Tjoa, A. (2009). Blending the sketched use case scenario with license agreements using semantics. In Karagiannis, D. and Jin, Z., editors, *Knowledge Science, Engineering and Management*, volume 5914 of *Lecture Notes in Computer Science*, pages 275–284. Springer Berlin Heidelberg.

Carmen, K. and Desislava, Z. (2011). Lexico-syntactic patterns for automatic ontology building. In *Proceeding of the Student Research Workshop. International Conference on Recent Advances in Natural Language Processing. RANLP*, pages 109–114.

Christian, R., Wolfgang, G., Fritz, P., and Woflgang, K. (2008). Integration of heterogeneous building automation systems using ontologies. In *International Conference on Industrial Electronics IECON*, pages 2736–2741. IEEE.

De Paola, A. (2014). An ontology-based autonomic system for ambient intelligence scenarios. In Gaglio, S. and Lo Re, G., editors, *Advances onto the Internet of Things*, volume 260 of *Advances in Intelligent Systems and Computing*, pages 1–17. Springer International Publishing.

Dekdouk, A. (2013). A mobile-based automation system for maintenance inspection and lifesaving support in a smart ict building. In *Workshop AmI 2013, CCIS*, pages 320–335. Springer.

Kroner, W. M. (1997). An intelligent and responsive architecture. *ELSEVIER, Automation in Construction*, 6:381–393. Issue 5-6.

Mario, J. K. and Wolfgang, K. (2010). A knowledge base for energy-efficient smart homes. In *International Energy Conference and Exhibition (EnergyCon)*, pages 85–90. IEEE.

Massimiliano, G. and Giuseppe, P. (2013). Visual computer managed security: A framework for developing access control in enterprise applications. *IEEE Software Journal*, 30:62–69. Issue: 5.

Michele, R., Floriano, S., Loseto, G., and Eugenio. Di, S. (2014). Semantic-based resource discovery and orchestration in home and building automation: A multi-agent approach. *IEEE Transactions on Industrial Informatics*, 10:730–741.

Nicolle, C. and Cruz, C. (2011). Semantic building information model and multimedia for facility management. In Filipe, J. and Cordeiro, J., editors, *Web Information Systems and Technologies*, volume 75 of *Lecture Notes in Business Information Processing*, pages 14–29. Springer Berlin Heidelberg.

Paul, M., Rob, B., Declan, O., Marcus, K., Kris, M., and James, O. (2009). Pervasive knowledge-based networking for maintenance inspection in smart building. In *International Workshop on Managing ubiquitous Communication MUCS*, pages 59–65. ACM.

Paul, S., Karsten, M., Denis, F., Ammar, A., and Sean, M. (2012). A cloud-based platform for energy and maintenance management. In *International Conference on Computing in Civil and Building Engineering, ISCCBE*, pages 27–29.

Rob, B., Wei, T., Declan, O., Muhamamd, S. A., Susan, R., and Dirk, P. (2009). Open framework middle-ware for intelligent wsn topology adaption in smart buildings. In *International Conference on Ultra Modern Telecommunication & Workshops*, pages 1–7. IEEE.

Seppo, T. (2013). Semantic linking of building information models. In *International Conference. on Semantic Computing (ICSC)*, pages 412–419. IEEE.

Wong, J., Li, H., and Wang, S. (2005). Intelligent building research: a review. *ELSEVIER Automation in Construction*, 14:143–159. Issue: 1.

Yulia, E., Aleksandra, D., Jose, L., and Martinez, L. (2013). Semantic information management for user and context aware smart home with social services. In *International Conference on Cognitive Methods in Situation Awareness and Decision Support CogSIMA*, pages 262–268. IEEE.

Zarrad, R., Doggaz, N., and Zagrouba, E. (2012). Toward a taxonomy of concepts using web documents structure. In *Proceedings of the 14th International Conference on Information Integration and Web-based Applications & Services*, IIWAS '12, pages 147–156, New York, NY, USA. ACM.