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RATEWORKSPACE: BIM INTEGRATED POST-OCCUPANCY EVALUATION SYSTEM FOR OFFICE BUILDINGS

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SUMMARY: *The feedback obtained from occupants regarding their comfort needs and performance of buildings is critical for assessing occupant satisfaction, identifying the operation and maintenance (O&M) issues in time and for improving resource efficiency in buildings. Current facility management (FM) systems and occupant feedback collection practices, however, have limitations in supporting effective decision-making in FM, as they lack the necessary contextual data related to the occupant feedback (e.g., building geometry, systems, elements). Building Information Modeling (BIM)-enabled FM systems are used for combining different types of FM information with building models; however, occupant feedback is still not effectively utilized in FM since it is not integrated with BIM. In this study, a BIM integrated post-occupancy evaluation system prototype is developed for: (1) collecting occupant feedback along with the contextual information related to the feedback items in a structured way, and (2) presenting this information as integrated with BIM to the facility managers. This enables conducting spatio-temporal queries and supports effective decision-making by visualizing the collected feedback. The prototype was designed by using qualitative shadowing with FM teams to identify information needs and use case analysis to determine how contextual data integrated with BIM could be collected from office occupants who are non-technical persons with limited information on building models. This paper identifies the FM query categories that are required to process the occupant feedback and describes the RateWorkSpace prototype developed for office buildings. The deployment of the prototype in a real-world office demonstrates that the proposed system is applicable, practical, usable, and that real-time building performance data can be both collected and analysed with the developed system. This has the potential to increase the effectiveness of the FM and O&M processes, and help to create office spaces with optimized energy use and occupant comfort that also supports occupant well-being and productivity.*

KEYWORDS: *facility management, occupant feedback, post-occupancy evaluation (POE), building information modeling (BIM), office buildings, use case analysis.*

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1. INTRODUCTION

Occupants are considered the most reliable source of information about their comfort needs (Jazizadeh et al, 2014, Frontczak et al, 2012) and occupant feedback is as important as the sensor data for evaluating the performance of facilities (Azar and Menassa, 2016, Li et al, 2018) since automated controls often fail to meet occupant needs (Luna-Navarro et al, 2021). It has been widely recognized that increasing occupants' control over their environment improves occupant comfort (Andargie and Azar, 2019). However, the role of building occupants has not been sufficiently considered to date (Kjærgaard et al, 2020), and current systems mostly provide conditions based on standards or mean preference values resulting in decreased occupant satisfaction (Park et al, 2019). Occupant satisfaction is considered a key performance indicator (KPI) in facility management (FM) along with maintenance efficiency, cost to operate, labor hours spent, and system availability (Lavy et al, 2014). Occupant feedback is the primary tool for assessing occupant satisfaction, which is also a significant factor in employee well-being, cognitive functions, and productivity (Korkmaz et al, 2010, Wang et al, 2021, Mansor and Sheau-Ting, 2020, Sun et al, 2020), as well as for determining the actual performance of the building for comparing it to its design performance (Bordass, 2003). Instant occupant feedback helps to diagnose operation and maintenance (O&M) issues rapidly (e.g., overheating, repair needs), and it often results in saving resources (e.g., energy, building materials) (Way and Bordass, 2005, Han et al, 2019). Moreover, it assists the decision-makers in adjusting set points to optimize energy use and comfort (Schott et al, 2012) as well as in identifying future needs related to renovations and retrofitting (Coates et al, 2012, Woo and Menassa, 2014). Occupant feedback is also an indispensable part of the occupant-centric controls (OCC) approach, which focuses on adapting building controls to occupant preferences and can simultaneously achieve higher occupant satisfaction and energy savings up to 60% (Park et al, 2019), as it is evident that occupants have an important impact on building energy performance (O'Brien et al, 2020).

Existing FM systems fail to collect and process occupant feedback in a structured way. Lack of adequate systems that respond to and interact with occupants does not allow for a holistic analysis of occupant environmental perception involving several domains, which are location-specific and transient; hence there is a need for interfaces to capture this information with high granularity in both space and time (Luna-Navarro et al, 2021). In the current practice, occupant feedback/complaints related to a building component or space are mostly collected over the phone or via emails. This results in a large amount of manual data input and processing, which is inefficient and prone to error (Shalabi and Turkan, 2016) and difficulties in interpreting occupant data to support effective decision-making in FM (Cao et al, 2014). An effective way to collect occupant feedback is using Post-Occupancy Evaluation (POE) tools, which are surveys performed periodically to measure occupant satisfaction related to the performance of the building (Zagreus et al, 2004). However, the main limitation of the POE tools is that they mostly focus on the overall occupant satisfaction rather than specific issues observed in the buildings; besides they lack vital contextual information (e.g., building geometry, systems, and elements) that is required by the decision-makers to effectively utilize the feedback in FM. Moreover, the information is not gathered continuously (Jazizadeh et al, 2011) and this hinders instant response to the discomfort of the occupants. Lassen et al (2021) also concluded that collecting continuous subjective occupant feedback can gather crucial knowledge, help close the performance gaps, and empower holistic decision-making in the post occupancy phase. As a result of a detailed analysis on the state of the art and practice of POE, Li et al (2018) suggested that a more effective strategy would be to have a detailed, continuing, occupant-oriented POE approach, which can also provide more vivid visualization of the results integrated with other FM information.

Recent studies suggest BIM, which contains rich geometric (e.g., dimensions), topological (e.g., connections), and semantic (e.g., material properties) information of a building (Nepal et al, 2012), to be used as a platform for managing the FM information via BIM-enabled FM systems, where this information is integrated with 3D building elements to enable querying, visualizing, and locating components rapidly (Becerik-Gerber et al, 2012, Motawa and Almarshad, 2013, Motamedi et al, 2014, Ilter and Ergen, 2015, Pishdad-Bozorgi, 2018, Chen et al, 2019). Visualizing FM information can lead to new insights, more efficient decision-making, and improve problem-solving capabilities (Akcamete et al, 2011, Gocer et al, 2015). In order to use building models in the FM phase effectively, it is imperative to integrate the required FM information with BIM (Matarneh et al, 2019); however, integration of occupant feedback information with BIM is lacking in the previous studies.

The main objective of this study is to develop a BIM integrated post-occupancy evaluation system that (1) instantly collects occupant feedback along with the contextual information related to the feedback items in a structured way and (2) presents it to the facility managers as integrated with the building model so as to enable spatio-temporal queries and visualization of the collected feedback to support effective decision-making in FM. An important point is that occupants do not have the technical background and thus, a simple and user-friendly system is required to enable them to enter their feedback effectively. To achieve this objective, a prototype called RateWorkSpace was developed for office buildings and tested in an office space located at a university campus. This paper presents the FM query categories which are required to utilize occupant feedback, further presents the system architecture and graphical user interfaces (GUIs) as developed in this study with a user-centered design approach, and finally presents the validation of the prototype in a real-world office via a case study.

2. LITERATURE REVIEW

2.1 Previous studies on occupant feedback collection

Occupant feedback is an important data source in FM studies for performing O&M activities, since the occupants continuously experience building-related problems (Zagreus et al, 2004, Carbonari et al, 2018). Current FM systems, however, do not collect and process occupant data (i.e., feedback/complaints) effectively (Han et al, 2019). A widely adopted practice is using telephone calls, emails, or instant messages (Inyim et al, 2016, Pritoni et al, 2017), allowing data collection in an almost real-time manner. On the other hand, these methods generate unstructured and often incomplete data, since the feedback is transmitted verbally or in text format, and this results in a large amount of manual data input and processing (Shalabi and Turkan, 2017). Koch et al (2014) reported a loss of time and labor due to the manual processes performed for accessing, sorting, grouping, and selecting the data in FM activities. The other conventional practice is using the POE tools for periodically collecting occupant feedback. Since POE tools aim to measure the overall occupant satisfaction, the contextual details that are required by facility managers to identify specific problems and their root causes in buildings are not collected (Way and Bordass, 2005, Leaman, 2011, Gocer et al, 2015, Li et al, 2018). Recent studies also criticized POE tools for failing to collect occupant feedback in a real-time manner (Jazizadeh et al, 2011, Li et al, 2018) and suggested continuous data collection to capture the effect of environmental factors that vary with time (Choi and Lee, 2018). Moreover, both practices do not allow evaluating the occupant feedback in relation to other important building information (i.e., building spaces, elements, time) and therefore cannot support effective decision-making in FM (Jazizadeh et al, 2011, Cao et al, 2014), although it is evident in the literature that operation of responsive and resource-efficient buildings requires high-resolution data on building performance including location, time and the associated occupant response (Luna-Navarro et al, 2021).

The review of the previously developed systems that collect occupant feedback on a continuous basis shows that most of these systems focus on one particular aspect of occupant feedback data (e.g., thermal comfort, energy use) and that there is a lack of a comprehensive study which collects occupant feedback about all building-related issues. These studies also did not aim for collecting the related contextual data that is required to describe and formalize the feedback. In several studies, for instance, data about the occupant's thermal comfort or thermal interval preferences were collected via mobile applications to find the optimum temperature set point of the air conditioning systems (Pritoni et al, 2017, Gupta et al, 2016, Ghahramani et al, 2015, Jazizadeh et al, 2014). In another study, instead of occupant feedback, occupants' energy usage data were collected with location information (Inyim et al, 2016). Researchers also used occupant feedback data to make renovation decisions using virtual environments to decorate building spaces (Heydarian and Becerik-Gerber, 2017, Du et al, 2018). In other studies, maintenance requests enriched with sensor data were used to create work orders by adding property sets as text data; however, it should be noted that these requests are not structured and do not include contextual data (Shalabi and Turkan, 2017, Chen et al, 2018). Some platforms were developed to combine FM systems with occupant feedback, however, they were not integrated with BIM (Schott et al, 2012). It is agreed in the literature that visualization can be a powerful tool for communicating large volumes of data regarding the environmental conditions in buildings, and visualization in a building model context allows for fast and effective comprehension of building-related data with greater accuracy (Patlakas et al, 2017, Li et al, 2018). To achieve this, many researchers pointed out the need to represent occupant data in the BIM context (Coates et al, 2012, Gocer et al, 2015, Shoolestani et al, 2015, Patlakas et al, 2017).

2.2 Integration of occupant feedback with BIM

Recent studies emphasized that the required FM information for O&M activities is collected and stored in multiple platforms and facility managers have difficulties in accessing and evaluating this scattered information (Motawa and Almarshad, 2013, Pishdad-Bozorgi, 2018). Many researchers recommend BIM as a suitable tool to provide a single platform for storing and collecting the FM information (Becerik-Gerber et al, 2012, Motawa and Almarshad, 2013, Motamedi et al, 2014, Ilter and Ergen, 2015, Pishdad-Bozorgi, 2018). So far, the focus of the previous efforts has been on the use of BIM in the FM handover processes of projects. For instance, researchers studied identifying the BIM data exchange needs during the FM handover phase (Becerik-Gerber et al, 2012, Cavka et al, 2017, Yang and Ergan, 2017, Zadeh et al, 2017, Thabet and Lucas, 2017). Also, an information exchange standard, called Construction Operation Building information exchange (COBie), was developed (East, 2007) and adopted by the buildingSMART alliance for storing maintenance information in BIM in a structured manner in the design and construction phases and for transferring the related information to the facility manager during the handover process (Codinhoto et al, 2013). Both widely used FM software packages in practice (i.e., EcoDomus, Dalux) and related academic studies in the literature have used the Industry Foundation Classes (IFC) schema for representing various FM information and for mapping the related data stored in FM systems to BIM (Shalabi and Turkan, 2017, Chen et al, 2018, Sadeghineko et al, 2019). Some types of O&M-related information have been formalized and integrated with BIM in previous studies. For example, sensor data (Kazado et al, 2019), O&M-related data collected with Radio Frequency Identification systems (Motamedi and Hammad, 2009, Suprabhas and Dib, 2017), change history of building components (Akcamete, 2011), maintenance inspections (Shalabi and Turkan, 2017), as-is condition of facilities (Hamledari et al, 2017), and plans for maintenance and work orders (Kim et al, 2018, Chen et al, 2018). Colour coding/mapping of building spaces in the building model based on average occupant satisfaction scores or the total number of feedback issues have also been presented (Hua et al, 2014, Gocer et al, 2015, Patlakas et al, 2017, Pin et al, 2018, Alavi et al, 2021). However, these studies do not allow for (1) representation of instances of occupant feedback in BIM by implementing them in IFC, or (2) integrating occupant feedback with the building contextual information (e.g., exact location, building elements), or (3) visualization of the spatio-temporal queries performed on the collected feedback to support effective decision-making in FM. Therefore, effective integration of occupant feedback information with BIM during the FM phase is currently missing in the previous studies. Since the occupant feedback information is not structured, it needs to be formalized to be represented in BIM in an integrated manner. Previous researchers commented on the difficulties experienced with unstructured data while trying to integrate FM information to BIM (Gerrish et al, 2017, Raghubar et al, 2017). Although the need for integrating occupant feedback with BIM has been highlighted by many researchers (Coates et al, 2012, Hua et al, 2014, Gocer et al, 2015, Shoolestani et al, 2015, Patlakas et al, 2017), it has been addressed for the first time in the proposed prototype presented in this paper by utilizing the previously developed semantic data model that formalizes occupant feedback information to implement it in the IFC schema (Ergen et al, 2021).

3. METHODOLOGY

To develop a BIM integrated post-occupancy evaluation system, this research study followed three steps: (1) determination of occupant feedback types, (2) formalization of occupant feedback information and implementation in the IFC schema, and (3) determination of the FM query categories for processing occupant feedback and development of the 'RateWorkSpace' prototype for utilizing occupant feedback in BIM-enabled FM (Fig. 1). In the first step, the authors have identified occupant feedback types by conducting a systematic literature review and evaluating the parameters used in the existing POE tools. A total of 5,000 occupant complaints that were received and the work orders which were generated in the FM phase were also analyzed in two office buildings hosting 3,000 occupants. A hierarchical structure of indicators was developed in focus group meetings with facility managers, which was then validated by structural equation modeling using the data collected from 308 office occupants (Tekce et al, 2020). The occupant feedback types (e.g., noise level, odor) identified in the first step were employed as the 'feedback list' used in the prototype, which assists the occupants in categorizing the issue being experienced in the building. In the second step, the properties and relationships of occupant feedback information were formalized in a semantic data model, which was implemented in the IFC schema by using the IfcPerformanceHistory and IfcAnnotation entities in the most recent IFC standard (IFC4.1) (Ergen et al, 2021). The semantic data model developed in the second step was used to define the 'contextual information items' (e.g., location, related element) to be collected by the prototype from the occupant. Also, the semantic data model of occupant feedback was used to represent the collected occupant feedback information in BIM as part of the prototype developed in the third step.

RESEARCH STEPS	RESEARCH ACTIVITY	METHODS USED	OUTPUT
Step 1 (presented in Tekce et al. 2020)	Determination of occupant feedback types	Structured review of literature and existing POE tools, analysis of 5000 occupant feedback recorded in two office buildings hosting 3,000 occupants and focus group meetings with facility managers	Occupant feedback list used in the prototype to assist the occupants in categorizing the issue being experienced in the building (e.g., noise level, odor)
		Validation by SEM using data collected from 308 office occupants	
Step 2 (presented in Ergen et al. 2021)	Formalization of occupant feedback information and implementation in the IFC schema	The properties and relationships of occupant feedback information formalized in a semantic data model and implemented in the IFC schema by using the IfcPerformanceHistory and IfcAnnotation entities	Contextual information items to be collected by the prototype (e.g., location, related element) and their representation in the IFC schema
Step 3 (current paper)	Determination of the FM query categories for processing occupant feedback	Qualitative shadowing with 2 FM teams managing 2 office buildings hosting 3,000 occupants for 4 days	Current procedures in processing occupant feedback
		Validation by in-depth interviews with the upper management of an international large scale facility management company	Query items needed by the facility managers to filter and sort a selected set of occupant feedback in the prototype (e.g., building space, building element, timespan) (Table1)
	Development of the system architecture of the prototype	Observations related to the shortcomings of the current practice during qualitative shadowing	Prototype elements and the information flow (Fig. 2 and 3)
		In-depth interviews with the facility managers on alternative approaches to designing the system architecture	
	Development of the use cases for collecting and processing occupant feedback	Analysis of the existing occupant complaints collected from the case study office	Eight use cases developed, three of them presented in the paper (e.g., food odor in the office, leaking tap in the toilet)
		In-depth interviews with the facility managers on how collected complaints should be processed	
	Development of the prototype GUIs	Storyboarding method was used by utilizing the developed use cases	GUIs of the prototype's occupant and FM modules (Fig. 5-10)
		User-centred design practice of HMIs was followed for occupants, who do not have technical background	
	Testing the prototype via a case study	Lab tests including indoor localization and functional tests	Revisions of the prototype as a result of the experience and feedback from occupants and facility managers
		Verification via using the prototype in practice in a real-world office for 3 weeks	
		Validation via usability questionnaires with 15 occupants and 7 facility managers	Usability, Applicability and Practicality scores of the prototype

FIG. 1: Methodology.

The third step presented in this paper concludes the research by identifying the FM query categories required to process occupant feedback as well as by developing the prototype and testing it in an office space located at a university campus via a case study. The determined FM query categories were employed as the information items used by the facility managers to filter and sort a selected set of occupant feedback (e.g., based on building space, building element, timespan) in the prototype. Also, the system architecture and use cases that were developed to create the GUIs of the prototype are presented in this paper. Finally, verification and validation of the prototype were performed in a real-world office environment. As a result of these three steps, a BIM integrated post-occupancy evaluation system has been developed that (1) instantly collects occupant feedback along with the contextual information related to the feedback items in a structured way, and (2) presents it to the facility managers integrated with the building model to enable spatio-temporal queries and visualization of the collected feedback to support effective decision-making in FM.

In identifying the FM query categories, the qualitative shadowing method and in-depth interviews were used to determine the information items required by the facility managers to effectively retrieve and utilize occupant feedback. Shadowing involves a researcher closely observing members of an organization and asking questions, which will prompt a running commentary from the persons being shadowed. This can provide unique insights into the day-to-day workings of professionals by virtue of its emphasis on the direct study of problems and actions in the real-world context (McDonald, 2005). In this part of the study, three FM teams comprising seven engineers with an average of 21 years of experience in FM and four technicians with an average of 13 years of experience in FM participated in the study. Two of the teams, who were responsible for the management of office buildings with 1,200 and 1,800 occupants respectively, participated in the shadowing process. The third team was representing the upper management of an international large-scale facility management company and in-depth interviews were performed with this team to validate the results of the shadowing exercise and to discuss the system needs. The upper management was represented by two members of the executive board and the director of facility managers. Earlier studies tackling the determination of information requirements (Kiziltas and Akinci, 2009, Becerik-Gerber et al, 2012, Akcay et al, 2017, Yang and Ergan, 2017) also utilized this well-established method of interviewing the respondents of similar sample size, who are performing the task being examined on a daily basis. Researchers analyzed the following aspects of FM during the shadowing process that took approximately four days: (1) current procedures that are adopted for processing occupant feedback, (2) how facility managers archive and later retrieve occupant feedback data, and (3) query items required to analyse feedback data instantly and over time. This analysis provided the list of FM query categories, which were integrated with the prototype.

The system architecture of the prototype was developed based on the shadowing exercise and on the in-depth interviews with the facility managers on alternative approaches to designing the system. In the next step, eight use cases were developed based on the existing occupant complaints (e.g., food odor in the office, leaking tap in the toilet) collected from the case study office and in-depth interviews were performed with the facility managers on how collected complaints should be processed. Use case development is very beneficial for capturing the processes and defining the requirements (Gregor et al, 2002, Rosenberg and Stephens, 2007) and has been used extensively in similar research tackling development of facility information management prototypes (Lucas et al, 2013). In the development of the GUIs, the storyboarding method was used by utilizing these use cases to tackle how an effective GUI could be designed to collect information from occupants, who do not have a technical background and how this information could be presented to facility managers in a visual format integrated with BIM. The storyboarding process integrates use cases and mock-up GUIs to assist users in discussing and verifying their demands from the prototype and provide the foundation for the design of the final user interfaces (Gregor et al, 2002). This strategy is central to the user-centered design practice of Human-Machine Interfaces (HMIs) (Quimby et al, 2014) to enable system users to provide feedback on potential GUIs. Three of the eight use cases are presented in this paper with the related GUIs to explain this process.

The proposed prototype was verified and validated through a case study. In the case study, 15 occupants in the office and seven FM team members, including managers and technicians, used the prototype in a real-world office context for three weeks and provided feedback on its performance via usability questionnaires. The questions were adapted from Usefulness, Satisfaction, Ease of Use (USE) (Lund, 2001) and System Usability Scale (SUS) (Brooke, 1996), which are based on Likert scales. These methods aim to get feedback from the users after interacting with a system or a product (Albertazzi et al, 2012) and have been used in studies from different domains to measure user satisfaction and usability of new systems (Hangli et al, 2020, Litvak and Kuflik, 2020).

4. SYSTEM ARCHITECTURE AND ELEMENTS

4.1 System architecture

As a result of the shadowing exercise, the main shortcomings in the current practice emerged as the lack of a procedure that will enable (1) thorough collection of the contextual information required to utilize different types of occupant feedback, (2) effective archiving as well as representation and visualisation of the collected feedback in the building models, and (3) querying the collected feedback based on categories that help to integrate feedback with the building elements to understand the root causes of the experienced issues (e.g., based on building space, building element). In-depth interviews with the facility managers on alternative approaches for designing the system resulted in the following needs: (1) a single platform/application for feedback collection rather than multiple platforms, as the latter will jeopardize the standardization of collected data and require manual processing, (2) providing options to show the retrieved feedback as statistical results or visualize them in the building model, and (3) simple GUIs to enable occupants (non-technical persons) and inexperienced FM personnel to interact with the system.

To address these needs, the proposed system architecture and GUIs were designed to store collected occupant feedback data in a database (Fig. 2a) and integrate it with the building model (Fig. 2b) in the quest to visualize and query the feedback data in BIM.

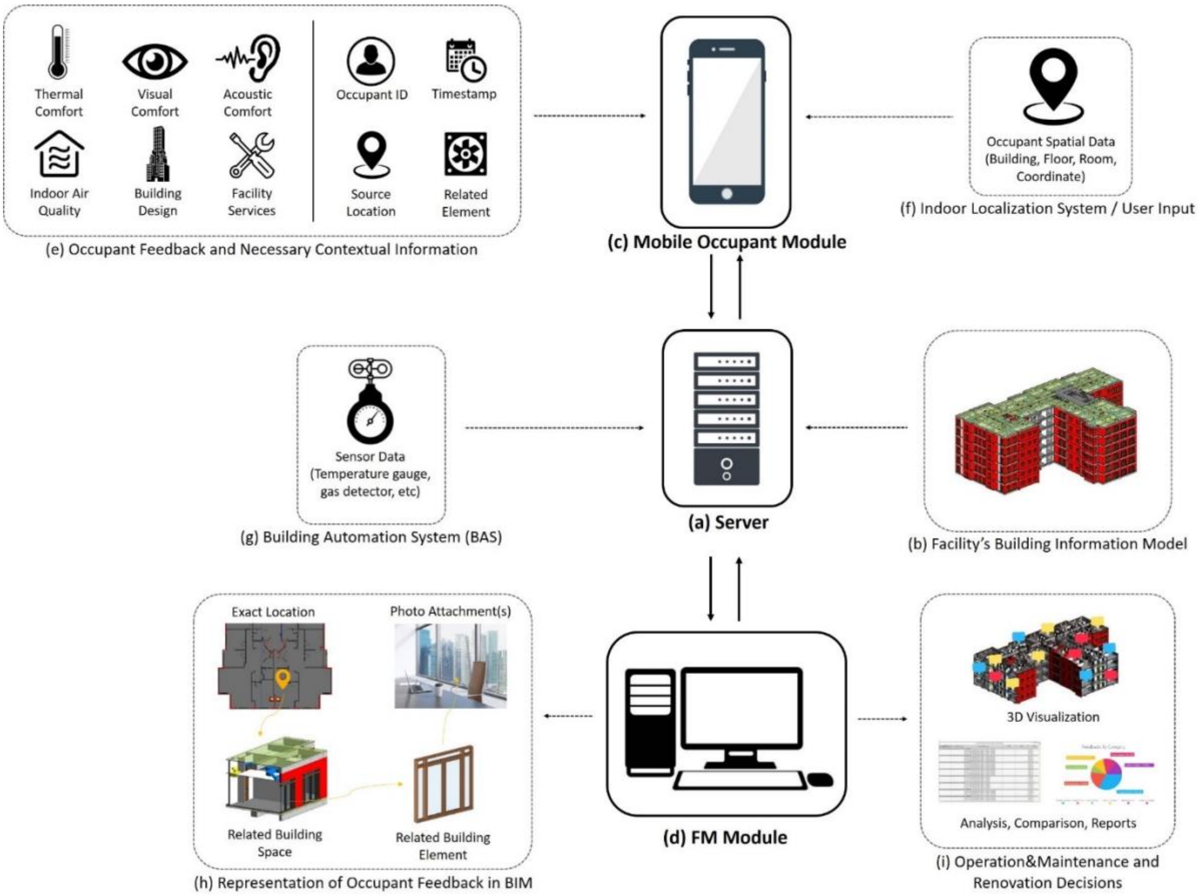

FIG. 2: System architecture.

The proposed system has two modules: (1) a mobile occupant module to collect the occupant feedback (Fig. 2c), and (2) a desktop FM module to view and query the feedback (Fig. 2d). The system collects two types of information/data: (1) occupant feedback/complaint information (Fig. 2e), which is categorized into 27 feedback types under six dimensions (i.e., thermal comfort, visual comfort, acoustic comfort, indoor air quality, building design, and facility services), along with the necessary contextual information related to the feedback (i.e., occupant/office name, feedback location, building element, source location, timestamp) and (2) occupant spatial data (Fig. 2f) including building, floor, room information or exact location of the occupant with coordinates, which is automatically collected via indoor localization system or entered by the user from a pre-determined list. These two data types are collected from the occupant via the occupant module (Fig. 2c). Sensor data (e.g., temperature, humidity), which were envisioned to be obtained from the building automation system (BAS) (Fig. 2g), are also used to enable comparisons and evaluations in relation to the occupant feedback where necessary. Feedback information is stored in the database as individual occupant feedback, and each occupant feedback item is represented in BIM in relation to the location of the occupant, as well as to the associated building elements/spaces in the model (Fig. 2h). The photo related to the feedback can also be viewed if it was attached by the occupant. The FM team can view, edit and query the occupant feedback that is associated with BIM via the prototype's FM module (Fig. 2d). Feedback lists and reports can be exported and graphs of filtered feedback data can be created via this module. In addition, queried feedback information can be visualized in the building model to improve problem-solving capabilities and for more effective O&M and renovation decisions (Fig. 2i). In the following sections, the main elements of the prototype are explained. It should be noted that integration with the BAS was not implemented in this study.

4.2 Occupant feedback types and spatial data

Occupant satisfaction indicators identified by the authors in Tekce et al (2020) were used as the occupant feedback types in the RateWorkSpace prototype to guide the occupants in categorizing the issue being experienced in the building. These are: (1) thermal comfort (temperature, radiant temperature, relative humidity, temperature variation, airflow); (2) indoor air quality (freshness of air/air quality, natural ventilation, odor); (3) acoustic comfort (noise levels, echo, acoustic privacy); (4) visual comfort (daylight, artificial light, glare, reflection, visual privacy, view from window); (5) building design (amount of space, layout, interior design, furniture, exterior design, vibration conditions); and (6) building services (personal control, usability of control devices, facility management/service quality, maintenance/repair).

The second input of the RateWorkSpace prototype is the occupant's spatial data including building, floor, room information, or exact location of the occupant with coordinates, which is automatically collected via the indoor localization system. Indoor localization technologies were analysed for their suitability to occupant feedback collection (Ergen et al, 2017). As a result, Bluetooth technology is utilized in the RateWorkSpace for localization of the occupants, due to its advantages of wide range of usage, low cost, and simple equipment needs (e.g., Beacons). Alternatively, the user can select his/her location from a list of rooms in the building.

4.3 Implementation of occupant data in the IFC schema for BIM integration

To integrate the collected occupant data with BIM, the authors have developed and presented a semantic data model that formalized occupant feedback information in a previous study (Ergen et al, 2021). The proposed semantic data model was implemented in the IFC schema, which is a non-proprietary building data model for storing and exchanging BIM data (buildingSMART, 2018). The occupant feedback properties and relationships identified as part of the semantic data model were represented in the latest IFC release (i.e., IFC4.1). To implement the semantic data model in the IFC schema, IfcPerformanceHistory entity was used to store machine-measured data (i.e., when data is obtained from BASs) or human-specified data (i.e., occupant feedback data), while IfcAnnotation entity was used in relation to the IfcPerformanceHistory entity for localization and visualization of the occupant feedback in the geometric model. The developed semantic data model is used to determine the 'contextual information items' (e.g., location, related element) to be collected by the prototype from the occupant for each type of feedback. Also, the collected occupant feedback information was represented in BIM by implementing the developed semantic data model in the IFC schema as part of the developed prototype.

4.4 FM query categories for occupant feedback

The collected occupant feedback information needs to be filtered and sorted effectively to be utilized in decision-making. The goal was to enable decision-makers to query the occupant feedback, which is integrated with BIM, based on certain categories in the RateWorkSpace prototype (e.g., querying feedback related to a certain element or space) for identifying spatio-temporal patterns of occupant feedback. To identify the required categories, query items used in the existing FM systems (e.g., computerized maintenance management systems) were evaluated in the shadowing process. However, these systems mostly include query categories related to maintenance history and work orders and do not include query categories to analyse occupant feedback data. In the shadowing exercise, researchers observed how facility managers prepare the work orders to fix the issues in the building and identified the query categories required to retrieve information from the occupant feedback records so as to support the work order preparation. Possible query categories were discussed with the facility managers during the shadowing exercise and the in-depth interviews. Facility managers reported that they need to query occupant feedback information to understand the feedback issue (i.e., feedback type, occupant), relate the feedback issue to the building (i.e., feedback location, related element, source location), group the feedback (i.e., root cause, priority), select appropriate technicians and follow-up on the feedback (i.e., related trade, status), plan work orders and maintenance activities (i.e., preferred date and time for action) and analyse the feedback trends over time (i.e., timestamp) in order to make effective decisions. Hence, the query categories used in the RateWorkSpace prototype were identified as follows and examples are presented in Table 1.

(1) Feedback Type: Collection of the feedback using a pre-determined list allows automatic determination of the feedback type in the system. To enable this, a hierarchical structure was developed based on occupant satisfaction parameters: 'feedback category' being the highest level (e.g., thermal comfort), 'feedback type' representing the mid-level (e.g., 'temperature' within thermal comfort), and 'feedback' being the lowest level (e.g. 'very cold' within temperature). Querying feedback type is needed to examine complaints about a certain issue (e.g., noise level).

(2) Occupant: This is the identification information of the person or unit in the building that sends the feedback to the system. Querying the related occupant is required to understand the satisfaction/complaints in separate units and also to communicate the process and results of the feedback.

(3) Feedback Location: User coordinates are needed to perform queries based on location to better understand the spatial relationships between the complaints and the building (e.g., accumulated complaint of 'glare' due to malfunctioning shades on a particular façade) or main service system connections to building elements receiving the complaints (e.g., 'dry air' complaints in several locations due to the same air handling unit).

(4) Related Element: Identification of the specific building element causing the problem decreases the time required to detect the problem. For example, a specific lighting fixture that is entered by the occupant is the 'related element' for `the noise coming from a lighting equipment' feedback. Querying historical feedback information based on element ID will contribute to making effective decisions in O&M, for example, as to whether repair or replace the element. Also, by performing queries based on building elements, facility manager can view and evaluate other information related to that element, that is stored in BIM such as geometrical data, maintenance history, or work orders.

(5) Source Location: The facility manager needs to know if there is a specific building space causing a problem in another location. For example, 'cafeteria' is the source location for food odor coming to the office from the cafeteria downstairs. Using this query item, spatial relations between the source location and the location that the problem is observed can be visualized in the building model.

(6) Timestamp/Preferred date and time for FM action: Querying feedback timestamp enables seasonal, monthly, weekly, daily trend analyses. Performing queries based on the 'preferred date and time for FM action' helps facility manager in planning work orders and maintenance activities.

(7) Feedback Root Cause: Assigning a root cause allows grouping the problems experienced in the building (e.g., inadequate capacity, breakdown) and make queries based on root causes.

(8) Feedback Priority: Prioritizing the feedback (e.g., low, medium, high, critical) allows more efficient use of resources and better management of occupant satisfaction and emergencies.

(9) Feedback Trade: Categorizing and querying occupant feedback according to the trade (carpentry, electrician, plumbing, cleaning) enables facility manager to select appropriate technicians to fix the problem and make better planning in FM personnel recruitment.

(10) Feedback Status: Assigning a status to each feedback (i.e., pending, approved, rejected, or completed) helps facility manager with following-up for the issues that occupants reported.

TABLE 1: FM query categories required to process occupant feedback in the RateWorkSpace prototype.

FM Query Categories	Examples of Query Category Values	
Feedback Category	Thermal Comfort	
	Building Design	
Feedback Type	Temperature	
	Amount of space	
Feedback	Very Cold	
	Insufficient storage area	
Occupant	Person	Mr. John Burrows
	ID	ID: 501171110
	Office Name	ABC Office
Feedback Location	Building	Workshop Building
	Floor	2nd Floor
	Room	Meeting Room
	Location	Longitude:29.272727362
		Latitude:42.7327273827
Related Element	IFC-GUID(*)	hfgrywd152734
	ID	Mech123456789
		Furn123456789
	Maintenance History	13.03.2018/ 14.30
	Manufacturer Information	XYZ Distributor
	Work Order History	Repair
		Replacement
Source Location	Building	Tower A
	Floor	Basement
	Room	Cafeteria
	Location	Longitude:29.272727362
		Latitude:42.7327273827
Timestamp / Preferred date and time for action	Year	2021
	Month	September
	Day	01.04.2021
	Hour	13:00
Root Cause	Inadequate Capacity	
	Breakdown	
Priority	Low	
	Medium	
	High	
	Critical	
Trade	Cleaning	
	Electrician	
	Plumbing	
Status	Pending	
	Approved	
	Completed	

(*) IFC-Globally Unique Identifier

The RateWorkSpace prototype provides an effective platform to collect and query the information items required to utilize the occupant feedback in office buildings. While feedback type, location, related element, source location, timestamp, and preferred date and time for action are entered by the occupant via the mobile occupant module; root cause, priority, trade, and status are assigned to the collected feedback by the facility managers via the FM module. The last four query categories were suggested by the facility managers in the validation process. These are similar to the query categories used in the existing FM systems and are included in the prototype for possible future integration of the prototype with existing FM systems. Also, 'preferred date and time for action' was suggested by the facility managers who participated in the case study. The FM team can make queries based on these items and visualize the retrieved feedback as statistics or in BIM.

5. PROTOTYPE INFORMATION FLOW AND DEVELOPMENT OF GUIS

This section describes the prototype information flow and explains the development of GUIs based on the use cases.

5.1 Prototype information flow

When an occupant observes an issue, the feedback can be sent to the system in five steps via the mobile occupant module. The feedback type is entered by searching or selecting it from a list of categorized feedback types (Fig. 3a). The location of the observed issue/occupant is either automatically detected by the indoor localization system, or the occupant selects it from the list of building spaces and/or manually pins the exact location (Fig. 3b). The occupant selects the related building element and/or related building space, which is the source of the problem, by using the 2D plan view (Fig. 3c). The time and date of the observed issue are recorded by the occupant module and if needed, the preferred FM action date and time are entered by the occupant (Fig. 3d). If there is a piece of additional information that the occupant wants to include, it can be manually entered. Finally, the occupant will confirm the entered information and send it to the facility manager (Fig. 3e). The feedback will be stored in the database hosted on a server, which is connected with the FM module.

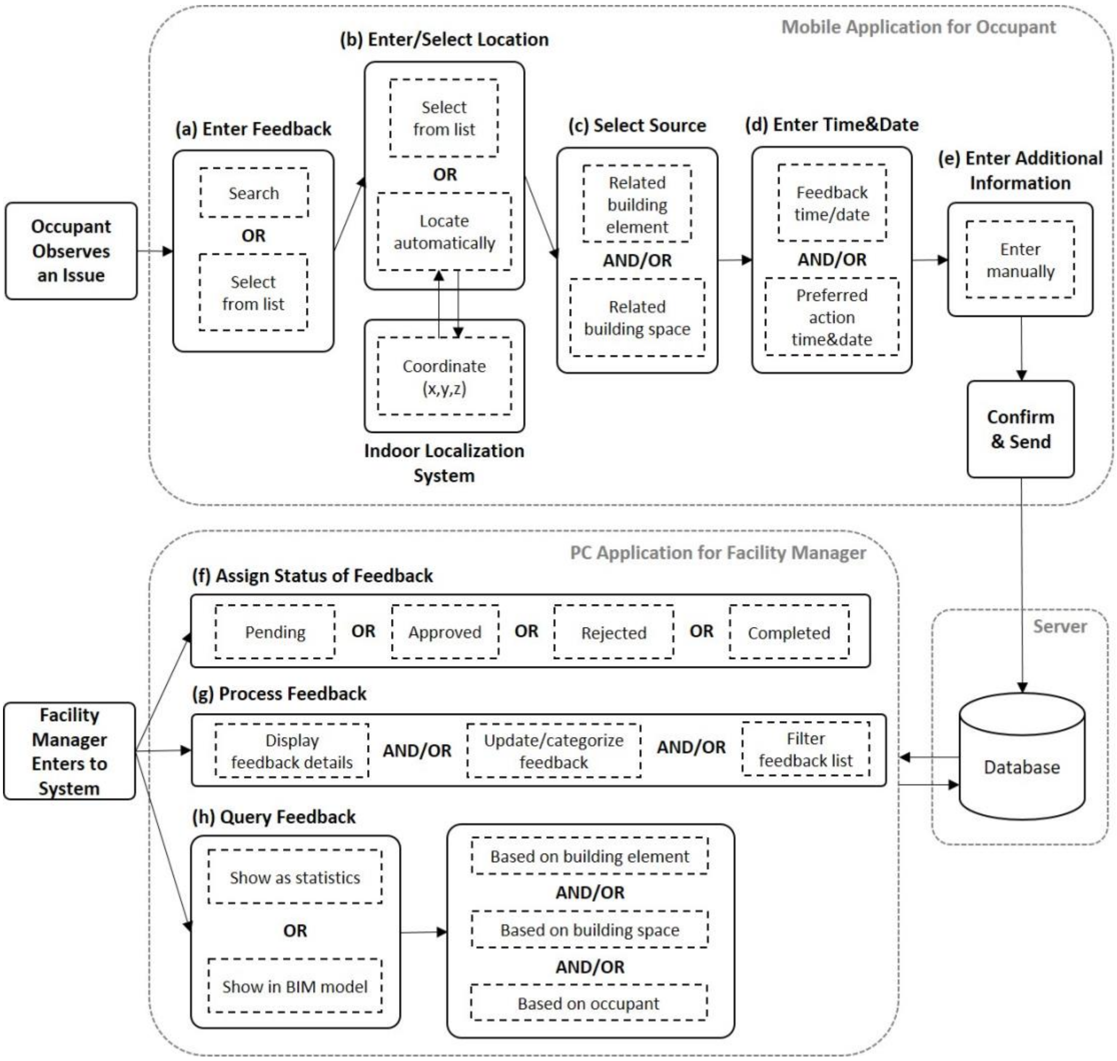

FIG. 3: Prototype information flow.

The FM module was developed as a desktop application to enhance usability. It is connected with the server and can access the occupant feedback stored in the database. The FM team checks the recently entered occupant feedback items to determine their status and enter it as "in progress" or "rejected". When the feedback issue is solved, its status is changed to 'completed' by the FM team (Fig. 3f). The FM team can display and update all the entered feedback and their details in this module (Fig. 3g). Also, the collected feedback can be queried according to the identified categories (e.g., feedback type, related building element). The FM module can show queried feedback as statistics or in the building model (Fig. 3h).

5.2 Development of the use cases and graphical user interfaces (GUIs)

This section provides technical information on the developed GUIs for both the occupant and FM modules and explain how these GUIs function. The main considerations in the design of the GUIs were: (1) how occupant feedback information could be collected most effectively from occupants with minimum steps while avoiding unstructured and incomplete data, (2) how contextual data integrated with BIM could be collected from office occupants who are non-technical persons with limited information on building models, (3) how collected feedback could be presented to the facility managers in both graphical and visual format, and queried by using the determined categories to improve problem-solving capabilities.

The case study office, where use cases were developed, is a 580 m2 mechanically ventilated incubation hub serving 60 occupants and located at a university campus. There are 40 desks located in 10 zones spreading on an open plan area, four office rooms, three meeting rooms, one seminar room, one workshop, one server room, one kitchen, and a hot desk area (Fig. 4a). The test case was chosen because an interior refurbishment was planned for the near future and the FM team wanted to analyse the current issues in the office in more detail. The use cases were developed based on the review of the existing occupant complaint database available in the case study office. In total, eight use cases were developed and storyboarding method was used to design the GUIs. Three of the use cases and the related GUIs are presented in the following sections to explain this process and illustrate the use of the prototype.

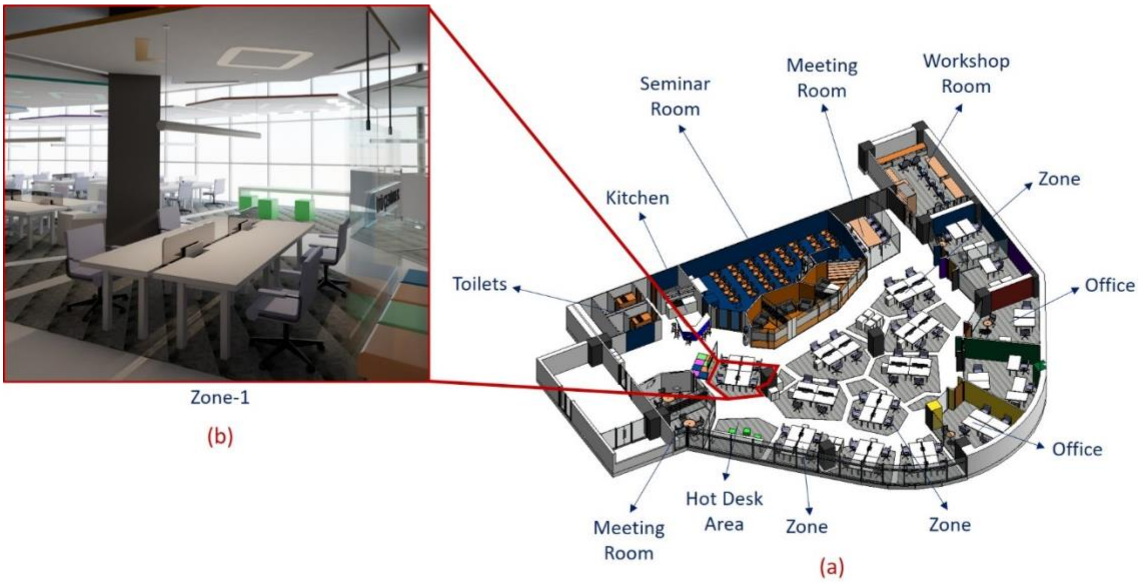

FIG. 4: (a) Case study office, and (b) close up of Zone-1.

5.2.1 Use case #1: Food odor in the office

Jane is disturbed by the food odor coming from the office kitchen while she was working at her desk in Zone-1 (Fig. 4b). She decides to report this issue as it happens regularly. By logging in to the occupant module from her mobile phone, she creates a feedback item by selecting the feedback category (i.e., indoor air quality), the feedback type (i.e., odor), and the feedback (i.e., food odor) from the drop-down menu (Fig. 5a). On the next window, Jane's location that is automatically detected by the indoor localization system (i.e., Zone-1) is presented to her for confirmation (Fig. 5b). The system automatically zooms in and highlights Zone-1 (i.e., Z1) as a transparent box on the building model, and Jane selects her desk to confirm her location in Z1. On the next window, Jane is asked to select the source element or the source location related to the issue she is experiencing (Fig. 5c). She enters K1-Kitchen (i.e., source location) from a predefined list as the source of her problem.

FIG. 5: Creating a feedback item in the occupant module by (a) entering the feedback, (b) confirming detected location, and (c) selecting the source location.

Next, Jane confirms the current date and time and moves to the next window without entering a preferred date and time of action for the problem to be solved as this is an optional field (Fig. 6a). In the next step, she wants to emphasize that the odor problem gets worse especially when the grill is used in the kitchen, and enters this as additional information (Fig. 6b). Finally, she is presented with a preview of the feedback for confirmation before sending the feedback to the FM module (Fig. 6c).

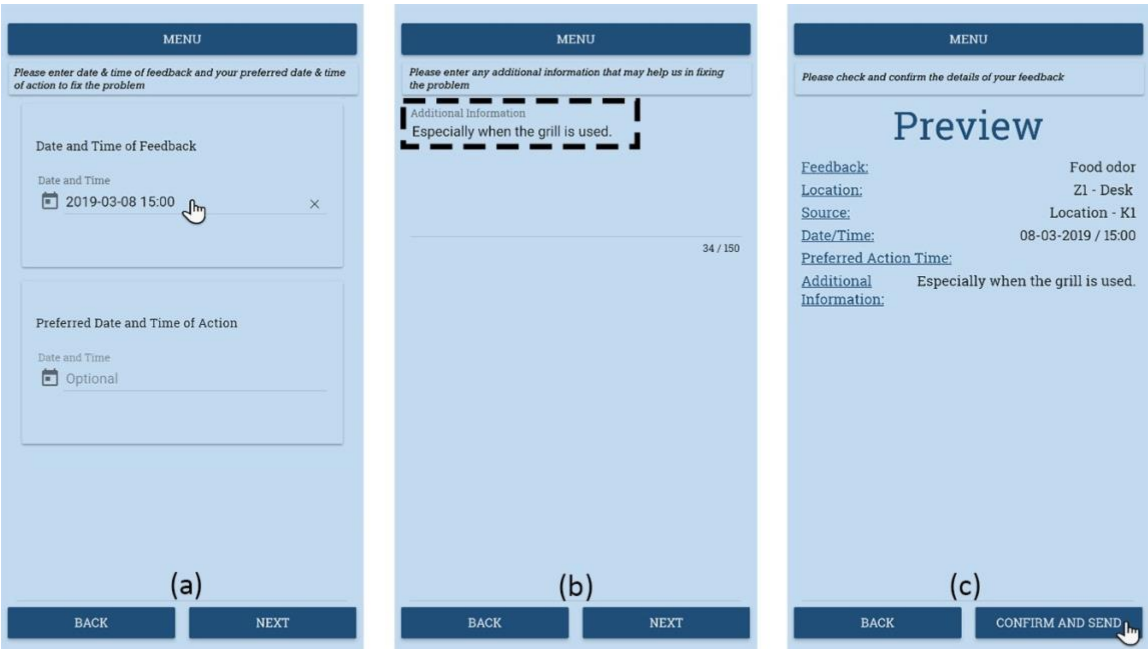

FIG. 6: Entering information related to the feedback by (a) selecting the date and time of feedback, (b) entering additional information, and (c) confirming and sending the feedback.

This feedback is automatically saved in the system in relation to the BIM. The implementation of the occupant feedback in the IFC is explained in more detail in Ergen et al (2021). An ID is automatically assigned to the feedback (i.e., #363), and the status of the feedback appears “pending” by default. Also, the Facility Manager is alerted that new feedback is created in the FM module and it is added to the list of feedback. When the Facility Manager opens the system, he is presented with the list of feedback with all statuses (i.e., pending, approved, rejected, and completed), and he selects the “pending” menu from the left to view the list of all pending feedback (Fig. 7a). The Facility Manager selects Feedback #363 from the list and the details of the feedback are displayed (Fig. 7b). Also, the related part of the model is presented, showing the location of the feedback and also the source location entered (Fig. 7c). The Facility Manager reviews the information associated with Feedback #363 and clicks on the “Edit” button to edit the feedback as he processes the issue reported by the occupant (Fig. 7b). In the edit window, he is provided with a field to write instructions and comments about the feedback, and to assign a technician to the feedback item. As the Facility Manager reviews the feedback, he changes the status of the feedback to “approved”, and assigns John (i.e., the technician) to solve the problem. In addition, he selects "breakdown" for the root cause, "high" for priority, and "electrician" for trade from the drop-down list.

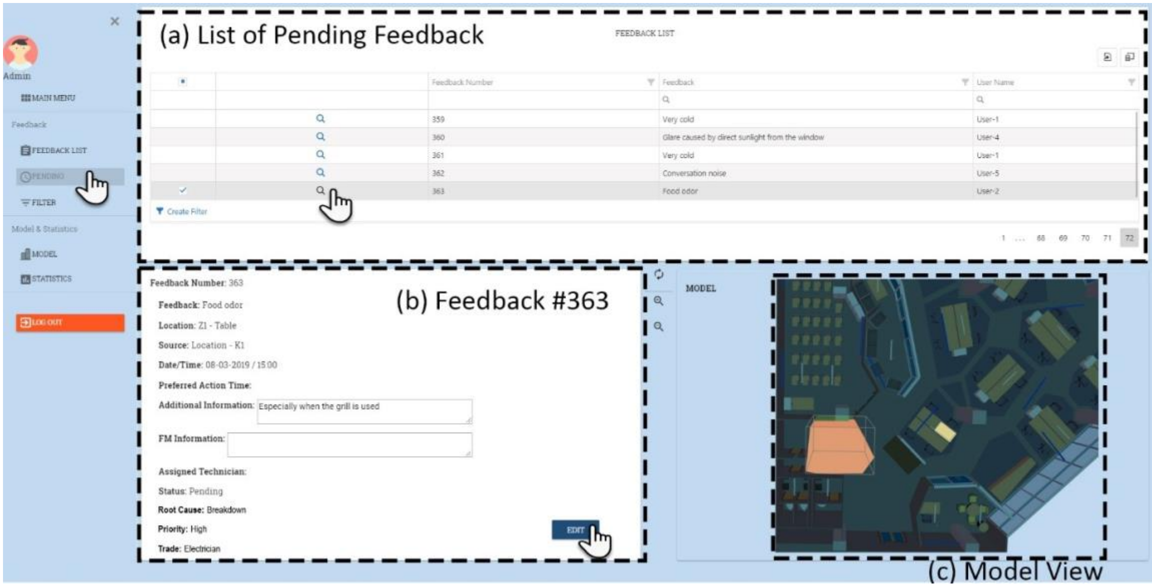

FIG. 7: FM module showing (a) list of pending feedback, (b) feedback details display and edit menu, (c) model view.

Before recommending an action to solve the odor problem in the kitchen, the Facility Manager wants to view and examine all the odor-related feedback in the office and use this information for planning a renovation to solve all the odor-related problems. Thus, he goes to the Filter page of the FM module (Fig. 8) and filters the feedback items that have the status of “Approved” and the feedback type of “Odor” (Fig. 8a). By looking at this two-page list of filtered issues, he identifies that various problems have been reported related to odor, such as ‘odor due to humidity or mold’, ‘carpet odor’ and realizes ‘K1-kitchen’ was entered as the ‘source location’ in some of the odor related problems reported over the last few weeks. Then, he wants to apply another filter to see all the feedback items that have the K1-kitchen defined as the ‘source location’. Therefore, he first selects the ‘source’ option, where both locations and building elements can be selected as the source of feedback, and then clicks on the K1-kitchen on the model view (Fig. 8b). He wants to use this information as a basis to plan the renovation, and the means and methods to be used while renovating the kitchen to overcome the odor problem. He clicks on the ‘Export’ button to save the filtered results to an Excel sheet and to use it in the FM meeting. The Facility Manager then goes back to the Edit menu (Fig. 7b) and adds a recommendation for the technician in the FM information field, stating that the kitchen hood and related piping must be checked to ensure that they function properly. When John, the technician, checks the kitchen hood as suggested by the Facility Manager, he realizes that the kitchen hood doesn’t work and makes a record of this in the FM Information section of the FM module.

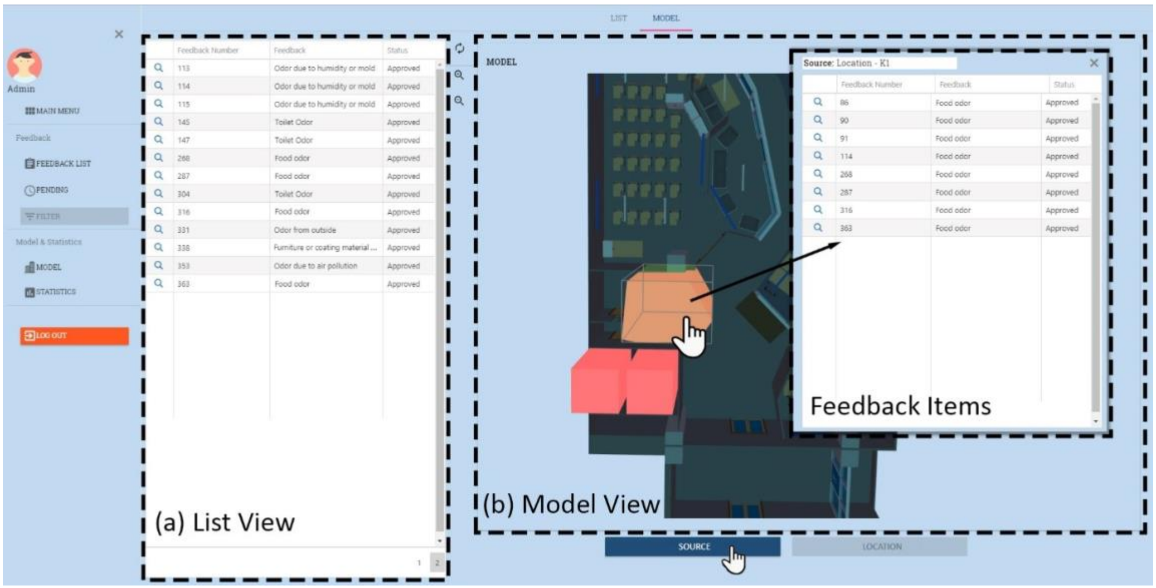

FIG. 8: Filter menu (a) showing the feedback items that have the status of 'Approved' and the feedback type of 'Odor', (b) selecting kitchen from the model as the 'source location' for viewing the related feedback items.

5.2.2 Use case #2: Leaking tap in toilet

Judith notices that a tap in the toilet is leaking and wants to report this issue by using the RateWorkSpace prototype. She searches for the "fixture" keyword, and the application lists the fixture-related feedback types (Fig. 9a). She selects "Fixture, equipment or furniture renewal", and continues to the next page to confirm her automatically detected location (i.e., T2-toilet) (Fig. 9b). On the next page, to define the building element that causes the problem, she clicks on the "source element" tab, selects the floor plan view since the tap is shown on the floor plan, and selects the leaking tap (i.e., T21-Tap) on the floor plan (Fig. 9c).

FIG. 9: Reporting feedback by (a) entering keyword, (b) confirming location, and (c) selecting source element.

She confirms the current date and time as the feedback date and time and states that the problem is urgent by entering ASAP in the preferred date and time of action field. She defines the problem in the additional information section on the next page (i.e., Tap is leaking). Finally, she previews the overall feedback, confirms, and sends the feedback (as shown for Use Case 1 in Fig. 6). The feedback is assigned a number (e.g., #364) and added to the list of feedback in the FM module.

5.2.3 Use case #3: Creating feedback reports and graphs

The Facility Manager wants to examine the current situation in the building to help with her decision on the prioritization of the maintenance and repair tasks in the building, as part of the monthly reviews she performs. She uses the FM module's 'queries' menu and views the number of feedback items that fall under each feedback status by date (Fig. 10a) and by category (Fig. 10b), and enters a one-month period (i.e., from February 20th to March 20th, 2021) to create the related graphs. Feedback items are summarized in terms of their statuses (i.e., pending, approved, rejected, and completed) in the form of a bar chart, while the feedback categories are shown in a pie chart. Since most of the feedback items are pending, the Facility Manager decides to prioritize the issues related to occupant thermal comfort as this is the category with the highest number of problems reported. She plans the maintenance and repair works for the upcoming month accordingly.

As there is a planned maintenance activity in the toilets, the Facility Manager also wants to query the occupant feedback, whose location was entered as 'toilet'. She analyses the feedback clustered on the building elements in the toilet (i.e., T21-Tap and WC4-Urinal) using the building model (Fig. 10c) to visualize the spatial relationships. She understands that there is a leakage in the washbasin supply pipe that is feeding both T21-Tap and WC4-Urinal and prepares a work order for checking the related pipe.

FIG. 10: FM queries based on (a) date, (b) feedback category, (c) building element.

6. DEPLOYMENT AND VALIDATION OF THE PROTOTYPE IN A CASE STUDY OFFICE

The prototype was tested in a lab environment and a real-world office for verification and validation. This included several incremental steps and main activities involved signal tests for indoor localization (Fig. 11a) and functional tests performed at the university laboratory (Fig. 11b) as well as verification (Fig. 11c) and validation (Fig. 11d) of the prototype at a real-world office via a case study.

During the two-week lab tests, the researchers initially focused on the integration of Beacon devices to the prototype for automatic detection of occupant location via Bluetooth technology. Three Beacons were installed in the lab and the following corrections were performed after the signal tests: (1) beacon equipment was repositioned so that they were not obscured by the building elements (e.g., placing them on the desks in the middle of the room), (2) the signal levels were optimized to avoid interference between the Beacon signals (e.g., in the open plan area the lowest signal level was selected), and (3) beacons were tagged against accidental replacements by the occupants (they were not permanently installed due to the experimental setting). As a result, a lab signal map was prepared showing the ideal positioning of the Beacons. The second step was the functional tests, in which the researchers performed the possible activities at each GUI and checked whether the information items related to the occupant feedback were accurately represented in the building model. Corrections included minor issues about data entry and user interfaces.

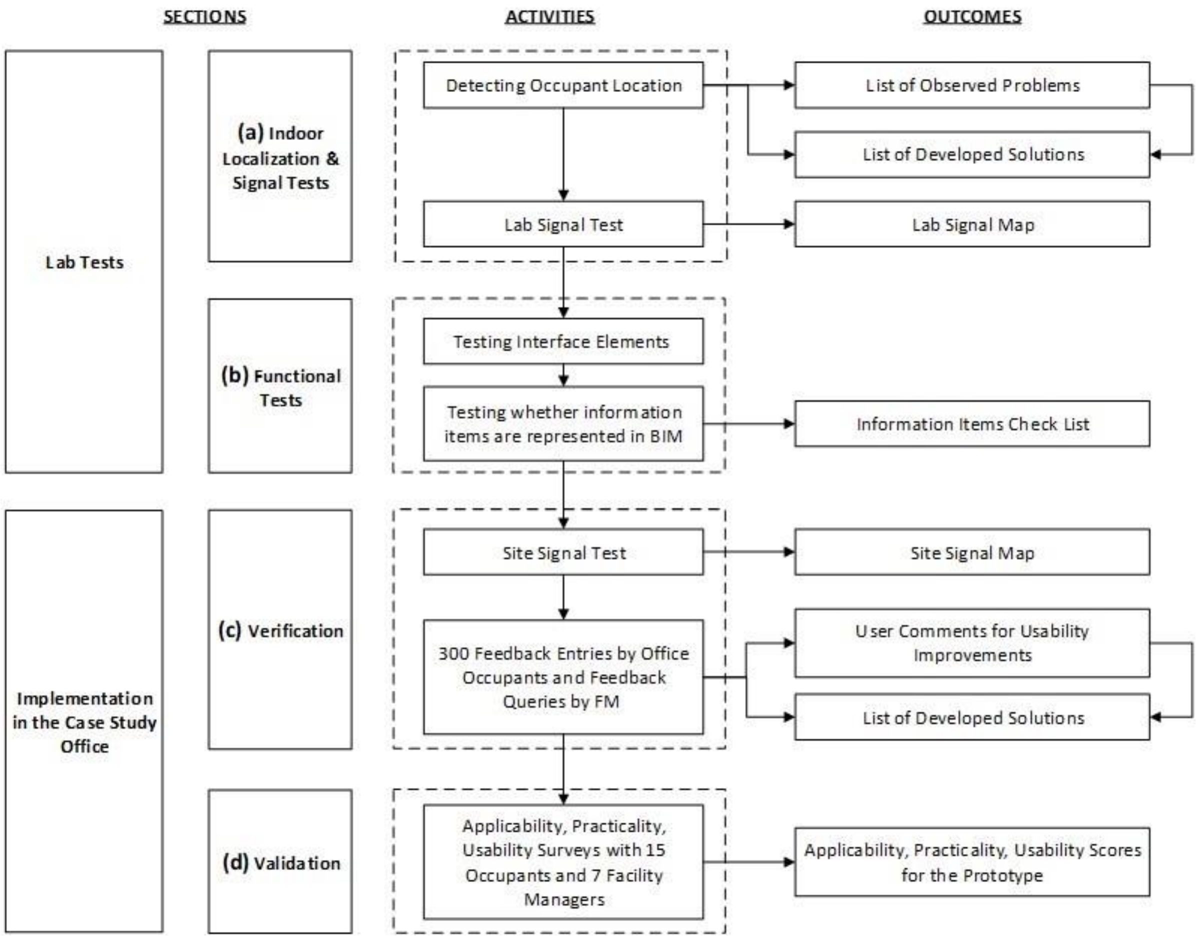

FIG. 11: Prototype verification and validation process.

This is followed by the deployment of the prototype in a real-world office space for three weeks to verify its functionality in the required tasks (e.g., feedback entry, automatic location detection, building element/space selection, visualization of the feedback in BIM, performing queries on feedback items, creating reports). Signal tests were also performed with the twelve Beacons installed in the case study office. Following the optimisation of the site signal map, information was given to the office occupants and FM team about the prototype and the case study. During the case study, 15 out of 60 occupants volunteered to use the mobile application, RateWorkSpace occupant module, to enter their feedback about their current office. The participants' experience with the prototype and their suggestions were recorded to be used for prototype verification. A total of 75 feedback issues were entered by the office occupants. Also, 225 feedback items were entered by the research team to determine the possible errors. Simultaneously, seven FM team members who were responsible for the management of the case study office, including managers and technicians, used the prototype's RateWorkSpace FM module to view the entered information, perform queries, and create reports.

The office occupants' experience and feedback obtained during verification can be summarized as follows: (1) each occupant was able to enter five different feedback issues instantly without any errors, (2) occupants stated that they completed reporting their feedback in a shorter time compared to traditional methods (i.e., verbally or in text format) owing to automatic location detection and the guidance of the application in entering the contextual information items (e.g., location, related element) required for each type of feedback, and (3) none of the occupants were contacted by the FM team after using the prototype to provide further contextual information for the issues they reported. The difficulties encountered and related suggestions were as follows: (1) the occupants mostly preferred using 2D plan view rather than 3D model view while selecting the related building element and/or related building space, (2) although each occupant successfully completed five feedback entries without any technical support, one of the occupants stated that they would prefer to have written guidance to perform the task, (3) one occupant suggested uploading a photo may support the occupants who cannot select the related element or space in the 2D plan views, (4) selection of multiple locations, related elements and source locations for single feedback should be made possible, (5) a list of prior feedback and their statuses should be provided to the occupant, and (6) occupants had difficulties in understanding IFC entity names of the elements in the building model.

Following the prototype testing, FM team members reported that (1) the prototype collects the necessary contextual information items to understand the reported issues in detail, (2) the query categories used in the prototype are adequate to effectively filter the collected occupant feedback, (3) being able to perform queries on the structured occupant feedback database saved them time and effort required for manual data input and processing, (4) visualization of the occupant feedback in the 3D model saved them time in locating the problems in the office and identifying building elements that need inspection, and (5) they had no issues regarding identification of a building element or space while using 2D plan view or 3D model view. Moreover, the FM team was able to utilize occupant feedback stored in the database to evaluate the performance of the case study office and support their decisions on the refurbishment planned in the near future. In this way, the FM query categories required to process occupant feedback in the RateWorkSpace prototype (Table 1) and the prototype information flow (Fig. 3) were validated. The suggestions for improving the prototype were as follows: (1) 'preferred date and time for action' should be added in the query categories for planning work orders and maintenance activities, (2) if 'related element' cannot be determined by the occupant, entry should be possible in the FM module for future analyses, (3) results of the complaint (e.g., completed, waiting for purchasing, under inspection) should be communicated with the occupant via the system, (4) options to obtain the query output listed in a spreadsheet (e.g., for a query on 'humidity' complaints based on 'feedback time') or visualized in the building model (e.g., for a query on 'noise level' complaints based on location) should be included, (5) querying should allow both filtering and sorting, (6) the main service system connections to the building elements receiving the complaints (e.g., 'dry air' complaints due to the same air handling unit) should be represented, and (7) an approximate duration needed to fix the reported issue/complaint should be provided to the occupants.

For validation of the prototype, case study participants provided feedback on the performance of the prototype via questionnaires presented in the Appendix, which were then used to quantify the applicability, practicality, and usability of the system from the perspective of the end-users. According to the average scores obtained, the occupants think the RateWorkSpace prototype is applicable (4.03/5), practical (4.00/5), and usable (4.15/5), which shows end-user satisfaction. The findings indicated that the occupants thought the system met their needs (i.e., Question 4, avg = 4.53/5), they were able to use it without technical support (i.e., Question 7, avg = 4.53/5), and would recommend it to others (i.e., Question 13, avg = 4.53/5). The lowest average score (i.e., 3.07/5) was received in relation to the identification of the source element that had caused the problem, which highlighted the difficulties in visualizing building elements on a 3D model view. The facility managers, on the other hand, also found the proposed prototype applicable (4.54/5), practical (avg = 4.33/5), and usable (4.56/5). They had no issues with identifying a building element or space (i.e., Question 1, avg = 4.57/5), possibly due to familiarity with the office setting and the building model. Most importantly, the facility managers stated that visualization of the occupant feedback in the building model made their job easier (i.e., Question 13, avg = 4.86/5). The minimum average score was obtained for the simplicity of the design of the system (i.e., Question 9, avg = 4.14/5), indicating a more user-friendly interface design may be beneficial in future versions of the prototype.

Based on the valuable insights obtained by having actual office occupants and facility managers use and test the prototype and interacting with them while they are using the prototype, the following revisions were implemented to improve the user-centered HMI design and usability of the prototype: (1) 2D plan view is utilized instead of the 3D model view while selecting the related building element and/or related building space in the occupant module, (2) guidance was included at the top of each GUI, (3) photo upload option was included, (4) multiple selections for location, related element, and source location was made possible and (5) IFC entity names of the elements were converted to element names in the daily language (e.g., 'IfcCovering / Compound Ceiling:Plain:460806asd' converted to 'Suspended Ceiling'). On the other hand, to improve the querying and retrieval efficiency of the prototype, (1) 'preferred date and time for action' was added in the query categories for planning work orders and maintenance activities, (2) options to obtain the query output listed in a spreadsheet or visualized in the building model was included, and (3) filtering and sorting option was made available in the queries. The system architecture and prototype GUIs were revised accordingly.

7. DISCUSSION

The verification and validation process revealed the following contributions and limitations of the developed BIM integrated post-occupancy evaluation system.

7.1 Contributions

7.1.1 A user-friendly system to communicate occupant comfort needs instantly and in a continuous manner

RateWorkSpace is an effective platform for office occupants to communicate their comfort needs, which is a significant factor in employee health and productivity. Inspired by the criticism of the current POE practice in the recent literature, the developed system is designed to collect the feedback instantly and in a continuous manner, which ensures instant response to the discomfort of the occupants. Also, by focusing on specific issues observed in the buildings rather than the overall occupant satisfaction; the root causes of the occupant discomfort are unfolded. Moreover, automatic location detection utilized in the prototype allows the occupant to easily report the location of the discomfort. This prototype also constitutes a prominent example of occupant interaction with BIM. Building occupants are non-technical persons with limited information on building models. Although they had difficulty navigating in the 3D building model, they were able to interact with 2D plan views when they were presented in a simple, user-friendly format. RateWorkSpace occupant module is designed as a mobile application that can collect the contextual information necessary to effectively respond to a discomfort in only five simple steps. This user-centered and simple HMI makes the system easy to operate while reducing the user error rate and was found applicable, practical, and usable by the occupants when used in practice.

7.1.2 Effective utilization of the occupant feedback in FM

The prototype enables timely, structured collection and storage of occupant feedback along with the contextual information, such as location and the building element or space that is the source of the problem. This prevents loss of time and labor observed in the manual processes for accessing, sorting, grouping, and selecting the data in FM activities. Unlike the existing POE methods, instant and continuous data collection enables capturing the effect of environmental factors. Utilization of the collected occupant feedback through effective retrieval and reporting tools adopted in the prototype helps facility managers to identify specific problems and their root causes in buildings, rapidly diagnose O&M issues, adjust set points to optimize energy use and occupant comfort, and determine future needs related to renovations and retrofitting more accurately.

7.1.3 Integration of occupant feedback information with BIM

Another important contribution of the study is the BIM integration to both collection and processing of occupant feedback information. BIM integration helps facility managers to visualize results in the 3D model by highlighting the related elements/spaces of the feedback, thus, save time in locating the problems and identifying building elements that need inspection. Being able to visually comprehend the spatial relationships, which are easily overlooked, reveals the repeating patterns and root causes by evaluating the occupant feedback in connection with other important building information stored in BIM. This way, spatio-temporal queries can be performed, and this can lead to new insights, improvement in problem-solving capabilities, and eventually more effective decision-making in FM. Ultimately, the proposed prototype has the potential to improve the overall FM performance through leveraging each of the FM KPIs (i.e., occupant satisfaction, maintenance efficiency, cost to operate, labor hours spent, and system availability) defined in the literature.

7.2 Limitations

Integration of the prototype to existing FM systems, such as the retrieval of sensor data from BAS, has not been implemented in this study. However, common query categories used in the existing FM systems (i.e., root cause, priority, trade, and status) were included in the developed prototype for possible integration in the future. Another possible extension is the addition of a 'technician interface' in the FM module. With this interface, the prototype can enhance communication between the facility managers and technicians on site. Moreover, as a response to the insights gained from the case study, future work involves adding a 'feedback history tab' in the occupant module, which will include a list of prior feedback of the occupant, along with information, such as the progress status (e.g., completed, waiting for purchasing, under inspection) and an approximate duration needed to fix the reported issue/complaint, which can enhance the communication between the occupants and the FM team. Finally, since the scope of this study is limited to office buildings, further assessment of the common occupant complaints is required to develop different versions of the prototype for other building types (e.g., hospitals, education buildings). The prototype is highly generalizable for different building types, provided that feedback categories are updated to include special complaint types, if any, depending on the building type (e.g., problems related to equipment for hospitals).

8. CONCLUSIONS

This paper describes a BIM integrated post-occupancy evaluation system that enables conducting spatio-temporal queries and visualization of the collected feedback to support effective decision-making in FM. The contributions of this study are (1) a user-friendly system to communicate occupant comfort needs instantly and in a continuous manner, (2) effective utilization of the occupant feedback in FM for decision-making, and (3) integration of occupant feedback information with BIM for visualizing the results in the 3D model by highlighting the related elements/spaces of the feedback. Querying and visualization of occupant feedback based on building elements, spaces, and time in BIM provide benefits for FM by simultaneously showing most problematic areas, clusters of common issues over time and relations of the issues to the building geometry and systems, which can support root cause analysis. For example, clustered thermal or indoor air quality issues could indicate improper HVAC set points, complaints regarding the building design (e.g., insufficient storage areas) could help effective decision-making during renovations. Seasonal or daily patterns would also become more identifiable. Overall, the prototype could increase the effectiveness of the FM and O&M processes, and help to create office spaces with optimized energy use and occupant comfort that also supports occupant well-being and productivity.

The developed approach also leverages the inherent capabilities of BIM by integrating an HMI best practice, allowing not only the facility managers but also the occupants who do not have the technical background to interact with and navigate through the building model. Real-time building performance data can be collected and analysed with the developed system, and this assists facility managers in making critical decisions about the building. RateWorkSpace prototype also contributes to the improvement of POE practice by providing continuous insight into the frequency and type(s) of complaints and unveiling their relations to the specific building elements and spaces.

As part of the future work, immersive technologies, such as augmented reality, could be integrated within the prototype to ease the interaction of the occupants with the building model while navigating in the model for providing feedback. Also, the prototype could be easily adapted to other building types (e.g., hospitals, schools, residential buildings). In this sense, the developed prototype is highly generalizable and ready for a widespread implementation as a commercial product in buildings operated with BIM-enabled FM. After multiple implementations, artificial intelligence (AI) can be used to analyse the data collected by the prototype, in order to discover more effective ways in designing and operating buildings and contributing to realizing sustainable cities and societies.

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APPENDIX A. SUPPLEMENTARY DATA

TABLE 2: Validation questions for occupants.

	Questions (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree)	1	2	3	4	5	N/A
Applicability	**Q1:** I did not have any difficulties in finding the type of feedback I wanted to enter.						
	Q2: I did not have any difficulties in finding my location on the floor plan.						
	Q3: I did not have any difficulties in identifying the source (building element) of the problem on the floor/ceiling plan.						
	Q4: The designed system meets my needs.						
Practicality	**Q5:** I did not need a lot of training before I used this system.						
	Q6: I would use this system frequently.						
	Q7: I would not need the support of a technical person to be able to use this system.						
	Q8: I would imagine that most people would learn to use this system very quickly.						
Usability	**Q9:** I think the design of the system was simple enough.						
	Q10: I think the system is easy to use.						
	Q11: The system was very easy to use for me.						
	Q12: I find the designed system useful.						
	Q13: I would recommend the designed system to others.						

TABLE 3: Validation questions for facility managers.

	Questions (1: strongly disagree, 2: disagree, 3: neither agree nor disagree, 4: agree, 5: strongly agree)	1	2	3	4	5	N/A
Applicability	**Q1:** I was able to identify the source element/space of the problems related to the building.						
	Q2: The designed system meets my needs.						
	Q3: I was able to filter the problems based on my needs.						
	Q4: I think I can make more effective use of occupant feedback utilizing this system.						
Practicality	**Q5:** I was able to easily and quickly detect the problems about the building.						
	Q6: I would not need the support of a technical person to be able to use this system.						
	Q7: I would imagine that most people would learn to use this system very quickly.						
	Q8: I would use this system frequently.						
Usability	**Q9:** I think the design of the system was simple enough.						
	Q10: I think the system is easy to use.						
	Q11: The system was very easy to use for me.						
	Q12: I find the designed system useful.						
	Q13: Visualization of the occupant feedback made my job easier.						
	Q14: I would recommend the designed system to others.						