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A Review of BIM-Enabled Daylighting Control System for Office Buildings

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Abstract: Despite the acknowledged benefits by incorporating daylighting in the lighting system of office buildings to enhance energy efficiency and ensure occupants' well-being, a significant gap in understanding the integration of daylighting control system (DCS) with Building Information Modeling (BIM) exists, which can lead to improved energy efficiency and enhanced building design, specifically regarding the impact of daylight on occupant comfort. Previous studies have highlighted the potential of BIM to revolutionize both architectural design and building performance. However, an untaped potential of BIM in facilitating daylighting control in office areas is yet to be explored. The significance of this study lies in prioritizing occupants' well-being and enhancing building performance. This research identifies the feasibility of BIM-enabled DCS through a literature review from three perspectives: BIM-enabled DCS and daylight strategies, BIM-assisted façade system improvement, and user-centric daylight utilization within BIM platforms. As for results, a sensor network diagram illustrating network structure, data flow, and connections between devices of BIM enabled daylight control system for office buildings are established. Additionally, a BIM assisted daylight control strategy diagram is presented to outline user-centric control facilitated by BIM platform. In terms of contribution to the body of knowledge, this research will provide a comprehensive synthesis of existing literature in this domain. Additionally, this research could provide architects, DCS designers, and sustainable building professionals with potential advancements and inspirations to promote energy-efficient and user-centric building design in the future.

Key words: daylight control system, office buildings, Building Information Modeling, energy efficient.

1. INTRODUCTION

Among all the electricity consumption in office buildings, lighting is estimated to account for 40% of the total consumption [1]. In order to decrease energy consumption while maintaining the visual comfort of occupants inside the building, various daylight control systems (DCS) are introduced and installed [2]. Due to the variations in daylight parameters from case to case, significant disparities in the potential of DCS in terms of energy-saving and visual comfort-improving have been reported. Atif and Galasiu assert that the annual savings in electrical consumption of utilizing DCS could be up to 46% through filed measurements [3], Jennings et al. and Yun et al. prove that about 21% to 43% of lighting energy consumption could be saved with the aid of automatic daylight dimming control by monitoring the electrical consumption for several months [4], [5]. Amoruso et al. achieve a 15% improvement in the daylight factor and a 30% increase in daylight autonomy by utilizing parametric environmental analysis tool.

As a digital approach of architectural design, Building Information Modeling (BIM) has provided the construction industry with a brighter future in which building design, construction, and management could be more efficient and integrated [6]. In the context of DCS, BIM could serve as a powerful tool for visualizing and simulating daylight analysis. In addition, BIM also has the potential for assisting with data-driven decision-making process for DCS because BIM could store real-time and real-world data in a standardized and organized way. Also, various analysis could be applied using machine learning with the aid of API plug-ins and web-based software [7]. Moreover, BIM could streamline the integration of DCS components in the IoT network, including sensors, lighting control units, and illuminating components [8]. Consequently, BIM-enabled DCS is really promising since the stakeholders of Architectural, Engineering, and Construction (AEC) industry could visualize, simulate, and utilize daylight strategies in a more data-driven, parametric, and user-centric way.

Based on the review of current literature, previous research has focused on the field of (1) daylight control system (DCS) design and strategies to increase daylight harvesting and lighting efficiency, (2) achieving daylight balance in office buildings with façade system, and (3) analyzing impact of occupant behavior in terms of daylight utilization on energy performance. However, to investigate the potential of BIM-enabled DCS, three topics should be under discussion: (1) BIM integration in the simulation and real-time monitoring of daylight harvesting for different daylight strategies (2) façade design improvement for DCS design using BIM, and (3) BIM assisted data collection and management for user-centric and retrofit-focused DCS.

In this paper, a literature review addressing the three research gaps and three objectives mentioned above will be conducted. The result would be a sensor network diagram illustrating sensor network, data flow, and connections between devices of BIM enabled daylight control system for office buildings. Additionally, an Entity Relationship (ER) diagram will be presented to outline user-centric daylight control enabled within BIM platform.

2. RESEARCH METHODOLOGY

Here is a flow chart demonstrating the research methodology for this research (see Figure 1). The whole process could be divided into seven steps, including preparation of research, literature review, data collection, analysis and synthesis, diagram development, results and conclusions, and implementations and recommendations.

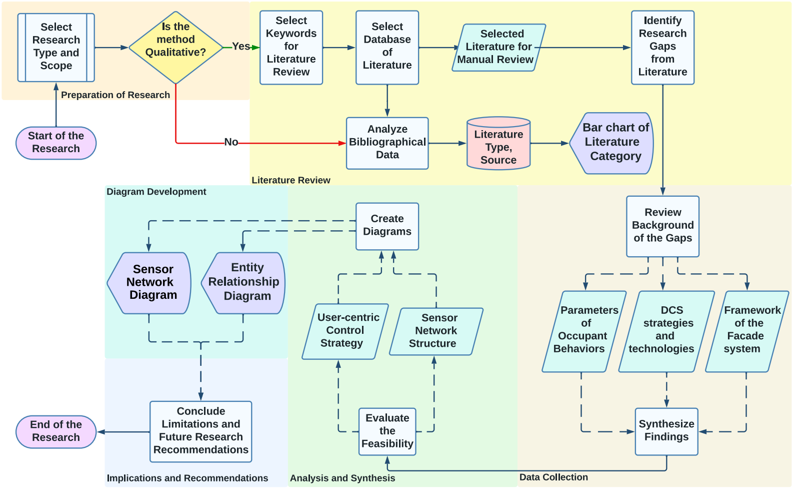

Figure 1. Process Flowchart of the Research Methodology

The selected keywords are categorized into six groups (see Table 1). The search engine used in this study is Web of Science (WOS) core collection due to its trustworthy citation index and coverage of leading scholarly literature [9]. First, the keywords selected are “daylight control system” or “daylight utilization” and “office” which are used for conducting literature review for “the need of daylight control system in office buildings”. There are a total of 30 articles filtered by WOS core collection. Similarly, the following steps of keywords selection are demonstrated in Table 1. The number of articles filtered by WOS core collection are 19, 53, 13, 24, and 32 individually. The decision to thoroughly review literature depends on its relevance to the topics and the number of citations. Six bar charts showing the top 3 sources of literature in terms of literature number are displayed in Figure 2, in which significant contributions have been made by prominent journals such as “Energy and Buildings” (11), “Automation in Construction” (6), “Sustainability” (6), “Building and Environment” (5), and “Buildings” (4).

Table 1. Keywords selection results and searching results on Web of Science

Categories of literature review	Keywords used for searching articles	Number of Articles	Top 3 Sources for Articles
The Need of Daylight Control System in Office Buildings (I)	“Daylight control system” OR “daylight utilization” AND “office	30	Energy and Buildings: 4 Energies: 2 Building and Environment: 2
Design and Strategies of Daylight Control System (II)	“Daylight strategies” OR “daylight control system” OR “daylight” AND “BIM”	19	Journal of Building Engineering: 2 Sustainability: 2 International Journal of Construction Management: 2
Façade System Improvement (III)	“Façade system” OR “shading system” OR “façade” AND “BIM”	53	Automation in Construction: 6 Journal of Green Building: 4 Remote Sensing: 3
Occupants’ Behaviors-driven Daylight Utilization (IV)	“Occupant behavior” OR “daylight utilization” AND “BIM”	13	Sustainability: 1 Buildings: 1 Symposium on Simulation for Architecture and Urban Design 2013: 1
User-centric strategy (V)	“user” OR “user-centric” AND “daylight” AND “preference” OR “requirement”	24	Building and Environment: 3 Energy and Buildings: 3 2019 SBFOTON International Optics and Photonics Conference: 1
Façade System Sensor Network (VI)	“façade system” OR “façade network” AND “daylight”	32	Energy and Buildings: 4 Sustainability: 3 Buildings: 3

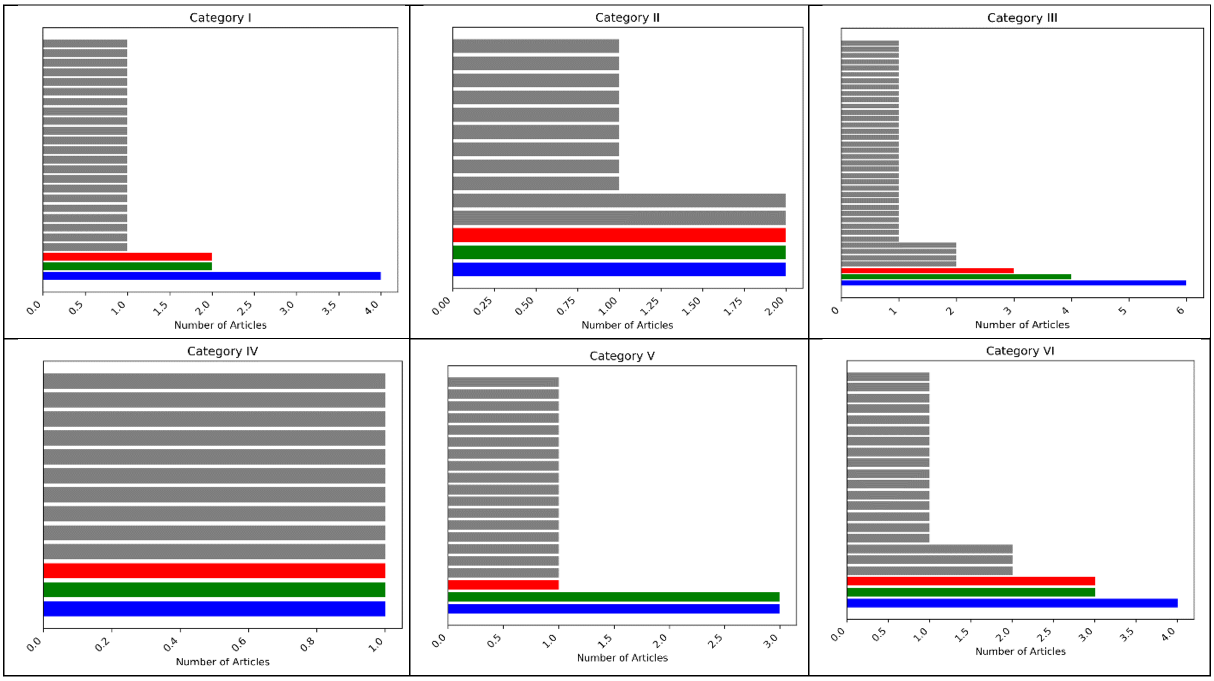

Figure 2. Bar Charts Showing the Top 3 Sources of Literature for each Category

As for the analysis which is to evaluate the feasibility of BIM-enabled DCS, this research contains two main aspects (1) establishing user-centric control strategy of daylight utilization within BIM Platform, and (2) integrating BIM with façade system sensor network for DCS. The steps are demonstrated in the following flow chart (see Figure 3).

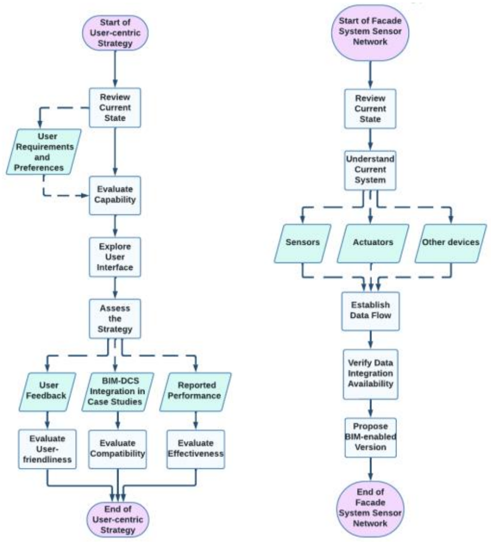

Figure 3. Process Flowchart of the Analysis and Synthesis Section

3. LITERATURE REVIEW

3.1. The Need of Daylight Control System in Office Buildings

DCS plays a significant and indispensable role in ensuring the lighting conditions, energy efficiency, and occupants' well-being in office buildings. In the office environment, various tasks require sufficient lighting to guarantee working productivity and efficiency [10]. With the strategic implementation of DCS to office buildings, optimal illumination could be ensured, while the regulatory compliance of office buildings standards and green building standards could also be satisfied, resulting in a commitment to both building sustainability and cost reduction [10]. Based on the research by Turan et al., offices with high levels of daylight obtain a premium rent with approximately 6% over those offices with relatively low levels of daylight [11], which underscores the value of daylight in the office area.

3.2. Design and Strategies of Daylight Control System

Through the design phase of a building, DCS should be under consideration to maximize the energy savings brought by daylight utilization. As a result, several studies provide various approaches of daylight utilization strategies in their studies. Han et al. introduces an artificial neural network-based modeling approach to address the challenge of evaluating annual daylight performance in the early design stages of office buildings, holding promise for expediting informed daylighting decisions in conceptual design [12]. Ngo et al. addresses energy-efficient building design in his paper through cloud-based energy simulation, focusing on building parameters' impact on energy consumption and cost [13]. Daylight utilization is one of the essential building parameters in that study. Additionally, Plörer et al. reviews several control strategies for daylighting and artificial lighting in office buildings, in which the need for simultaneous achievement of energy efficiency and user comfort are emphasized [14]. In conclusion, the incorporation of DCS during the building design phase holds great potential for maximizing energy savings in terms of daylight utilization.

In terms of the current state of BIM integration for simulation and DCS monitoring, several studies have reported limitations. As Delvaeye et al. mentioned in their study, lighting energy savings differ significantly between different DCS for different building types. They also stress the importance of installing and commissioning correctly of DCS [2]. Also, Atif and Galasiu believe that operation irregularities including dimming linearity reduction and incorrect lighting system adjustment could potentially diminish the saving potential of DCS. Additionally, Plörer et al. emphasize the significance to take various occupant-specific factors into account due to the reliance on occupants' behavior to determine system performance and acceptance [14]. Thus, given these limitations, if simulations on daylight utilization and energy consumption for different DCS could be conducted in BIM environment initially, real world experiments on buildings could be provided with references from the evaluation of these simulations. What's more, with the aid of BIM platform, data from daylight sensors, energy consumption sensors could be stored and applied to increase the accuracy and dependency of simulations. Therefore, BIM integration for simulating and monitoring DCS could be promising and meaningful for further research.

3.3. Façade System Improvement

Promising prospects lie in the integration of DCS with building façade systems to ensure effective harnessing and utilization of daylight. The design of building facades directly impacts the amount and quality of daylight distribution, which are determined by façade factors including window size, placemen, orientation, glazing properties, and light redirection [15]. As for DCS, it encompasses a range of technologies and strategies aimed at maximizing natural light usage while minimizing energy consumption. The synergy between DCS and façade design can not only regulate the amount of daylighting entering indoor space to adjust artificial lighting levels, but also create a comfortable and energy-efficient indoor environment.

Currently, several studies have focused on enhancing daylight utilization through façade design. Jayathissa et al. present a novel approach to design an Adaptive Solar Facade in Duebendorf, Switzerland [16]. This kind of façade allows the designer to shape the facade's form, assess structural integrity, analyze energy performance, conduct daylighting assessments, render images, and generate fabrication plans rapidly with the aid of a parametric design environment [16]. Yi also proposes a method combining quality and quantity performance goals to optimize façade design, so that the façade could be both aesthetic and functional [17]. He applies multi-objective evolutionary algorithms to find solutions that satisfy both daylighting performance and user preferences in his study. Additionally, M. ElBatran and Ismaeel propose the idea of double skin façade (DSF) to achieve a balance of daylight availability and visual comfort in office buildings [18]. Moreover, Lim et al. highlight the potential of passive daylighting strategies by demonstrating the effectiveness of window glazing and shading device modifications in tropical regions [19]. What's more, Konstantoglou and Tsangrassoulis mention automated shading and daylight solutions in façade design in their research to address the crucial role of user-friendly operation and potential impact of façade on daylight utilization [20]. Finally, Bui et al. introduce a computational optimization approach using an adaptive façade system design to achieve energy savings of 14.9% to 29.0% and 14.2% to 22.3% in their two case studies, demonstrating the potential for enhancing energy efficiency.

Collectively, these studies underscore the increasing emphasis on enhancing daylight utilization through innovative façade design strategies, ranging from parametric design environments and multi-objective optimization to passive daylighting solutions and automated shading systems. All these designs share the same goal as achieving aesthetic, functional, and energy-efficient building envelops as well as ensuring sufficient indoor daylight, leading to the assistance BIM could provide to the parametric design. Not only can the BIM software be significant tools for creating simulation models to evaluate the façade's performance, but can BIM become essential platform to synthesize different data sources to enhance the parametric design. Since Han et al. conclude in their study that the major shortcoming of their research is the lack of environmental obtrusion and access to site specific data [12], the integration between BIM and Geographic Information System (GIS) could be a promising solution to this problem. According to the study of Song et al., BIM-GIS integration based solutions are extremely benefit for progress management, environment performance evaluation, and coordination of various sectors [21], which is a great match for the problems brought up by Han et al. Additionally, other building systems need to be taken into consideration while designing the façade, which makes BIM a perfect choice for this task. As Yi mentions in his study, other environmental factors including natural ventilation and thermal comfort are required for further research [17]. Moreover, Lim et al. state in their study that their paper only focuses on daylight performance from the perspective of visual comfort, without the consideration of thermal comfort [19]. If the design does not avoid direct sunlight glare, intensive solar heat could lead to discomfort in thermal conditions to some extent. That's why BIM should be included to coordinate with different building systems while designing the façade.

3.4. User-Centric Daylight Utilization

Occupants exhibit varying preferences for blinds or shades in their workspaces, and their tolerance levels for glare and desired daylight intensity also vary. Consequently, it's necessary to personalize daylight distribution and level and enhance occupants' interaction with daylight control system. Currently, numerous studies have focused on the impacts of occupants' behavior on daylight preferences, utilization, and control. For example, Day et al. investigate the impacts of multiple shading strategies on occupants' visual comfort and productivity in office buildings, including automatic blinds, electrochromic glazing, and roller shades [22]. Meerbeek et al. explore the impact of automated blinds systems with expressive interface on user satisfaction [23]. By reporting two user studies with a sample size of 72 people, they find out that occupants' adherence and acceptance to the suggestions from the system increased with expressive interface, stressing the importance of human-computer interaction on this application [23]. Additionally, Tabadkani et al. underscores the importance of user-centric strategies in management of adaptive facades [24]. They also highlight the limitation of the automatic control systems if lacking user interventions, which could lead to reduced satisfaction and comfort. What's more, Kandasamy et al. present a novel Artificial Neural Networks (ANN) enabled daylight control system to incorporate personal information for effective daylight harvesting [25]. In conclusion, the idea of user-centric design is gaining importance among researchers, especially in the control of building systems.

However, since occupants-related data usually contains a wide range of variables and characteristics describing behaviors, preferences, and specific needs of occupants, the data could be quite diverse, complex, and nested. Consequently, BIM could not only be used for storing and organizing these data, but also be used for providing a standardized platform for analyzing occupants' lifestyle and route patterns with further analysis using machine learning algorithms [26]. In addition, as Uddin et al. assert in their study, two of the six research gaps identified are lacking real data for model validation and BIM integration with existing occupant behavior modeling or simulation [27]. As DCS could support BIM with real time and real-world data as well as occupants' behavioral data concerning daylight utilization and the equilibrium between daylight and artificial lighting, it could be feasible and promising to leverage BIM for promoting user-centric and retrofit-focused DCS development.

3.5. Evaluation of the feasibility for BIM-enabled DCS

As mentioned in the research methodology, the evaluation of the feasibility could be divided into two sections: develop the user-centric strategy of daylight utilization and establish the sensor network of façade system enabled by BIM.

As for the first section, the primary work would be understanding user preferences and requirements, along with the related quantitative parameters. Based on the summarization of results from literature review, user requirements contain illuminance levels, glare, view access, and privacy, while user preferences contain daylight autonomy, individual control, health promoting, and energy efficiency.

Illuminance levels vary significantly among different occupants. Some prefer brighter workplace, others prefer softer and diffused lighting [28]. Sometimes occupants have specific tasks that require different lighting conditions. Marins et al. also propose the concept of Below Useful Daylight Illuminance (BDUI) to demonstrate the differences between illuminance thresholds among occupants [29]. Glare could directly affect occupants' visual comfort and productivity. Hence, shading systems are required to mitigate the glare issues, as mentioned in the study by Lim et al. [30]. View access is also considered one of the requirements as occupants value it as the connection to the external environment [31]. Another important requirement is occupants' privacy, especially in the open office layouts where people have to share the space with others. Therefore, a shading system which could offer privacy when needed while providing enough daylight instead of blocking it entirely may be preferred by the occupants [32]. As for occupants' preferences, individual control and daylight autonomy are one of the choices since it allows people to adjust the shading to personalize their working environment and balance the utilization of artificial lighting as well [28], [33]. In addition, health promoting and energy efficiency are also essential preferences to occupants since people prefer design with biophilic elements that would minimizing potential disruptions to circadian rhythms [29] and energy saving implications which could encourage more sustainable behaviors [34].

As for the second section, the primary work would be reviewing the current sensor network of DCS and façade system. Based on the summarization in the literature, the current network includes the elements of sensors, actuators, network communications, user interface, other building management systems (BMS), and power supply [35]. Sensors include photometers, occupancy sensor, and temperature sensors to collect daylight levels, occupant presence, and indoor thermal conditions [36]. These sensors are all interconnected via a network for data exchange and control commands for real-time monitoring and alternating [36]. User interface is the bridge between occupants to the façade system, consisting of control panels, touch screens, mobile devices, and web interfaces for remote control, interaction, and monitoring [37]. Other BMSs include HVAC and security systems, which are used for coordinating operations for the overall building performance. Lastly, power supply is the energy source for the system. The power could come from the building's electrical system, in which energy sensors and actuators are used for energy saving and increasing energy efficiency.

RESULTS AND DISCUSSION

The first result would be the BIM enabled sensor network for the façade system for daylight utilization. As shown in **Error! Reference source not found.**, the left part displays the current sensor network of DCS, which consists of "Internet", "Firewall", Router", Server", "Switch", "Façades", "Wireless Access Point", and the user interface including "Smart phone", "Controls", and "Laptop device". Both "Switch" of the façades and "Wireless Access Point" are connected to the "Server" that exchange data with "Internet" through the router protected by "Firewall". Compared with the left part, the right part demonstrates how BIM could improve the current façade system by enabling data-driven analysis to optimize façade design, achieving real-time interactions with occupants, and coordinating with other building systems. All the available and related parameters of the façade system will be considered to improve the design. The user interfaces including smart phone apps or website services will also send the control logic and real-time data from sensors and actuators to the BIM platform. After that, these data will also be sent to the server in case they are required by other building systems, or it will be sent in the internet cloud and stored as historical data for future analysis. Consequently, with the implementation of BIM platform, façade system, building control systems, and control through user interfaces are connected and coordinated, along with data transmission.

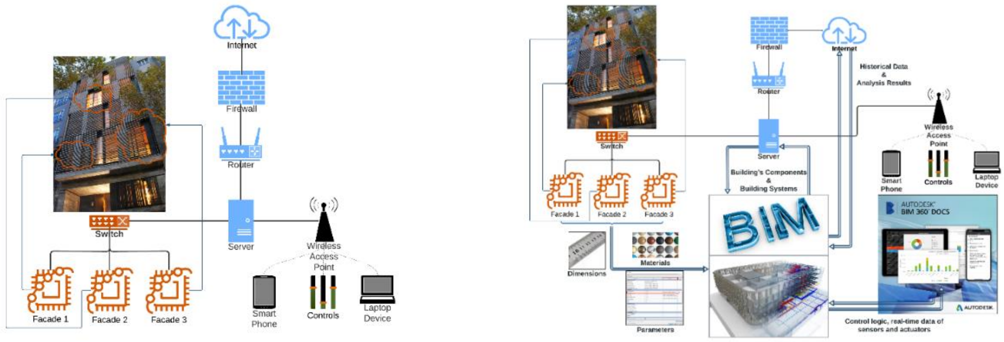

Figure 4. Comparison of Current Sensor Network Diagram for DCS and Sensor Network Diagram for BIM-enabled DCS

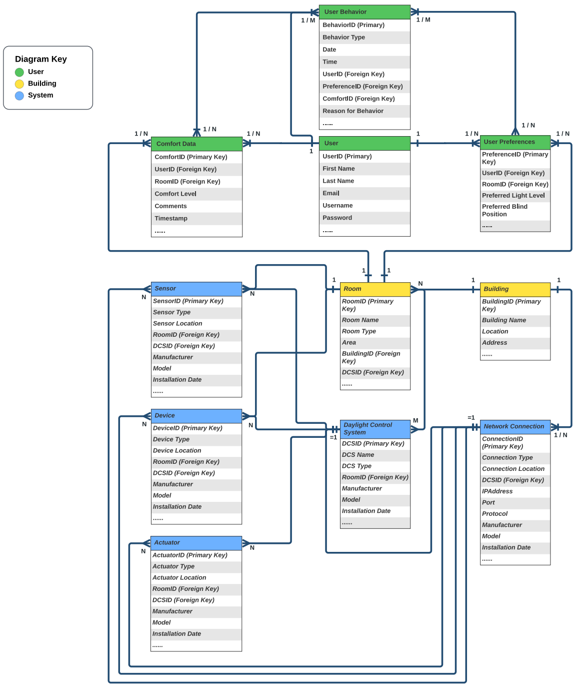

Figure 5. Entity Relationship Diagram for User-centric Database

According to the review of literature, the establishment of the user-centric BIM database is of great necessity to document the diverse occupants' information in terms of their behaviors, preferences, and comfort levels. As for the details and data structure of user-centric database, an entity relationship (ER) diagram is made to illustrate the component and connections between each data entities in the BIM database. All the data could be categorized into three types: user related, building related, and system related. In the user related data, "user", "user behavior", "user preferences", and "comfort data" are within this category. "Building" and "room" are the data entities for building related category. "Sensor", "actuator", "device", "daylight control system", and "network connection" are within the system related category. Each data entity obtains with multiple attributes which are listed under the entity name. The lines connecting different entities indicate cardinality, including one-to-one, one-to-many, and many-to-many, directionality, and associativity between entities. The ER diagram provides an efficient approach to visualize the data schema of user-centric BIM database (see Figure 5).

CONCLUSION

This research explores the feasibility of BIM-enabled DCS through a literature review from the perspectives of BIM-enabled DCS and daylight strategies, BIM-assisted façade system improvement, and user-centric daylight utilization within BIM platforms. By summarizing the limitations from several studies, variability in lighting energy savings for different building types, correct and continuous monitoring and commissioning of the DCS, operation irregularities of lighting system, and dependence on occupants' behavior are of great potential for BIM implementation in terms of daylight system management strategies. What's more, several studies underscore the increasing potential for BIM to improve innovative façade design strategies, ranging from parametric design environments and multi-objective optimization to passive daylighting solutions and automated shading systems. With the aid of BIM implementation, aesthetic, functional, and energy-efficient building envelops could be designed to ensure sufficient indoor daylight. Last but not least, BIM could enhance the process of data organization and standardization for DCS, since occupants' preferences and behaviors, sensor data in DCS, and building spatial data are diverse, complex, and nested.

As for results, a sensor network diagram illustrating sensor network, data flow, and connections between devices of BIM enabled daylight control system for office buildings have been created. Additionally, a BIM assisted daylight control strategy diagram is also presented to outline user-centric control enabled within BIM platform. Not only does this research provide a comprehensive synthesis of existing literature in this domain, but also provide architects, DCS designers, and sustainable building professionals with potential advancements and inspirations to promote energy-efficient and user-centric building design in the future.

While this research presents insightful results regarding the integration of DCS and BIM in office buildings, certain limitations exist. First, the feasibility assessment relies on hypothetical scenarios which are based on the literature. Future studies could build on the findings of this research by conducting case studies. Second, a comprehensive quantitative assessment is needed to examine the effectiveness of the user-centric DCS within the BIM platform. In summary, empirical studies and case studies or analysis are needed to validate the theoretical framework proposed in this research. Practical applications of BIM-enabled DCS in office buildings should be explored to diverse building types.

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