On the Applicability of Open Standard Exchange Formats for Demand-Oriented Facility Management (FM) Service Delivery in the Context of the Cross-Lifecycle Building Information Modeling (BIM) Method

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Abstract

Data is a decisive success criterion for efficient provision of services in Facility Management (FM). Therefore, various IT systems are used to process static and dynamic data. The Building Information Modeling (BIM) method offers a possibility to optimize the cross-lifecycle data exchange between these IT systems through open data formats, such as the IFC format. Currently, BIM is mainly used to map static data, while dynamic data for FM is rarely mapped. In particular, the integration of dynamic data, such as runtime and monitoring data generated by sensor technologies, for results-oriented FM service provision is still insufficient within the framework of the BIM and the associated data formats.

This paper will present a possibility for integrating dynamic data into BIM-based, open data exchange formats. For this purpose, the data and IT systems relevant to FM are analyzed and the open data exchange format IFC is evaluated concerning the integration of dynamic FM data. Based on this, approaches for the integration and use of dynamic data in IFC are developed.

Keywords: Building Information Modeling (BIM), Facility Management (FM), neutral data exchange formats, cross-lifecycle process consideration

1. Introduction

Data represents a key success criterion for Facility Management (FM) provision of service (Otto & Bartels 2018). FM uses various data to perform and maintain multidisciplinary activities of all building life cycle phases as part of its integrated processes. A distinction must be made between dynamic and static data processed in different software systems and tools (May 2018). Especially in the maintenance phase, dynamic data are crucial to fulfilling building performance contractually defined by Service Level Agreements (SLA) between service providers and clients (Hirschner et al. 2018). In recent years, there has been a trend towards outcome-based and activity-based contracts. By this, data-based Key Performance Indicators (KPIs) and monitoring of building performance gain in importance.

Dynamic data can be generated by sensor technologies, IoT technologies, or IT systems. Hereafter, the sources of dynamic data are referred to as sensor technologies. The integration of sensor technologies in FM offers new opportunities for assembling, exchanging, and using data required to provide FM services, such as predictive maintenance and repairs (Lu et al. 2020, Edirisinghe & Woo 2021). Using dynamic data generated by sensor technologies for building maintenance represents the most commonly used approach applying sensor technologies for FM, but focuses on building systems and energy management (Atta and Talamo 2020, Edirisinghe & Woo 2021). Due to date, fewer synergies exist between sensor-based and FM-based IT systems, but sensor data is processed in proprietary systems. That means that hardware components (e.g. sensors or building automation systems) could only be maintained using the vendor's software. Due to many software systems and tools, missing interoperability leads to a loss of static and dynamic data (Teicholz 2013, Behaneck 2018). To counteract data loss, using Building Information Modeling (BIM) enables a possibility to exchange data interoperable, open, and lifecycle-spanning (Teicholz 2013, May 2018, Bartels 2020).

An essential factor in applying the BIM method is the use of open data exchange formats. However, BIM-based data exchange formats mainly focus on transferring static data to FM (Atkin & Brooks 2015). While recent research endeavors have identified the advantages of using BIM in FM, there is a clear need to examine scopes of exchanging dynamic data through different life cycle phase. Therefore, it is the purpose of this article to investigate if an extension of the international and neutral data exchange format IFC is suitable for mapping dynamic data. A solution approach for the integration of sensor data in IFC will be presented and analyzed.

2. State of research

The main task of FM is the support of primary processes while providing services around facilities, e.g., real estate for the production of specific goods (Kaiser et al. 2018, GEFMA 2004). The primary basis for FM processes is contracting, which classically distinguishes between performance-based and results-based commissioning and service provision (Kummert et al. 2013, Schawel & Billing 2012, Kaiser et al. 2018). Using sensor technologies in FM offers potential for building performance optimization, particularly in the case of results-oriented service provision (Nävy 2018, Gerrits & Pilling 2021). In addition, IT systems in FM are crucial for efficient and successful service provision. By this, dynamic data and IT systems in FM will first be examined.

2.1 Dynamic data in FM

Dynamic data, also known as runtime or transactional data, is periodically updated and show a change of condition. Sensor technologies and IoT devices measure dynamic data. Dynamic data already form an essential basis for the Building Management System (BMS). Data aggregated in the building (e.g. from sensors and hardware) provide information on mechanical and electrical equipment, such as ventilation, pumping, or lighting, and controlled and managed using the BMS software (Wilde 2018). Typical sensor-technology measures for FM are temperature and humidity monitoring in ventilation and heating systems, presence detectors in buildings, or filling levels for controlling technical building equipment (Hossenfelder et al. 2019). Sensor technologies in buildings are used for assembling data on climate, energy and resource consumption, building condition, and space demand (Jaspers et al. 2018). Thus, the collection and processing of dynamic data enable FM strategies that support outcome-based service delivery based on predictions and controls, such as condition-based and predictive maintenance (Atta & Talamo 2020).

2.2 Software in FM

All dynamic data generated for providing facility services must be aggregated, stored, and analyzed in IT systems. Computer Aided Facility Management systems (CAFM systems) are the primary IT system to store and process data for FM. A consistent definition of CAFM systems is missing, but it can be stated, that a CAFM system is an administrative tool for automatizing processes of FM. Therefore, CAFM systems focus on people, assets, and financial aspects (Reddy 2013, Teicholz 2012, Nävy 2000). Storing all data relevant for FM is a crucial factor for efficient CAFM systems. A CAFM system consists of three components. The first component, the CAFM functionality, constitutes all CAFM systems and contains the software, programming, and applications. Customizing, the second component of CAFM systems, enables customizing of the specific use cases in the property. The third and most crucial component of a CAFM system constitutes the CAFM data. In this component, all property-relevant data is stored and displayed in the CAFM system by using both other components (May 2018, Otto & Bartels 2018).

Besides the CAFM system, various other FM software for fulfilling facility services exist, e.g.

- Integrated Workplace Management Systems (IWMS) for organizing and optimizing workplace resources and assets located in a facility (van Sprang 2021),
- Computerized Maintenance Management Systems (CMMS) for scheduling, managing, and documenting the maintenance of assets in a facility (Keady 2013) and
- Enterprise Resource Planning Systems (ERP) for supporting commercial aspects are worth mentioning. (Nävy 2018).

The systems are mainly used to provide facility services. Furthermore, Document Management Systems (DMS) for storing documents, and Geographic Information Systems (GIS) for further geographical data might be helpful. The IWMS, CMMS, or ERP are connectable to CAFM systems or other systems for exchanging data. Depending on the consideration, a commercial (ERP) or a technical system (e.g. CAFM) is the leading system (Nävy 2007). Fig. 1 displays a CAFM-centered FM software system.

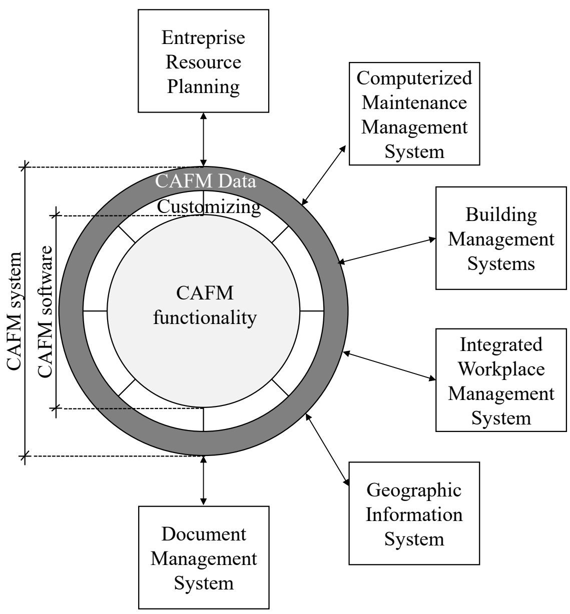

Fig. 1: CAFM-system and connected systems

As shown, many software tools for gathering and storing building-relevant static and dynamic data are necessary to conduct facility services. To avoid a loss of data, using open data exchange formats is required. By using the BIM method, all static and dynamic data can be stored in a structured way and exchanged in open data exchange formats. In addition to that, a BIM-based structure for storing data is crucial because

1. due to the increasing use of sensors, the object orientation in facilities will become more critical to handle all the data,
2. object orientation enables better analysis, visualization, and assignment of errors during monitoring, which in turn enables optimization of KPIs and
3. due to object orientation, the model forms the basis for a digital twin (Boje et al. 2020, Talamo & Atta 2019).

Therefore, integrating all static and all dynamic data into an object-oriented digital building model based on IFC and BIM is required for supporting the result-oriented provision of services by affording all relevant data.

2.3 Ongoing projects and scientific related work

Although the number of scientific projects and publications related to BIM and FM is increasing, a trend of the scientific BIM projects in dealing with as-built models instead of dealing with the planning and construction phase of buildings is recognizable (Fassl 2020). Ongoing scientific projects, that aim to integrate BIM, IoT and FM focus on energy monitoring, the visualization of values like temperature or humidity in 3D (e.g. Kazado et al. 2019) and sustainability (e.g. Desogus et al. 2021). By analyzing various papers, it becomes obvious, that proprietary exchange formats (e.g. Autodesk Revit) are regularly used.

For this reason, an analysis of projects that work with data exchange formats was carried out in a second step. The project BIM4BEMS, for example, investigates the use of BIM for reporting purposes of energy and comfort-related parameters in the maintenance phase. Combining building data with building management system data creates a dynamic system. Such a model may significantly improve the analysis and visualization of changes in the current state of a facility. The BIM is derived semi-automatically from available design, operational and maintenance data with semantic and geometric reasoning. In the final report, the authors state that various challenges existed during the data processing. Especially incomplete documentation, limited data interoperability, and a clear definition of data was mentioned (Gaida et al. 2020). Furthermore, the focus of the project was not on using open data exchange standards as IFC. Besides these scientific projects, various ontologies, such as ifcOWL, Colibri, Building Topology Ontology (BOT), and schemes have been developed to store, visualize and exchange sensor data and data of the building automation. In particular, the Brickschema, the ProjectHaystack, or the Smart Applications REFerence (SAREF) offer possibilities to integrate sensors and hardware of building automation (Sanz et al. 2018, Anjomshoaa & Curry 2020). Approaches for linking the BIM-methodology IFC classes with the conventions of the ProjectHaystack or with the Brickschema and the integration of SAREF models into the Brickschema already exist (Brick 2021, ProjectHaystack 2017). By analyzing these schemes, it can be stated that they focus on technical specifications so that various services of FM cannot be conducted by using only one of these schemes (e.g. cleaning due to the missing of various relevant geometric and equipment details). Furthermore, these schemes do not depict the whole lifecycle of a building, so that the integration of FM during the planning and construction stage is missing. As mentioned before, first scientific and practical approaches to integrating databases and additional ontologies with open standards have been investigated. However, due to frequent changes in service providers, software systems, or building owners, FM must store all data processed throughout the lifecycle using an open and lifecycle-orientated standard.

Moreover, an open standard should allow to store all data in one file format so that only one file needs to be exchanged between service providers and owners. That means that data loss and expenses for proprietary data formats can be avoided. Lastly, it is necessary that all FM tasks could be conducted by using the data, which are made available via an open data exchange format. Therefore, it is crucial to integrate the data into an object-oriented digital building model with an associated data exchange format by using BIM.

3 Course of Investigation

The use of BIM over the entire life cycle, and especially in FM, is steadily increasing (Falcão et al. 2021). BIM represents a method that operates over the entire life cycle and links different building models to exchange data between the technical participants in real-time and based on defined data standards (Borrmann et al. 2015, van Treeck et al. 2016, Bartels 2020). To enable data exchange, it is necessary to investigate open data exchange formats for integrating sensor data. The positive effects of using BIM become visible only by using open exchange formats, e.g., standardized, and open interface data exchange formats. This concept is called Open-BIM and avoids data loss while exchanging data between different software systems (Schiller & Faschingbauer 2016, Rajabifard et al. 2019, Jiang et al. 2019). The IFC standard currently forms an essential basis for Open BIM (Ha-Minh et al. 2020).

4 Approach for Integration of Sensor Technology in IFC

For investigating open data exchange formats on the applicability for FM, data required for the demand-driven provision of services in FM is analyzed. A categorization of the required data into static data and dynamic data is conducted. Then, the IFC standard is analyzed for the mapping of static and dynamic data. For data that is not linkable with the current IFC standard, new data sets, so-called PropertySets (PSets) are defined based on the data requirements of FM. Finally, solution approaches are shown and examined for possible restrictions.

4.1 Analysis of FM tasks

The main challenges faced by FM participants are demand-driven data collection, acquisition, and delivery (Matarneh et al. 2019). Therefore, standards and guidelines of the German Facility Management Association (GEFMA) or the German Institute for Standardization (Deutsches Institut für Normung, DIN) considering data relevant to FM exist, e.g. standards of GEFMA 100-2 or GEFMA 540. Based solely on the range of FM processes defined by GEFMA, an amount of 335 requirements for the operative provision of services exists. The data basis for these processes are static data and dynamic data with respective subcategories (GEFMA 2013). Fig. 2 visualizes the relevant and categorized data for service provision.

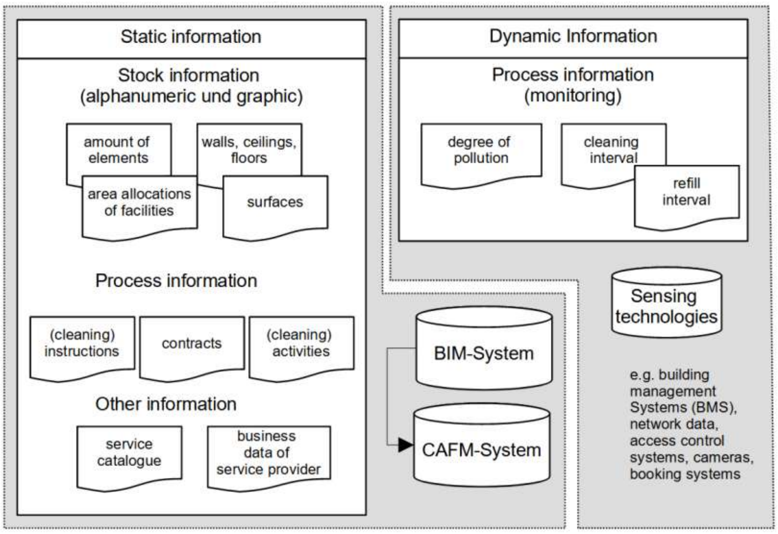

Fig. 2: Static and dynamic data for provision of services in FM

An examination of the relevant DIN standards and GEFMA guidelines shows the minimum of required data for the provision of services in FM:

- Facilities affected by the service provision (stock data)
- Area allocations of the facilities (e. g., floor-wing-room) (stock data)
- Service provider of the service provision (order data)

- Activity descriptions of the facility service to be provided (order data)
- Interval or time of service provision (condition data)
- Documents for supplementing the performance of services, e.g., execution certificates, acceptance protocols, or defect documentation (order data).

A BIM-based mode of operation enables an open transfer of the data mentioned above over the complete life cycle of a building. For example, the technical-geometric data from the BIM-based IT systems of planning and construction can be transferred automatically and linked with the organizational-commercial data from the FM systems (e.g. CAFM, ERP, or IWMS).

4.2 Analysis of the mapping possibility in open data exchange format IFC

This paper investigates the open exchange of sensor data by using the BIM method. In this context, the respective sensor types generate dynamic data for demand-oriented service provision in FM that consist of condition and consumption data. The measured variables are transferred to the IT systems of the FM for analysis and monitoring purposes. By defining rules (algorithms) for service provision, conditions in buildings can be analyzed based on current sensor readings and used to initiate service provision. The required algorithms put the generated sensor data into the relation of defined limit values. By reaching limit values, the demand of service provision is proofed.

Data generated by sensors is processed and stored in the IT systems of the FM. To avoid data loss, e.g., due to a change of the service providers, by a change of software systems, or by unstructured data storage, it is necessary to use open data exchange formats. The Industry Foundation Classes (IFC), standardized in ISO 16739, have become the established standard for data exchange within the BIM method (Baldwin 2019, Nawari 2018, Ha-Minh *et al.* 2020). The goal of IFC is to enable open data exchange between technical stakeholders throughout the whole lifecycle of a building (Wu 2017).

Other data formats for FM based on IFC, such as the Construction Operations Building Information Exchange (COBie) data format, transfer static data from the planning and construction phase to FM (East & Jackson 2016). COBie is an IFC-based specification developed by buildingSMART that explicitly defines building and equipment data transfer to the operator. Although all disciplines involved in a building life cycle can use and edit these spreadsheets, the COBie standard does not integrate dynamic data. COBie provides planning and execution data of buildings and technical equipment but does not include FM service delivery data (Bartels 2020). Therefore, it is necessary to take a closer look at IFC itself.

Section 4.1 identified the relevant static and dynamic data for FM. The static and dynamic data for FM, identified in section 4.1, are examined for representability in the open standard data exchange format IFC4. In May 2021, IFC4 includes 776 different entities (buildingSMART 2020). In IFC, an entity describes a concept for typifying and describing the structure and behavior of similar objects. (Borrmann *et al.* 2015) In addition, there are 418 PSets in IFC4, which combine attributes for a specific purpose (Borrmann *et al.* 2015, buildingSMART 2020). Many entities and PSets exist in IFC, focusing on the description of architecture and technology and forming the basis of the definition of as-built data of the building usage phase (Bartels 2020). An investigation on FM-interoperability in IFC4 shows that the current IFC standard does not support the representation of dynamic data for demand-oriented service provision. To represent dynamic FM data in IFC4, various attributes of individual IFC4 entities must first be connected.Implementation of FM processes in IFC.

Since IFC4 currently does not offer mapping sensor-based FM processes, extending the schema to ensure a lifecycle-oriented data exchange is necessary. For this purpose, a proposal for the class IfcSensor is presented below, intended to capture sensor-based process data. This IFC class enables a clear and understandable assignment of the data. The first step is to examine which general attributes of IfcSensor are directly related to service provision. The attributes GlobalId, author, name, description, and object type, are general attributes for the description of the (sensor) component. An immediate context to FM processes provision of services in FM does not exist. The general attributes represent the sensor identification and its physical description in a digital building model. Nevertheless, the location of the sensors, which IfcObject Placement represents, directly relates to the service provision. The physical location of a sensor implements a measurement environment.

An example are sensors for detecting the number of people frequenting an area. The identified amount of people constitutes the basis for decision-making on cleaning floor areas. If the sensor under consideration detects the limited number of people defined in the rule, cleaning the floor surface is required. This shows that the sensor location affects FM service provision. A formal representation of the sensor placement and its measuring area has to be fixed in IFC4. Furthermore, it is necessary to consider the type of sensors represented by IfcPredefinedType, to determine the demand of a service provision already in the planning phase of a building. Fig. 3 illustrates the dependency of the sensor placement and the used sensor type in dependency of the FM service provision. On the left side, the IFC class of sensors is shown, in which FM requirements are to be implemented. Influencing FM factors for the ground inclination are e.g. the weather and the number of people passing. While the IFC hierarchy can cover the building area to be cleaned, the influencing FM requirements have to be covered by suitable sensors. Service provision activities, e.g., cleaning and maintenance services, are categorized as events (IfcEvent). The sensors required to determine the measured values of a rule for identifying the demand of a service provision are attached to IfcEvent. PSets via IfcHasProperties assign the rules and rule types to the sensors. In turn, the sensors under consideration have properties through which the limits and rule types are determined for capturing the demand.

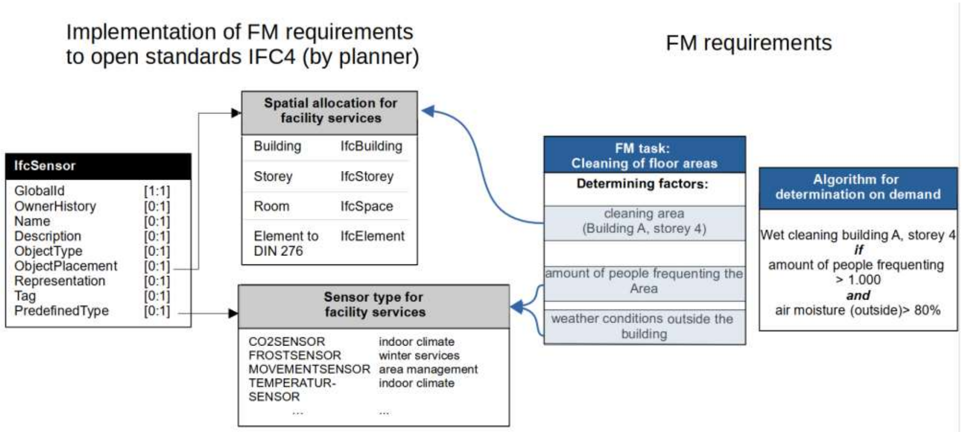

Fig. 3: Dependence of general attributes IfcSensor to provision of services in FM

In practice, the defined rules with their limit values and the control types are interdependent.

4.3 Application of IfcSensor

Fig. 4 shows an example of the IFC link for determining the need for cleaning floor surfaces using the IfcSensor entity. The boxes symbolize IFC classes and relationships between each other. Multiple links between different classes are required to display the event “floor cleaning” in IFC, though only the minimum linking entity of required IFC4 entities for acquiring service demand is shown. Only two sensor types (sensor for determining the number of people passing an area and sensor for determining the relative humidity) are considered, as shown on the right side of Fig. 4. However, the number of sensors used for detecting demands of FM service delivery is much higher. IFC allows the mapping of thresholds and control types as PSets, but does not offer the possibility to set the thresholds and control types to each other. Determining the demand for service delivery assigns a consideration of all physical sensors that determine the demand of service provision to the elements and facilities affected by the service provision.

Consequently, a multidimensional and complex relationship between building elements, sensors, and sensor data arises that does not include any runtime data. Proprietary systems must then first access the IFC construct again.

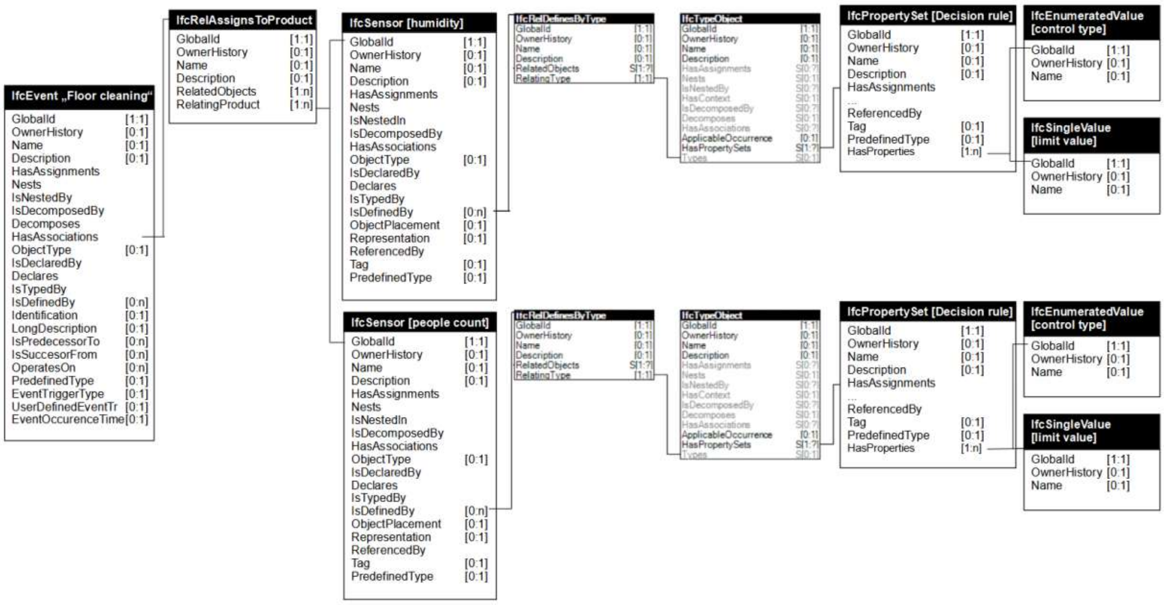

Fig. 4: Exemplary application of IfcSensor for determining the cleaning requirement

As can be seen, IFC focuses primarily on the geometric, supply-related, and process-related mapping of a building. In particular demand-oriented service provision, the mapping of dynamic service provision is only possible in IFC via many links. Therefore, IFC is not yet capable of capturing dynamic parameters of BMS and sensors. Linking geometric classes with process-oriented classes is a significant challenge.

5 Recommendation for further development

The integration of dynamic data in open data exchange formats is crucial for FM, because proprietary systems create a dependency on vendors and data platform providers, what leads to data loss, inefficiency and high effort with every change. Therefore, a further development of IFC is necessary, e.g. by mapping parameters relevant for demand-oriented FM service provision (e.g. limit values and control types) in IFC as static data in PSets. However, to enable demand determination and service assignment, the two parameters must be dynamically related to each other. Such a direct and dynamic relationship is not possible in IFC by now. The presented mapping only represents an intermediate result for the applicability of IFC in the context of demand-oriented service provision in FM.

Another requirement of FM is that a demand definition, e.g. the definition of limit values, should be flexible, so that the FM can react dynamically to external influences. In the case of large numbers of people or construction work and the resulting pollution inside a building, a change of limit values is possible. The limit values in the PSets can only be adjusted in the IFC for the respective sensor to which they are connected. Accordingly, the demand is only determined for one activity and not for several activities that belong to one decision and access the same sensors. This is not a fully comprehensive solution for the needs of FM, since it can be stated that the dynamics achieved by using the PSets are not sufficient for mapping IoT-based FM processes and should therefore not be the goal of open data formats.

Two solution approaches arise for the further development of IFC concerning integrating dynamic data, particularly sensor data. The first solution approach for further developing IFC for integrating sensor technology bases on a native extension of IFC. For this, the development of specified classes for FM is required, which enable the linking of sensor technology with FM processes. Thus, IFC must undergo an evolution from a static data format to a dynamic data format. Furthermore, it will be necessary to extend the domain layer about FM to map the FM processes in a new FM domain. This will enable an optimal combination of all classes and PSets necessary to provide services in FM. Therefore, further development of the IFC from a static to a dynamic data format is necessary for a demand-oriented service provision. This is realizable by a native further development of the IFC concerning the integration of sensor measurement data. The development of specified classes for FM, which enable a linking of sensor technology with FM processes, a dynamization of the data, and the integration of sensor measurement data in IFC classes, is necessary. The PSets developed for demand assessment would then be directly linkable to the classes for sensor technology. Furthermore, the domain layer must be extended to map the FM processes in a new FacilityManagementDomain. This enables an optimal combination of all classes and PSets that are necessary for FM service provision.

A second recommendation for further development aims to integrate sensor data into FM processes by linking IFC with other schemas, e.g., BRICK or ProjectHaystack. For FM, further developments of IFC are essential, as it allows project participants to access and using current sensor data for respective disciplines. In addition, it is necessary for FM to continuously record both static and dynamic data in a digital building model to ensure cross-lifecycle building operation. This enables the FM to ensure that all data is available in a uniform and standardized data exchange format so that data loss between the individual lifecycle phases in the event of a software change or a change of service provider is avoided. If only static and no dynamic data can be exchanged via IFC, the use of another third-party system is required, which would have to access standardized IFC data and proprietary measurement data. A dynamic IFC class, in which measured value data can be stored and exchanged, could allow evaluations and thus FM requirements assessments to be carried out wholly based on an open data exchange format.

Bibliography

Anjomshoaa, A.& Curry, E. (2020): Interspace Machine Learning in Smart Environments. In: Machine learning and knowledge extraction - International Cross-Domain Conference, CD-MAKE 2020, Dublin, Ireland, August 25-28, 2020, Proceedings. Cham, Switzerland: Springer, 535-549.

Atkin, B. & Brooks, A. (2015): *Total facility management.* 4th ed. Chichester, West Sussex: John Wiley & Sons Inc.

Atta, N. & Talamo, C. (2020): Digital Transformation in Facility Management (FM). IoT and Big Data for Service Innovation. In: *Digital Transformation of the Design, Construction and Management Processes of the Built Environment*, Cham: Springer International Publishing, 267-278.

Baldwin, M. (2019): *The BIM Manager. Practical Guide to BIM Project Management*, 2nd ed., Berlin: Beuth Verlag.

Bartels, N. (2020): *Strukturmodell zum Datenaustausch im Facility Management*, Wiesbaden: Springer Vieweg.

Behaneck, M. (2018): Industry 4.0 on the construction site? Why the digital (r)evolution in construction also affects FM. In: *Facility Management* 2. Available: https://www.facility-management.de/artikel/fm_Industrie_4.0_auf_der_Baustelle__3135159.html.

Borrmann, A., König, M., Koch, C., Beetz, J. (2015): *Building Information Modeling. Technologische Grundlagen und industrielle Praxis*, Wiesbaden: Springer Fachmedien Wiesbaden (VDI Book).

Brick (2021): *Brick. A uniform metadata schema for buildings*. Available: https://brickschema.org/, 23.03.2021.

buildingSMART (2020): *Industry Foundation Classes 4.0.2.1. version 4.0 - Addendum 2 - Technical Corrigendum 1*. Available: https://standards.buildingsmart.org/IFC/RELEASE/IFC4/ADD2_TC1/HTML/, 15/03/2021.

GEFMA 400, 2013: Computer Aided Facility Management CAFM.

Desogus, G., Quaquero E., Rubiu, G., Gatto, G., Perra, C. (2021): BIM and IoT Sensors Integration: A Framework for Consumption and Indoor Conditions Data Monitoring of Existing Buildings. In: *Sustainability* 13, 1-22.

East, E. W. & Jackson, R. (2016): *Delivering construction-operations building information exchange (CoBie) in GRAphisoft ARCHICAD*, Parkview Drive, Mahomet, IL: Prairie Sky Consulting LLC.

Edirisinghe, R. & Woo, J. (2021): BIM-based performance monitoring for smart building management. In: *Facilities* 1, 19-35.

GEFMA 100-1, 2004: Facility Management.

Falcão S., Maria J., Couto, P. (2021): Facility and Asset Management on BIM Methodology. In: *Sustainability and Automation in Smart Constructions*. Cham: Springer International Publishing, 75-79.

Fassl, A. (2020), Building Information Modeling (BIM) als Werkzeug im Bereich des kleinteiligen Baumanagements, TU Wien.

Gaida, S., Kastner, W., Preindl, T., Montazer, M., Suter, G., Shadrina, A., Blöchle, M. and Schiefer, C. (2020), *Building Information Modeling for Building Energy Management Systems BIM4BEMS*, Wien.

Gerrits, P. & Pilling, A. (2021): *Das neue Bauen mit BIM und Lean. Praxisbeispiel eines mittelständischen Bauprojekts der öffentlichen Hand*, Berlin: Beuth-Verlag.

Ha-Minh, C., van Dao, D., Benboudjema, F., Derrible, S., Huynh, D. V. K., Tang, A. M. (2020): CIGOS 2019, Innovation for Sustainable Infrastructure. *Proceedings of the 5th International Conference on Geotechnics, Civil Engineering Works and Structures*, Singapore: Springer Singapore.

Hirschner, J., Hahr, H., Kleinschrot, K. (2018): *Facility Management im Hochbau. Grundlagen für Studium und Praxis*, 2nd ed., Wiesbaden: Springer Vieweg.

Jiang, S., Jiang, L., Han, Y., Wu, Z., Wang, N. (2019): OpenBIM: An Enabling Solution for Information Interoperability. In: *Applied Sciences* 9, 35-58.

Kaiser, C., Nusser, J., Schrammel, F. (2018): *Praxishandbuch Facility Management*, Wiesbaden: Springer Vieweg.

Kazado, D., Kavgic, M., Eskicioglu, R. (2019): Integrating Building Information Modeling (BIM) and sensor technology for Facility Management. In: *Journal of Information Technology in Construction* 24, 440-458.

Keady, R. (2013): *Guide to equipment inventories. Standards, strategies and best practices for owners and facility managers*, Hoboken: Wiley.

Kummert, K., May, M., Pelzeter, A. (2013): *Nachhaltiges Facility Management*, Berlin, Heidelberg: Springer.

Lu, Q., Xie, X., Parlikad, A. K., Schooling, J. M. (2020): Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. In: *Automation in Construction* 118, 103277.

Matarneh, S. T., Danso-Amoako, M., Al-Bizri, S. , Gaterell, M. , Matarneh, R. T. (2019): BIM for FM. In: *Facilities* 5/6, 378-394.

May, M. (2018): *CAFM Handbuch. Digitalisierung im Facility Management erfolgreich einsetzen*, 4th ed., Wiesbaden: Springer.

Nävy, J. (2000): *Facility Management. Grundlagen, Computerunterstützung, Systemeinführung, Anwendungsbeispiele,* 2nd ed. Berlin, Heidelberg: Springer.

Nävy, J. (2007): IT Trends. Integrated Workplace Management Systems. In: *The Facility Manager* 4, 30-35.

Nävy, J. (2018): *Facility Management. Grundlagen, Computerunterstützung, Systemeinführung, Anwendungsbeispiele,* 5th ed., Berlin: Springer.

Nawari, N. O. (2018): *Building information modeling. Automated code checking and compliance processes*, Boca Raton, FL: CRC Press.

Otto, J. & Bartels, N. (2018): Integration von FM-Prozessdaten in ein digitales Gebäudemodell. In: *Bautechnik* (12), 823-831.

ProjectHaystack (2017): *Working Group. BIM/Haystack Working Group. Forum*, Available: https://project-haystack.org/forum/topic/530, 23.03.2021.

Rajabifard, A., Atazadeh, B., Kalantari, M. (2019): *BIM and urban land administration*, Boca Raton, FL: CRC Press / Taylor & Francis Group.

Reddy, K. P. (2013): *BIM for building owners and developers. Making a business case for using bim on projects*, Hoboken, N.J.: Wiley.

Sanz, R., Alvarez, S., Valmaseda, C., Rovas, D.V. (2018): Automatic development of Building Automation Control Network (BACN) using IFC4-based BIM models. In: *eWork and eBusiness in Architecture, Engineering and Construction*, Proceedings, London: CRC Press, 223-230.

Schawel, C. & Billing, F. (2012): Facility management. In: *Top 100 management tools*, Wiesbaden: Gabler Verlag, 102-104.

Schiller, K. & Faschingbauer, G. (2016): *Die BIM-Anwendung der DIN SPEC 91400*, Berlin: Beuth.

Talamo, C. & Atta, N. (2019): *Invitations to Tender for Facility Management Services. Process Mapping, Service Specifications and Innovative Scenarios*, Cham: Springer International Publishing.

Teicholz, E. (2012): *Technology for facility managers. The impact of cutting-edge technology on facility management*, Hoboken, NJ: Wiley.

Teicholz, P. M. (2013): *BIM for facility managers*, Hoboken, NJ: Wiley.

van Sprang, H. (2021): *Introduction to Facility Management*, London: Rouledge.

van Treeck, C., Elixmann, R., Rudat, K., Hiller, S., Herkel, S., Berger, M. (2016): *Gebäude.Technik.Digital*, Wiesbaden: Springer Vieweg.

Wu, P. (2017): *Integrated building information modeling*, Sharjah: Bentham Science.