Past, Present, and Future of BIM-Enabled Facilities Operation and Maintenance

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Abstract

By offering a powerful means to retrieve information from a virtual model of a facility, building information modeling (BIM) has the potential to save the costs borne by owners and operators during facility operation and maintenance (O&M). Currently, researchers and industry professionals require a state-of-the-art overview of the various BIM-related inventions and innovative applications in the facility O&M field. Through a literature review, this paper aims to evaluate and summarize current BIM-O&M research and application developments, analyze research trends, and identify promising future research directions. Publications studied in this research have shown BIM's capabilities in providing new functionalities for facility managers and supporting them in O&M tasks. Many comprehensive systems are established on the foundation of BIM and they can efficiently acquire, store, and process information, perform analysis to inform facility managers' decisions, and automate some of the O&M functions.

Keywords: Building information modeling (BIM); Facilities management (FM); Operation & maintenance (O&M); Literature review.

INTRODUCTION

According to a study conducted by the U.S. National Institute of Standards and Technology (NIST), the estimated cost of inadequate interoperability in the Architecture, Engineering, Construction, and Operations (AECO) industry in the U.S. is $15.8 billion per year (Gallaher et al., 2004). Approximately 57.8% of the cost is borne by owners and operators during facility operation and maintenance (O&M) (Gallaher et al., 2004) and historically is not taken into consideration early in the project development phase (Akcamete et al., 2010, Liu and Issa, 2015).

Building Information modeling (BIM) technology has the potential to save the costs caused by inadequate interoperability by offering owners and operators a powerful means to retrieve information from a virtual model of a facility (Teicholz and IFMA, 2013). In recent years, the proliferation of BIM has provided designers and builders new opportunities to achieve better quality buildings at lower cost and shorter project duration (Eastman et al., 2011, Krygiel and Nies, 2008, Hardin and McCool, 2015, Weygant, 2011). However, even though the need for BIM in facility O&M has been acknowledged since 2010 (Akcamete et al., 2010, Becerik-Gerber and Kensek, 2009, Parsanezhad and Dimyadi, 2014, Volk et al., 2014, Ilter and Ergen, 2015), facility operators have yet to embrace the benefits of BIM. Researchers and industry professionals require a state-of-the-art overview of BIM implementation and

research in facility O&M. For a facility manager, given the BIM model and the information contained, how to use them to improve the facility management (FM) performance is the question.

This research provides insights into current BIM capabilities in supporting facility O&M, by examining how each O&M activity can be leveraged by BIM and to what extent their efficiency and effectiveness can be improved.

The scope of this research includes the academic publications on BIM applications in improving facility operation and maintenance. The studied articles are published after 2007. This research excludes publications pertaining to infrastructure, the survey of existing buildings, BIM model creation and assessment.

REVIEW APPROACH

To identify related publications involving BIM applications in the facility O&M field, a keyword search is performed in academic databases, including ELSEVIER, EMERALD, EBSCO, WILEY, ASCE, CIB, SPRINGER, T&F, and ISPRS. Articles with abstracts contain "Building Information Modeling" (or "BIM") and the keywords "O&M", "operation", "maintenance", and "repair" are identified and reviewed. These articles are published from 16 journals, 11 conferences, and 2 book chapters. Each reviewed paper is examined in the following aspects: 1) which O&M activity is leveraged by BIM and how, 2) applicable facility type, 3) whether an innovative system, framework or approach is proposed, 4) whether a new work process is discussed, 5) whether a case study or simulation is presented, 6) other technologies integrated (such as, Augmented Reality, Geographic Information System, and etc.), and 7) whether challenges and obstacles are discussed. The results and findings from the analysis, and the recommendations for future research are provided in the following sections.

55 publications are reviewed— 36 journal papers, 17 conference papers, and 2 book chapters. Among these publications, except for 13 literature reviews and 13 papers that generally discuss BIM for FM, 29 papers have explicit research goals that involved utilizing BIM to improve the efficiency and effectiveness of one or multiple O&M activities. Within these 29 papers, 69% of the publications propose an innovative system, framework or approach; 48% of them include contents regarding integrating BIM with other technologies, including Augmented Reality (AR) (Lee and Akin, 2011, Koch et al., 2014, Irizarry et al., 2014), Geographic Information System (GIS) (Liu and Issa, 2012a, Isikdag et al., 2008, Wu et al., 2014, Wu and Zhang, 2016), Computerized Maintenance Management System (CMMS) (Liu and Issa, 2012b, Shalabi and Turkan, 2016, Asen et al., 2012, Motamedi et al., 2014), Building automation systems (BAS) (Shalabi and Turkan, 2016, Lawrence et al., 2012, Forns-Samso et al., 2012), Web/cloud-based calculation (Lin and Su, 2013), 2D barcode (Lin et al., 2014), Wireless Sensor Network (WSN) (Shen et al., 2012, Marzouk and Abdelaty, 2014), and Electrical instrumentation and control systems (EIC) (Zhou et al., 2015).

CURRENT RESEARCH AND APPLICATIONS OF BIM IN FACILITY O&M

Building Operation

Most building operation tasks are routine but important. A properly operated building tends to have a better energy performance and less maintenance workload. Centralized building management leads to more efficient and effective building operations (Roper and Payant, 2014). Currently, Building Automation Systems (BASs) control and monitor the major building systems and equipment, including ventilation, lighting, power, fire, and security systems (Ehlers et al., 1996). However, even though today's BAS collect a tremendous amount of data on building operation (Xiao and Fan, 2014), they are not designed to perform in-depth analysis that would inform FM managers in their decision-making processes.

BIM can serve as the platform of a Central Facility Repository (CFR), which houses and integrates 3D object parametric data, facility management data, building drawings and specifications, real-time sensor data, etc. (GSA, 2011). The outstanding question is how to leverage the CFR to improve the efficiency of building operation and reduce operators' workload. Existing studies in this field have either targeted to address part of this problem with BIM or showed that BIM has the capability to help FM reach higher efficiency in building operation. The major developments in this field are real-time monitoring (Sun and Che, 2012), information management (Zhou et al., 2015), building components localization (Motamedi et al., 2013), indoor navigation (Koch et al., 2014), supporting decision-making (Irizarry et al., 2014, Golabchi et al., 2016), and improving occupants thermal comfort (Marzouk and Abdelaty, 2014, Costa et al., 2015).

Fig. 1 depicts graphically the research findings of existing publications on BIM-enabled building operation. Assume a BIM model is available for the building. The first step is collecting the building's real-time information and storing it in BIM. The real-time data collection process can be done automatically using a wireless sensor network (WSN) (Marzouk and Abdelaty, 2014, Cheng et al., 2016, Wu et al., 2015, Shen et al., 2012). Once the data is collected, processing the data and mapping it to BIM can be a labor-intensive work (Marzouk and Abdelaty, 2014, Shalabi and Turkan, 2016), depending on the purposes of the proposed system and the BIM platform chosen. In most cases, a large amount of information needs to be transmitted from one system to another and interoperability issues are the major challenge (Pärn et al., 2017, Volk et al., 2014, Shalabi and Turkan, 2016).

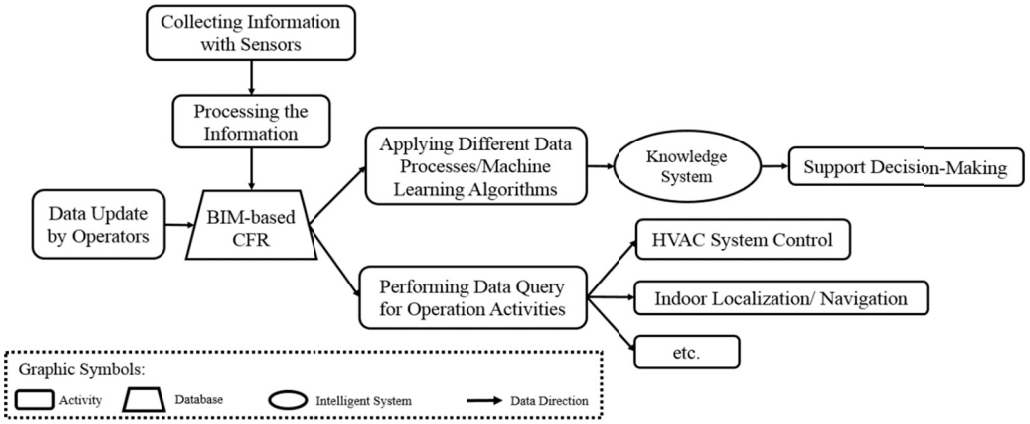

Figure 1: Current BIM-enabled building operation process

Different publications have introduced a variety of BIM-based CFRs. The BIM-based CFRs can be the BIM models housed in BIM-authoring software programs, such as Revit (Sun and Che, 2012) or AECOsim Building Designer (Golabchi et al., 2016), or in BIM-supporting tools, such as IES-VE (Marzouk and Abdelaty, 2014), or in some independent platforms developed by the researchers (Costa et al., 2015).

Once the BIM-based CRF is established, building operators can query data in support of their tasks, such as assets localization (Motamedi et al., 2013), equipment maintenance and fault handling (Sun and Che, 2012), and indoor navigation (Koch et al., 2014). Furthermore, BIM-based CFRs can be leveraged to build knowledge system by applying different data processing techniques and machine learning algorithms. Multiple studies have focused on turning the BIM information database into a BIM knowledge database to provide decision-making support for facility managers (Motawa and Almarshad, 2013, Shen et al., 2012, Skandhakumar et al., 2012, Schatz et al., 2014, Irizarry et al., 2014, Chen and Chu, 2015). Some proposed systems can perform automated decision-making (Golabchi et al., 2016).

Maintenance and Repair

BIM applications in facility maintenance and repair is the most extensively studied research area among facility management functions. The most common problem facility managers face is the information accessibility issues(Liu and Issa, 2015). During the facility operation phase, they usually do not have easy and quick access to the needed information to process work orders (Liu and Issa, 2015). The first step of addressing this issue is to establish a BIM-based CFR that provides FM managers timely access to facility information. Normally, the facilities data required to build the CFR is already available but it is fragmented and housed within different building management systems and archives. Studies are conducted involving digitalizing the archive, populating BIM with the maintenance data, and integrating BIM with other building management systems. These systems include building energy management systems (BEMS) (Shalabi and Turkan, 2016), electrical instrumentation and control (EIC) system (Zhou et al., 2015), CMMS (Liu and Issa,

2012b, Shalabi and Turkan, 2016, Asen et al., 2012, Motamedi et al., 2014), GIS (Liu and Issa, 2012a, Isikdag et al., 2008, Wu et al., 2014, Wu and Zhang, 2016), and BAS (Shalabi and Turkan, 2016, Lawrence et al., 2012, Forns-Samso et al., 2012). To tackle the interoperability issue in system integration, some studies adopt Industry foundation classes (IFC) as the data exchange schema for BIM (Shalabi and Turkan, 2016, Asen et al., 2012, Motamedi et al., 2014, Zhou et al., 2015, Isikdag et al., 2008, Wu et al., 2014, Wu and Zhang, 2016, Forns-Samso et al., 2012). Others perform data exchange by commercial software applications or programs developed by the authors (Liu and Issa, 2012a, Liu and Issa, 2012b).

Once the CFR is established, the next question is how to provide timely information access for facility managers and how to present the information in an intuitional fashion such that maintenance personnel can easily comprehend it. Some researchers proposed the integration of 2D barcode and RFID into BIM-enabled maintenance systems (Lin et al., 2014, Motamedi et al., 2013). Barcodes and RFID tags serve as identifications of building items and the relevant information is linked with the corresponding objects in BIM models. By scanning the barcode or RFID tag of the item, the mobile device will present its information, such as product information, purchase date, price, custodian, inventory, etc. (Lin et al., 2014, Motamedi et al., 2013).

Augmented Reality (AR) also provides a suitable interface for O&M fieldwork. In contrast with barcode and RFID-based systems, AR systems do not necessarily require installing identification tags on facility items to identify them. Visual markers can be defined within the BIM-AR system and captured by the AR equipment's camera (Lee and Akin, 2011). One example of the visual markers is the natural indoor markers, such as exit signs, position marks of fire extinguishers, signs with textual information hints, and device ID tags (Koch et al., 2014). As soon as the camera detects the visual marker, the information of the identified item will show on the AR equipment's screen.

Systems built on BIM-based CFR can also analyze maintenance related tasks. A major progress is BIM applications in equipment fault detection and diagnosis. Researchers improve maintenance and repair procedures by leveraging BIM's visualization and analysis capabilities to detect and locate system faults (Golabchi et al., 2016, Zimmermann et al., 2012) and identify failure cause-effect patterns (Motamedi et al., 2014, Asen et al., 2012). For example, Motamedi et al. propose a system that collects historical data from other systems, such as CMMS, to establish the knowledge base in BIM, and provides visual analytics to support facility managers' cognitive and perceptual reasoning when making decisions and addressing issues (Motamedi et al., 2014).

Multiple studies propose systems that would inform and support decisions made by facility managers when performing maintenance and repair tasks (Akcamete et al., 2010, Yang and Ergan, 2015, Shen et al., 2012, Motawa and Almarshad, 2013, Sampaio et al., 2016, Motamedi et al., 2014, Asen et al., 2012, Golabchi et al., 2016). These systems integrate the relevant information, perform comprehensive analysis, provide intuitional 3D visualization, and offer real-time access to users. However, even though the benefits of these systems are understood and accepted, only a few

studies have examined the quantified efficiency improvements brought by their proposed systems (Yang and Ergan, 2015, Lin et al., 2014).

DISCUSSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

Even though BIM provides a promising platform to house, process, and acquire facility data, research on BIM-O&M is still in its very early stage. In the facility O&M field, many important questions of BIM implementations have not been answered and more advanced systems are yet to be invented.

Currently there still exists a gap in understanding of the current workflow process involved in carrying out each FM activities, and the areas of inefficiencies that could potentially be addressed by BIM. The BIM-O&M field would benefit immensely from surveys that target this aforementioned gap. The BIM data requirements can vary with different O&M practitioners, types of facilities, and FM tasks. Learning about the different FM workflows, challenges encountered, and expectations of new technology is an urgent issue for researchers. Furthermore, one of the major goals of the emerging BIM-O&M systems is to reduce dependency on experts, which requires acquiring experts' knowledge and incorporating it into the systems. Obtaining the knowledge also requires extensive surveys. Currently, the surveys aiming to answer these questions are limited and more surveys need to be conducted (Becerik-Gerber et al., 2012, Rahman et al., 2013, Liu and Issa, 2015, Gheisari et al., 2014, Bosch et al., 2015, Sattenini et al., 2011).

Another noticeable gap in the existing body of knowledge is that very few studies discuss the changes on FM workflow processes by implementing BIM. BIM is a disruptive technology that already changed the design and construction industry. Facility O&M, however, has not fully embraced the benefits of BIM yet. Soon, the process change brought by the technology innovation will be a pressing issue. BIM has enabled integrated design and construction and has provided the technology foundation for Integrated Project Delivery (IPD). As the BIM-O&M applications continue developing, we can expect more discussions on the process changes in this area.

The challenges and obstacles for BIM implementation in facility management have been discussed by different studies (Ilter and Ergen, 2015, Volk et al., 2014, Pärn et al., 2017, Shen et al., 2010, Yalcinkaya and Singh, 2014, Becerik-Gerber et al., 2012). One question that has been mentioned but not extensively discussed is that most of the time facility managers and field technicians are lacking the necessary knowledge and skills to implement BIM-FM. As a result they are hesitant to change their current workflow and some proposed systems are difficult for new users. This issue can be addressed by designing user-centered systems that are easy to use and centered on the established workflows. With user-friendly interfaces and intuitive information presentations, BIM-based systems can serve as a support tool rather than a technology burden. Achieving this requires knowledge and techniques of Human-Computer Interaction. Prototype evaluation methods, such as cognitive walkthrough (Polson et al., 1992), can provide measurements on the usability of the proposed systems.

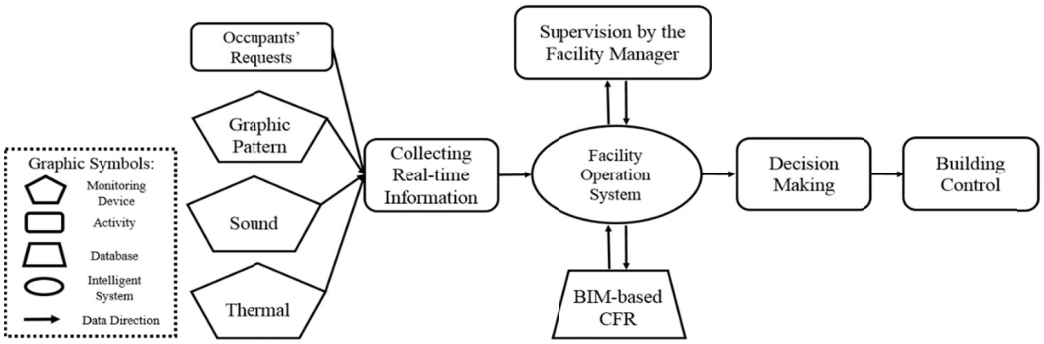

Figure 2: Future of facility operation

CONCLUSION

BIM-enabled facility Operation & Maintenance (O&M) is a new and growing area of research. The purpose of this paper is to evaluate and summarize current BIM-O&M research and application developments, analyze research trends, and identify promising future research directions. Publications studied in this research have shown BIM's capabilities in providing new functionalities for facility managers and supporting them in O&M tasks. Many comprehensive systems are established on the foundation of BIM and they can efficiently acquire, store, and process information, perform analysis to inform facility managers' decisions, and automate some of the O&M functions.

We have identified that more studies involving surveys are needed to understand the current FM workflows, challenges, areas of inefficiencies, and technology needs. New BIM-enabled FM workflow processes need to be developed to leverage the growing BIM-FM technologies. More user-centered BIM-O&M systems are desired and intelligent systems that can perform facility operation functions can be expected in the near future.

REFERENCES

AKCAMETE, A., AKINCI, B. & GARRETT, J. H. Potential utilization of building information models for planning maintenance activities. Proceedings of the international conference on computing in civil and building engineering, 2010. June, 151-157.

ASEN, Y., MOTAMEDI, A. & HAMMAD, A. 2012. BIM-Based Visual Analytics Approach for Facilities Management. *14th International Conference on Computing in Civil and Building Engineering*, 1-8.

BECERIK-GERBER, B., JAZIZADEH, F., LI, N. & CALIS, G. 2012. Application Areas and Data Requirements for BIM-Enabled Facilities Management. *Journal of Construction Engineering & Management,* 138, 431-442.

BECERIK-GERBER, B. & KENSEK, K. 2009. Building information modeling in architecture, engineering, and construction: emerging research directions and trends. *Journal of professional issues in engineering education and practice,* 136, 139-147.

BOSCH, A., VOLKER, L. & KOUTAMANIS, A. 2015. BIM in the operations stage: Bottlenecks and implications for owners. *Built Environment Project and Asset Management,* 5**,** 331-343.

CHEN, A. Y. & CHU, J. C. 2015. TDVRP and BIM Integrated Approach for In-Building Emergency Rescue Routing. *Journal of Computing in Civil Engineering***,** C4015003.

CHENG, M.-Y., CHIU, K.-C., HSIEH, Y.-M., YANG, I.-T. & CHOU, J.-S. Development of BIM-based Real-time Evacuation and Rescue System for Complex Buildings. ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, 2016. Vilnius Gediminas Technical University, Department of Construction Economics & Property, 1.

COSTA, A. A., LOPES, P. M., ANTUNES, A., CABRAL, I., GRILO, A. & RODRIGUES, F. M. 2015. 3I Buildings: Intelligent, Interactive and Immersive Buildings. *Procedia Engineering,* 123**,** 7-14.

EASTMAN, C., TEICHOLZ, P., SACKS, R. & LISTON, K. 2011. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors (2nd Edition). 1-648.

EHLERS, G. A., HOWERTON, R. D. & SPEEGLE, G. E. 1996. *Engery management and building automation system*.

FORNS-SAMSO, F., LAINE, T. & HENSEL, B. 2012. Building information modeling supporting facilities management. *Proceedings ECPPM Ework and Ebusiness in Architecture, Engineering and Construction.*

GALLAHER, M. P., O'CONNOR, A. C., DETTBARN, J. L. & GILDAY, L. T. 2004. Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry. 1-210.

GHEISARI, M., GOODMAN, S., SCHMIDT, J., WILLIAMS, G. & IRIZARRY, J. Exploring BIM and mobile augmented reality use in facilities management. Proceedings of the Construction Research Congress, 2014. 1941-1950.

GOLABCHI, A., AKULA, M. & KAMAT, V. 2016. Automated building information modeling for fault detection and diagnostics in commercial HVAC systems. *Facilities,* 34**,** 233-246.

GSA, G. S. A. 2011. BIM Guide For Facility Management

HARDIN, B. & MCCOOL, D. 2015. *BIM and construction management: proven tools, methods, and workflows*, John Wiley & Sons.

ILTER, D. & ERGEN, E. 2015. BIM for building refurbishment and maintenance: current status and research directions. *Structural Survey,* 33**,** 228-256.

IRIZARRY, J., GHEISARI, M., WILLIAMS, G. & ROPER, K. 2014. Ambient intelligence environments for accessing building information: A healthcare facility management scenario. *Facilities,* 32**,** 120-138.

ISIKDAG, U., UNDERWOOD, J. & AOUAD, G. 2008. An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes. *Advanced engineering informatics,* 22**,** 504-519.

KOCH, C., NEGES, M., KÖNIG, M. & ABRAMOVICI, M. 2014. Natural markers for augmented reality-based indoor navigation and facility maintenance. *Automation in Construction,* 48**,** 18-30.

KRYGIEL, E. & NIES, B. 2008. *Green BIM: successful sustainable design with building information modeling*, John Wiley & Sons.

LAWRENCE, T. M., WATSON, R. T., BOUDREAU, M.-C., JOHNSEN, K., PERRY, J. & DING, L. 2012. A new paradigm for the design and management of building systems. *Energy and Buildings,* 51**,** 56-63.

LEE, S. & AKIN, Ö. 2011. Augmented reality-based computational fieldwork support for equipment operations and maintenance. *Automation in Construction,* 20**,** 338-352.

LIN, Y. C. & SU, Y. C. 2013. Developing mobile- and BIM-based integrated visual facility maintenance management system. *ScientificWorldJournal,* 2013**,** 124249.

LIN, Y. C., SU, Y. C. & CHEN, Y. P. 2014. Developing mobile BIM/2D barcode-based automated facility management system. *ScientificWorldJournal,* 2014**,** 374735.

LIU, R. & ISSA, R. 2012a. 3D visualization of sub-surface pipelines in connection with the building utilities: Integrating GIS and BIM for facility management. *Computing in Civil Engineering***,** 341-348.

LIU, R. & ISSA, R. R. A. Automatically Updating Maintenance Information from a BIM Database. *In:* ISSA, R. R. & FLOOD, I., eds. Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering, 2012/01/01/ 2012b Place of Publication: Reston, VA, USA; Clearwater Beach, FL, USA. Country of Publication: USA.: American Society of Civil Engineers Tech. Council Comput. Inf. Technol. American Soc. Civil Eng. Tech. Council Comput. Inf. Technol. American Soc. Civil Eng., 373-380.

LIU, R. & ISSA, R. R. A. 2015. Survey: Common Knowledge in BIM for Facility Maintenance. *Journal of Performance of Constructed Facilities*.

MARZOUK, M. & ABDELATY, A. 2014. Monitoring thermal comfort in subways using building information modeling. *Energy and Buildings,* 84**,** 252-257.

MOTAMEDI, A., HAMMAD, A. & ASEN, Y. 2014. Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Automation in Construction,* 43**,** 73-83.

MOTAMEDI, A., SOLTANI, M. M. & HAMMAD, A. 2013. Localization of RFID-equipped assets during the operation phase of facilities. *Advanced Engineering Informatics,* 27**,** 566-579.

MOTAWA, I. & ALMARSHAD, A. 2013. A knowledge-based BIM system for building maintenance. *Automation in Construction,* 29**,** 173-182.

PÄRN, E., EDWARDS, D. & SING, M. 2017. The building information modelling trajectory in facilities management: A review. *Automation in Construction,* 75**,** 45-55.

PARSANEZHAD, P. & DIMYADI, J. 2014. Effective Facility Management and Operations via a BIM-based Integrated Information System. *CIB Facilities Management Conference.* Technical University of Denmark.

POLSON, P. G., LEWIS, C., RIEMAN, J. & WHARTON, C. 1992. Cognitive walkthroughs: a method for theory-based evaluation of user interfaces. *International Journal of man-machine studies,* 36**,** 741-773.

RAHMAN, M. A., SUWAL, S., JÄVÄJÄ, P. & LIC, T. Diverse approach of BIM in AEC industry: a study on current knowledge and practice. Proceedings of the CIB W78 International Conference, 2013. 2013.

ROPER, K. O. & PAYANT, R. P. 2014. *The Facility Management Handbook*, AMACOM Div American Mgmt Assn.

SAMPAIO, A. Z., SIMÕES, D. G. & BERDEJA, E. P. 2016. BIM Tools Used in Maintenance of Buildings and on Conflict Detection. *Sustainable Construction.* Springer.

SATTENINI, A., AZHAR, S. & THUSTON, J. Preparing a building information model for facility maintenance and management. 28th International Symposium on Automation and Robotics in Construction, Seoul, South Korea, 2011. 144-149.

SCHATZ, K., SCHLITTENLACHER, J., ULLRICH, D., RÜPPEL, U. & ELLERMEIER, W. 2014. Investigating Human Factors in Fire Evacuation: A Serious-Gaming Approach. *Pedestrian and Evacuation Dynamics 2012.* Springer.

SHALABI, F. & TURKAN, Y. 2016. IFC BIM-Based Facility Management Approach to Optimize Data Collection for Corrective Maintenance. *Journal of Performance of Constructed Facilities***,** 04016081.

SHEN, W., HAO, Q., MAK, H., NEELAMKAVIL, J., XIE, H., DICKINSON, J., THOMAS, R., PARDASANI, A. & XUE, H. 2010. Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics,* 24**,** 196-207.

SHEN, W., HAO, Q. & XUE, Y. 2012. A loosely coupled system integration approach for decision support in facility management and maintenance. *Automation in Construction,* 25**,** 41-48.

SKANDHAKUMAR, N., SALIM, F., REID, J. & DAWSON, E. 2012. Physical access control administration using building information models. *Cyberspace Safety and Security.* Springer.

SUN, C. S. & CHE, Q. 2012. BIM-Based Real-Time Monitoring of the Equipment Maintenance of Property. *Applied Mechanics and Materials,* 226-228**,** 2217-2221.

TEICHOLZ, P. & IFMA 2013. *BIM for Facility Managers*.

VOLK, R., STENGEL, J. & SCHULTMANN, F. 2014. Building Information Modeling (BIM) for existing buildings — Literature review and future needs. *Automation in Construction,* 38**,** 109-127.

WEYGANT, R. S. 2011. *BIM content development : standards, strategies, and best practices / Robert S. Weygant*, Hoboken, N.J. : Wiley, c2011.

WU, B. & ZHANG, S. 2016. INTEGRATION OF GIS AND BIM FOR INDOOR GEOVISUAL ANALYTICS. *ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences***,** 455-458.

WU, W., LI, W., LAW, D. & NA, W. 2015. Improving Data Center Energy Efficiency Using a Cyber-physical Systems Approach: Integration of Building Information Modeling and Wireless Sensor Networks. *Procedia Engineering,* 118**,** 1266-1273.

WU, W., YANG, X. & FAN, Q. 2014. GIS-BIM Based Virtual Facility Energy Assessment (VFEA)–Framework Development and Use Case of California State University, Fresno. *Computing in Civil and Building Engineering***,** 339-346.

XIAO, F. & FAN, C. 2014. Data mining in building automation system for improving building operational performance. *Energy and buildings,* 75**,** 109-118.

YALCINKAYA, M. & SINGH, V. Building information modeling (BIM) for facilities management–literature review and future needs. IFIP International Conference on Product Lifecycle Management, 2014. Springer, 1-10.

YANG, X. & ERGAN, S. 2015. Design and Evaluation of an Integrated Visualization Platform to Support Corrective Maintenance of HVAC Problem–Related Work Orders. *Journal of Computing in Civil Engineering,* 30**,** 04015041.

ZHOU, J., LOVE, P., MATTHEWS, J., CAREY, B. & SING, C. 2015. Object-oriented model for life cycle management of electrical instrumentation control projects. *Automation in Construction,* 49**,** 142-151.

ZIMMERMANN, G., LU, Y. & LO, G. 2012. Automatic HVAC fault detection and diagnosis system generation based on heat flow models. *HVAC&R Research,* 18**,** 112-125.