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INVESTIGATING THE POTENTIAL METHODS OF INTEGRATING BIM AND IOT

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Declaration

I hereby declare that this thesis is my own work and effort and that it has not been submitted anywhere for any award. Where other sources of information have been used, they have been acknowledged.

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Introduction

BIM

The built environment we experience today is far from ideal. As we know, the world is quickly becoming digitalised – we are currently entering the 4th industrial revolution which is driven by the digital transformation. Especially in AEC companies, digital information modelling has become the norm across many firms through use of BIM (Building Information Modelling). BIM is becoming a standardised method of designing and constructing today's buildings. It refers to digital representation of physical components of buildings and its facilities. Its functionalities have evolved from simple 3D modelling to assigning attributes containing information such as energy and structural performance of the materials and infrastructures as well as cost and schedules associated with constructing them. BIM has enormous potential in not only delivering construction projects in more time and cost efficient manner, but also to a much higher quality. In other words, it revolutionised the AEC industry from 2D lines with little meaning to 4D models capable of extracting or computing just about any information you may need about a building, room, wall or column (Woodhead, Stephenson, & Morrey, 2018).

Furthermore, the BIM model is not simply out of use once construction is complete. The functionalities and opportunities BIM brings extend to the operation of building. It may even bring more potential savings after the building is complete as 80% of all costs in a building lifecycle are consumed during the operation (Tyréns, 2016). Majority of the costs associated with running a building are used for energy and maintenance. Both have huge potential for more efficiency and decrease in costs. Maintenance management can benefit from sensor networks and IoT by implementing condition based monitoring (CBM) into the building's IoT and BMS systems. This allows for more control in resource allocation for maintenance tasks – certain activities will only be executed as required by the system, not based on a time schedule. Similarly, in energy consumption, IoT and BMS can allow the building respond to occupancy or weather changes and turn on heating, cooling, lighting etc. accordingly. It is evident there are huge potential savings in integrating BMS and IoT together to improve building performance. The technology is there, the main challenge today is the integration of these building systems together into a holistic smart system capable of controlling majority of the buildings facilities independently or with little human input.

IoT

The Internet is growing exponentially. The next generation of Internet, referred to as Internet of Things (IoT) is going to connect not only, computers and mobile devices, but also buildings, homes and their contents, electrical grids, water and gas networks, cars and so on. This connection across physical devices and objects is growing so fast, it is expected to grow from approximately 9 billion today to over 50 billion by year 2020 (Carrillo, Benitez, Mendoza, & Pacheco, 2015). Just like BIM changed the way we design, construct and operate buildings, IoT is changing the way we live – work, manage our homes and infrastructures, maintain our health, educate as well as how we secure, protect and entertain ourselves (Ahlgren, Hidell, & Ngai, 2016).

The rise of IoT leads to development of cyber-physical systems in our built environments. A Cyber-physical system reads sensor data containing information about conditions of physical objects or environment, processes the information, and sends it to the actuators or effectors for them to make an appropriate change to the object or environment (Banerjee, Venkatasubramanian, Mukherjee, & Gupta, 2012). A smart building or city can be described as a set of interconnected cyber-physical systems.

However, with all these opportunities for making our life significantly easier, also come challenges. In particular, the lack of standardised communication protocols is holding IoT back from being fully integrated with our environments. As the complexity and number of the cyber-physical systems increases, so do ICT (Information and Communication Technologies) costs associated with them. The key is finding the right balance between reducing ICT costs and fulfilling as many requirements as possible. Integration of IoT systems is particularly difficult because the cyber-physical systems, similar to systems in buildings are often designed as independent and isolated systems, strongly limiting the openness and compatibility with other systems (Charith, Zaslavsky, Peter, & Georgakopoulos, 2014).

As outlined in one study by (Framling, Kubler, & Buda, 2014), a messaging protocol for internet of things applications should meet the following requirements:

1. Ability to implement any kind of instances as independently of the application domain as possible.
2. Ability to implement for any kind of information system, including embedded and mobile systems.
3. Ability for synchronous messaging including immediate read and write operations
4. Should not be restricted to a single communication protocol, must be able to send messages using standard protocols such as plain HTTP, SOAP, SMTP, file copies etc.
5. Ability to create as hoc, loosely coupled, time-limited information flows “on demand”.
6. Possibility for peer-to-peer communication for all devices – client and server functionality can be implemented for any device, depending on available processing power, network connectivity etc.
7. Handling mobility and intermittent network connectivity – support for asynchronous messaging capabilities that imply for instance message persistence, time-to-live etc.
8. Possibility for context-dependent discovery of instances, instance-related services and meta-data about them
9. Support for context and domain specific ontologies
10. Queries by regular expressions for retrieving information about more than one instance and more than one kind of information
11. Historical queries – retrieving values between two points in time.

The main challenge for any communication protocol that aims to become standardised is to fulfil as many of these requirements while maintaining feasibility for implementation across a wide range of applications.

Integration of IoT and BIM

Currently, the majority of IoT devices are deployed in build environments (Tyréns, 2016).Therefore, to fully benefit from IoT’s benefits, the gap between integrating build environment data and IoT standards must be closed. Another important point to note is that because BIM and even more so IoT are still emerging technologies, now is the time to integrate and standardize both in a way that they are compatible with each other. BIM is currently being standardized thought OpenBIM and its IFC standards. While IFC, the standardized data format for BIM models has big potential, it is still a long way away from being perfect.

Internet of Things on the other hand is very different to BIM. There is less commonalities between each case and different solutions will suit various problems. There are many different communication protocols currently used in IoT, with little standardization. Cyber-physical systems ie. Sensor networks in building alone use quite a wide range of different communication protocols such as BACnet, KNX, LONWORKS, DALI, Modbus, oBIX, OPC, Zigbee, Z-Wave etc. (Dave, Buda, Nurminen, & Främling, 2018). The number of different communication networks used in buildings alone poses a significant challenge in integrating these systems and buildings together to from smart buildings and smart cities, respectively.

The aim of this report is to investigate feasible methods of integrating BIM and IoT in built environments to benefit from it both financially and from the occupants' comfort perspective. A systematic review of possible solutions has been undertaken and the findings are summarised in the following sections of this report. Section 2 will discuss the common communication protocols that are used in today's buildings' sensor networks. Section 3 will evaluate the tiers or layers of a typical frameworks used for integrating BIM and IoT. Section 4 will discuss the overall findings and finally section 5 will conclude the report.

Communication Protocols

Communication and network technologies are generally divided into two types: wired and wireless. Traditionally building metering and sensing equipment use wired technologies. However, given the recent developments in wireless networks and cloud services have initiated a transition from wired to wireless networks. Various studies have been undertaken analysis the feasibility of these networks in building automation such as (Corbellini et al., 2017). Both technologies have their advantages and disadvantages. For example, wireless networks tend to be cheaper due to low installation and operational costs while wired networks offer a more secure data transfer. Hence, the choice of technology will vary from case to case based on requirements of the problem. Choice of communication network plays a critical role in successful automation of buildings and development of smart buildings, grids and cities (Usman & Shami, 2013).

Zigbee

The design of ZigBee was based on IEE802.15.4 Standard and it operates in the 2.4 GHz and 900 MHz bands. ZigBee is a low cost solution with reliable data transfer and short range making it seemingly a perfect choice for building automation systems. However, ZigBee's low power and transition rate make it difficult to apply to strong real-time data transfer as well as cases with large transfer of data (Zhang, Sun, & Cui, 2010) making it insufficient for sophisticated and complex automation systems. The low power of less than 1 mW can also be a selling point depending on the requirements. One of ZigBee's major advantages is its security. It meets the requirements for seven-layer protocol layer and has additional security module (Xu, Gui, Zhao, & Yang, 2013). Another one of advantages going got ZigBee is its expandability – it can connect to 255 nodes (Lin, Liu, & Fang, 2007). Communications in a ZigBee network are based on a Master/Slave relationship. This means that the control system request data, hence data is only transferred when required and the receiver confirms the data was successfully transferred. Various studies have been undertaken evaluating the technical feasibility of using ZigBee for smart metering applications such as (Kang, Ke, & Li, 2011). Majority of the studies agree ZigBee's specifications are proficient at serving smart applications, however suitability for integration of BIM and IoT may be limited due to its inability to effectively transfer real-time data.

Modbus

Modbus is used for point-to-point connections with EIA-232C interfaces of programmable logic controllers. It was developed by Modicon Corporation and is now one of the most widely spread communication networks due to its simplicity and reliability. Similar to ZigBee, ModBus also operates in the Master/Slave relationship. Initially, ModBus was designed to communicate low speed serial in process control networks, hence security issues of this network were not addressed. The major concern is the operation of ModBus is the lack of authentication and encryption meaning the data transfer is less secure and more vulnerable to cyberattacks. Due to ModBus' simple design and open source availability, Modbus is most popular in cases involving local communication in buildings and industrial SCADA systems. (Yilin Mo et al., 2012) analysed the operation of ModBus in a building automation system using wired connections. The network worked well but the authors pointed out that wired solutions are not suitable to for retrofitting buildings hence power lines or wireless solutions are superior. There are also alternative options of Modbus wirelessly such as (Crouse-Hinds, n.d.). However, the suitability of these systems in building IoT systems is unknown.

PLCs

Power Line Carriers (PLCs) use existing networks such as electricity grid, mesh network, licensed and unlicensed radio, cellular network, WiFi etc. to upload data using IEC DNP (Depuru, Wang, & Devabhaktuni, 2011). PLCs are most suitable for remote locations with limited coverage and low number of consumers. The conjunction of data and electricity transmission can become problematic as distortion can occur and transformer points should be avoided. PLC's also have very low bandwidths making them unsuitable for certain cases. Majority of PLCs' advantages come from its low costs and convenience of utilising existing infrastructure. These networks are commonly used by utility providers due to easier control and management as the two networks are contained within one infrastructure which translates to lower costs. According to (Depuru et al., 2011) PLC's are a proficient technology in the automation of data transfer in smart meter applications. Its low bandwidth however only limits it to low bandwidth cases such as switching traffic and streetlights. (Kim, Lee, Wang, Choi, & Chung, 2007) evaluated the proficiency of PLCs in control data transfer. However, integration with other systems proved problematic. While PLCs are a suitable solution for various applications, its inability to coordinate with other systems and susceptibility to interferences make it undesirable for building automation and Internet of Things.

M-Bus

M-Bus stand for Meter-Bus and is used by utility providers to transmit heat, gas, oil meter readings. This network was designed specifically for meter reading and is therefore less popular than ModBus. One of the main benefits of using M-Bus is the large number of devices that may be connected in this network and the ease of expandability. M-Bus is traditionally a wired solution. However, a wireless version of M-Bus exists and recent studies such as (Flammini, Rinaldi, & Vezzoli, 2011) have focused on development of those systems. These wireless M-Bus networks are generally recommended for smart meter applications. However, its ability to transfer sensor and control data is limited. Therefore, it is not the best solution for integration of BIM and IoT in built environments.

GPRS and GSM

GPRS and GSM stand for general packet radio service and global system for mobile, respectively. These two network types are probably the most widespread communications technologies out there and even the most remote areas usually have coverage. The main issue with these networks in the reliability of SMS during time of high data transfer congestion (Usman & Shami, 2013). (Ashna & George, 2013) have suggested GSM as a billing network for smart meters. However, the lack of reliability during busy period is challenging along with low security causing a risk of customers hacking the network to alter their meter readings. Various studies have tested the suitability of GSM in other applications such as (Kang et al., 2011) where the author implemented a GSM system to a home load monitoring and control system. While there are many opportunities within these technologies due to its wide coverage, it should be implemented with caution. Building cyber-physical systems will have times of high data transfer and this networks limited reliability during these periods make it unusable in built environments.

Ethernet

Ethernet is a low cost solution often used as a communication link between PLCs and other systems. Ethernet is available is three media: coaxial cables, shielded twisted pair and optical fiber. Optical fiber operates by the means of light beams and hence is more secure and popular due to the absence of electromagnetic inferences (Strobel & Lubkoll, 2010). While Ethernet is not suitable for real-time data transfer due to priori estimation of the data packet's maximum transmission time being impossible as pointed out by (O'Driscoll & O'Donnell, 2013), there are other versions that allow for that such as RTE (real time Ethernet), Powerlink and EtherCAT. However, these solutions are still not favourable in smart buildings due to the need for cabling and strong involvement of IT in running of the system.

WiFi

WiFi gained huge popularity in the wireless sensing industry due to its low cost and ease of installation. WiFi networks are often already installed in buildings making these solutions even more favourable. They are not sufficient for certain purposes as of yet due to its security issues. (Mushtaq, 2010) has discussed in detail the extent of security concerns associated with WiFi networks. WiFi is often used for building automation, remote control etc. due to its low cost and availability. One study also used WiFi as occupancy detection medium in a commercial building and actuated HVAC accordingly. The resuts showed a reduction in energy consumption of 17.8%.

BACnet

BACnet stands for building automation and control network and was introduced by ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) and is now an American National Standard (ASHRAE 135-1995) and ISO Standard (ISO 16484-5) standard protocol [59]. The driving factor behind BACnets popularity in building automation is its ability to integrate with a variety of equipment without any additional hardware having to be installed. BACnet is typically a wired network. However, a wireless version has been developed using ZigBee allowing BACnet to capture both BACnets compatibility with other equipment as well as ZigBee's lower costs, expandability and connectivity to mobile devices forming a universal solution for building automation systems [13].

oBIX

oBIX (open Building Information Xchange) is a communication protocol developed for reading and writing data over a network of devices in a built environment. It was designed specifically to be used within an automation software. It was created as an effort to standardise XML and Web Services and facilitate open exchange of information between intelligent buildings and develop truly integrated systems ("oBIX," n.d.). In other words, oBIX enables building mechanical and electrical control systems to communicate with enterprise applications. Similar to OpenBIM data formats, information is represented in object form and objects with any structure and contents can be freely exchanged (Neugschwandtner, Neugschwandtner, & Kastner, 2007). oBIX has the functionality to receive three types of commands or "verbs". These are:

- Read – returns the current state of a specified object
- Write – updates the state of the object
- Invoke – triggers an operation on an object

Furthermore, oBIX provides a command called watch objects that allows the user to subscribe to object events – request certain information and receive latest updates through a poll enabled by URI from the server. Another useful feature this communication protocol brings is the alarm function – the user can define alarm triggering events or occurrences and the system will notify the users accordingly. (Kubler, Madhikermi, Buda, & Främling, 2015). This functionality allows for easier automation of data analysis often required in building management. While (Framling et al., 2014) stated that oBIX lacks certain functionalities to be used across other IoT applications and the oBIX Technical Committee does not plan on expanding it capabilities past mechanical and electrical control systems, it seems like It is optimal solution for integration of IoT and BIM in built environments.

Frameworks Integrating BIM and IoT

Following the first step of investigating the potential communication protocols that can enable communication between BIM and IoT networks, the second step is to research frameworks which will allow to connect these independent systems into a collaborative platform. This will allow the users to effectively manage these systems together and improve the performance of the building by implementing further technologies such as demand and predictive control logics. This approach can be further expanded to blocks of buildings, leading to creation of smart campuses and eventually smart cities. This is essential to multinational companies with global building portfolios who can benefit the most from integrated building management solutions (Schumann, Gorman, & Ploennings, 2014). This would have never been possible without the emergence of IoT. IoT allows placing sensors providing intelligence where it's needed, communicating the data to the BMS, and analysing it to gain further benefits from the obtained information.   Furthermore cloud capabilities can allow to scale up this approach to other buildings and develop a remote BMS system which can manage multiple buildings simultaneously.

The first step was to research communication infrastructures capable of supporting a framework that will enable the implementation of IoT and BIM. The second step is to investigate what frameworks exist that can make that happen. One of the first attempts at developing such framework was when (Dawson-haggerty et al., 2013) defined a three-layer software architecture made up of a hardware abstraction layer that integrated various systems together, a time series layer responsible for storing, selecting and cleaning real-time and historical data and a software layer which brings everything together. That architecture was then built in other studies, notably (Fierro & Culler, 2015) made a more expandable version of the building operating systems which has more flexibility to include more systems as well as improving on other aspects such as security, API (Application Programming Interface) and UX (User Experience). (Palmer et al., 2014) also attempted to improve the scalability of these BMS platforms by utilising XMPP communication protocol, which favours scalability and security. (Teizer et al., 2017) have proposed to integrate BIM data with IoT sensors, with a focus on making available performance, environmental and localisation data of workers in an indoor work environment. The goal of the research is to create a safe job site where information integrated from several sources such as production control and BIM can be synchronised with IoT sensors (lighting, proximity, etc.) to provide real-time feedback to workers. However, none of these efforts capture the new recent developments in the IoT space and hence don't take advantage of the benefits it offers such as improved scalability capable of developing centralised BMS systems that can control multiple buildings simultaneously.

There has also been progress in development of reference architectures in the general IoT industry. Some examples of such are:

- IIRA (Industrial Internet Reference Architecture) – Developed by Industrial Internet Consortium of America, IIRA is a standards-based architectural template and methodology enabling Industrial Internet of Things system architects to design their own systems based on a common framework and concepts (Industrial Internet Consortium, 2013).
- IoT-A (Internet of Things – Architecture) – EU project which had aimed to become a generic Reference Model, derived from Business considerations, application-based requirements and current technologies, able to generate different Reference architectures depending on domain-specific requirements, to be used as a blueprint for concrete architecture design (Savry, Leti, & Sap, 2013).
- oneM2M – Another European based project, which stands for one Machine-to-Machine, implying standard IoT framework. oneM2M delivers a set of standards to provide a horizontal platform architecture, enabling applications to connect securely, through standardized APIs, to data sources regardless of the underlying connectivity technology used (OneM2M, 2012).
- AIOTI (Alliance for Internet of Things Innovation) High Level Architecture – EU organisation publishing recommendations of reference architectures, both for experimentation and deployments within IoT domains and cross - IoT domains (Alliance for Internet of Things Innovation, 2017).

- ITU-T Recommendations - Developed by Internet of Things Global Standards Initiative Group. The Study Groups of ITU's Telecommunication Standardization Sector (ITU-T) assemble experts from around the world to develop these international standards which act as defining elements in the global infrastructure of information and communication technologies (ICTs) (ITU, 2015).

The above organisations and documents are leading concepts in development of reference model and reference architectures to allow for a common understanding of Internet of Things and common foundation for development of these systems in a way that they interoperable with outer systems. While diversity of organisations aiming to standardize IoT is concerning, it may need to be the case to some extent due to broad sectors IoT will affect and potential variation between architectures in various industries. However, there is a clear commonality between these frameworks – they all contain three major layers:

- Edge layer – Mainly consists of IoT devices. Primary function is to sense and communicate the conditions of the environment they are located in.
- Platform layer – The main function of this layer is consolidated processes and data storage & analysis. This layer uses the information flow from the edge layer devices and interprets the built environment data through standard formats (eg. IFC) either through directly stored local data or through data stored in servers and accessed through APIs. It also usually provides management functionalities for the devices contained in the edge layer.
- Enterprise layer – The last layer of most of the researched architectures to effectively manage the interaction with the users of the system. In practice, this layer can be implemented as websites, WebApps or smartphone apps. They consume data from the Platform layer transforming into a human friendly form. In addition, some cases use the Enterprise layer to collect user inputs and feeding back to the Platform layer for it to act upon.

Other than progress in standardization of IoT services, there has also been notable technological developments in the recent years. Some of these include wireless IP- enabled building automation devices, secure messaging protocols (e.g. AMQP, MQTT), web APIs (e.g. REST, COAP), IoT gateway devices (e.g. Intel IoT Gateway, Dell IoT Gateway), stream processing, analytic services etc. (McGibney, Rea, & Ploennigs, 2016) and (Dave et al., 2018) attempted to leverage these technologies in more recent studies. (Dave et al., 2018) created an IFC based architecture allowing its users to innovate functionalities of the platform via sophisticated APIs. Extensive enterprise layer provides its users with various interfaces allowing for full benefit from the different types of data and analytics available. The authors also perform a case study on an office building implementing 3D models of the rooms, room controls and room bookings in an integrated platform. They stated however, that data capture, storage and analysis is also a challenge in such a distributed and heterogeneous environment along with privacy and ethical concerns of capturing data from the occupants.

(McGibney et al., 2016) created a similar architecture in their attempt at developing an OpenBMS concept connecting multiple buildings into one integrated systems, heavily reducing the need for individual building operation systems as well administration work associated with managing these systems. The authors of this paper also applied the standard three-layer architecture to their platform. The illustration of the framework can be seen on Figure 1 below:

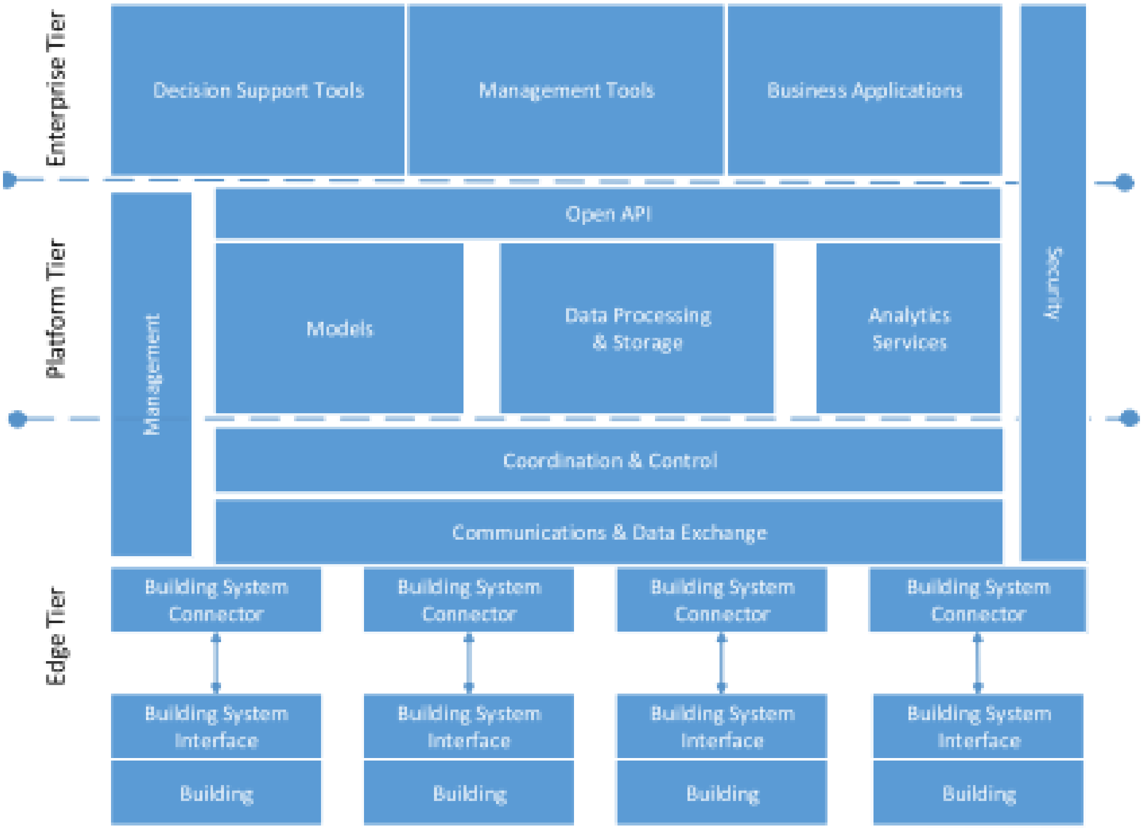

Figure 1: Platform Architecture

Each layer of the reference architecture contains a number of functional groups that represent a container for system components with common goals and functionality. The edge tier, as mentioned above is responsible for sensing the environmental data and communicating it up to the higher up layers. This layer is also primarily responsible for compatibility of the individual systems. The research and findings in communication protocols section is related to this layer of the overall architecture. However, the creators of this framework decided to go with a more flexible approach of using a hardware connector to communicate the required data – Motorola Remote Terminal Unit. It is a Linux based system that provides interfaces to physical systems as well as secure communications to the internet using encrypted internet protocols such as TSL and SSL. To connect to the various BMS protocols they utilized a lightweight resource based LINC middleware. LINC provides a uniform abstraction layer to encapsulate different software and hardware components (OPC, LON, KNX, ZigBee). This approach offers more flexibility to connect with the existing building communication networks. The two upper layers deal with data storage, cleaning analysis and presenting the data in a user friendly way and allowing the user to act upon the data.

Conclusion and Summary

A large proportion of IoT devices are deployed in the built environment providing an opportunity to develop interfaces that allow user interaction through open, intuitive interfaces. This research shows that it is possible to engage wide range of stakeholders with IoT devices by integrating them with BIM. There is currently limited standardization in these concepts, especially the IoT industry. There are various communication protocols available for building operation systems with little compatibility with each other. However, there has been recent developments in IoT technologies that add a degree of flexibility and enable communication with multiple communication systems. One example being the OpenBMS study where the authors used hardware connector to integrate the systems together. Overall, it can be said that the progress in development of IoT and BIM integrating software. There is a strong need for some level of standardization before the systems become too heterogeneous. This is quite challenging especially with many vendors in today's industry creating their own systems in order to lock-in their current customers. More progress is needed from government and academic initiatives to create a homogenous network that will allow buildings to freely communicate with each other through open standards and truly exploit the benefits of both BIM and IoT.

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