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Investigating the Technical and Economic Viability of Integrating Building Performance Monitoring and Measurement (M&M) Systems into Building Information Modeling (BIM)

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Abstract: This paper summarizes work conducted as a first part proof-of-concept within the context of a larger project to extend the effective use of Building Information Modeling (BIM) beyond design and construction stages into facility commissioning and operation. The work investigates the integration of building performance monitoring & measurement (M&M) systems into BIM. An existing small building at Red River College (RRC) was used for this part of the research. Building performance data is collected from disparate third party platforms that generate values for 1) temperature and moisture levels of building components; 2) energy consumption; and 3) indoor environmental quality. These live data streams are integrated with a 3D visualization of the selected building BIM model to provide a holistic view of building performance. The work began with identifying and selecting an effective integration platform. A web server was established to house the platform where a "stripped down" version of a BIM model, using the Industry Foundation Class (IFC) representation, was generated. Examples of different commercial building performance M&M systems were then selected and connected to the model via a developed interface. The focus of the proof-of-concept investigation was to address three issues; first: what are the challenges faced in connecting different M&M platforms to a BIM model and how to mitigate these challenges, second: how to transform data generated by these different systems into a "useful-for-analysis" format and third: how to perform changes in the BIM model, if analysis necessitates, and propagate these changes back throughout the system to keep the model current.

1 Introduction

Throughout its life, a building is supposed to provide a safe, healthy, and functional environment that allows accommodating intended activities according to some standards and projected targets. Generally, the life of a building and related work may be divided into two main parts, pre and post-occupancy. During pre-occupancy, work entails performing design and construction related tasks while during post occupancy, the work focuses on managing the building throughout the remainder of its life. Using tools based on design and construction standards, the first part ends with a created facility that promises a safe, healthy, and functional environment. The second part of the work uses different sets of tools that generally attempt to achieve and sustain projected targets and in turn deliver on those promises. It is the opinion of the authors that the industry has made quantum leaps in developing tools and processes that enabled design and construction of amazing buildings. However, also the opinion of the authors, there are still significant challenges that exist in managing these buildings, specifically in reconciling actual and projected performance. One of the primary reasons for these challenges is the disconnection between the two sets of tools and processes used in the work during the two stages of a building's lifespan. One likely technology that has the potential to bridge the gap between the two sides is Building Information Modeling/Model (BIM) where one of its earliest drivers was to utilize it during the whole facility lifecycle; not just during design and construction but through its management as well.

So, why not use BIM while managing buildings? There are a number of reasons. To start, many facility managers may still not be familiar with BIM. In addition, many technical barriers currently exist for integrating BIM and sensor data such as the size and computing power requirements for BIM models. In order to utilize a BIM model, users must acquire very powerful computers with significant storage and memory capabilities essential to run the model with all its features and dimensions, some of which may not be needed by users targeting a domain specific use of the model.

Another technical challenge is specifically related to the sensors and metering devices needed for building performance modeling. Currently, there are no mainstream BIM tools that have the capability to integrate live sensor information into the models. While there are some standards for modeling sensors, these all focus on the design of sensor networks for construction, and not on the use of the resulting data. On the physical sensor technology spectrum, many of the platform technologies are proprietary, and generally do not interact well with competing platforms. There is also the issue that the resulting sensor data can be sensitive to operating conditions and can be prone to producing anomalous data.

There have been some isolated research and technology demonstrations, as presented in the next section, to attempt to integrate BIM and sensor data, but to date none of the published studies have gone beyond a cursory example. Furthermore, these studies have not addressed some critical elements, such as how the proposed approaches can be scaled from lab experiments to building scaled examples.

Therefore, the overall objective of the proposed work is to address three important questions:

1. Is standardization essential to integrate BIM with facility performance M&M sensors?
2. Standardization aside; what are the technical challenges facing the integration of BIM and sensors data? And how to mitigate these challenges?
3. How beneficial and effective is the integration when scaled up for managing large facilities?

The work summarized in this paper essentially focusses on addressing question #2 with the intent of generalizing and scaling up the work to address question #3 is the next phase of the project.

2 Literature Review

In 2004, the National Institute of Standards and Technology (NIST) commissioned the report; “Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry”. In the report; Gallaher et al (2004) illustrated a $15,800,000,000 USD annual efficiency loss generated from process waste in 2002. The NIST report attributed the waste to the inadequate operability between CAD technologies, engineering, and other software systems. Such a significant loss, the report suggested, may further explain part of the reason for the construction industry productivity lag behind the manufacturing industry productivity “with little to no sign of improvement.”

In the same study, almost two-third of the estimated $15B loss in the productivity of the construction industry were borne by owners and operators; the operation and maintenance (O&M) phase has higher costs associated with it than other life-cycle phases as information management and accessibility hurdles hamper efficient facilities operation. The report further listed some examples of the causes of those losses such as: the cost of maintaining redundant paper systems for exchanging information, electronic or paper files that have to be re-entered manually into multiple systems and from searching paper archives, the cost of design and construction rework due to interoperability problems and the cost of verifying information when original sources cannot be accessed.

Since its introduction into the construction industry, Building Information Modeling (BIM) has presented a promise to tackle those interoperability related problems and to help the industry in reversing the declining productivity trends. While significant improvements have actually been realized by using BIM during design and construction, attempts made to utilize it for and during managing facilities are still confined to research efforts, such as those reviewed below.

Jalaei and Jrade **(**2014) proposed a method to link BIM and energy analysis tools for green building certification systems. (Chen et al, 2014) introduced an approach used to connect the sensor data to the IFC (Industry Foundation Class)-based BIM model. They used a geothermal bridge deck de-icing system, which involved embedded sensors as a case study.

McArther (2015) identified four key challenges that must be overcome to develop BIM models suitable for Sustainable Operations management: (1) identification of critical information required to inform Operational decisions, (2) the management of information transfer between real-time operations and monitoring systems and the BIM model, (3) the high level of effort to create new or modify existing BIM models for the building(s), and (4) the handling of uncertainty based on incomplete building documentation. The paper described the process used to addresses and overcome each of these challenges.

McNell et al (2015) discussed the potential use of BIM throughout facilities' lifecycle. In addition to its robust use in design and construction, the authors envisioned that BIM will be valuable in developing more sustainable buildings due to BIM's ability to capture and manipulate large amounts of data related to the built environment. The authors contended that it is difficult, however, to accurately and fully describe an emerging body of technologies, like BIM-FM in real-time.

Zhang et al (2015) investigated how BIM can contribute to the development of smart buildings environment (SBE). Since BIM is designed to host information of the building throughout its life cycle, their investigation has covered phases from architecture design to facility management. For the post-construction phase, they have designed a facility management tool to provide advanced energy management of smart grid-connected SBEs, where smart objects, as well as distributed energy resources (DERs) were deployed.

Oduyemi et al (2016) conducted a review to explore the benefits and challenges of integrating BIM and building performance modelling (BPM) software. Recommendations included the establishment of proper mechanisms to monitor the performance of BPM related construction to allow for its continuous implementation into the operation phase of buildings.

Gilmer (2012) explained how BIM technology translates from theoretical construction models to the real world of operating and maintaining facilities. She stated: "….While the need for planning and training will never go away, BIM technology and the standards developed around it might offer a way to knit these various systems together……..If the technology can improve maintenance and operations over its life cycle, streamline access to critical systems information, and provide a better means of diagnosing and assessing building performance, it is worth the effort."

Wang et al (2013) argued that in order to monitor the building energy performance management, it is important to set up real-time connection between live sensor data, Building Information Model (BIM) and other relevant information.

In addition to the work referenced above focusing on investigating application of BIM to facility management and integration with building performance sensors, others (Wyner et al, 2014 and Wu &Issa, 2012) have also discussed the benefits of using BIM to enhance building commissioning

The challenges facing the integration of BIM and M&M systems have also been addressed from the educational viewpoints by some researchers. Tang et al (2012) discussed the need for Construction engineers to have comprehensive understanding about sensing and modeling technologies for addressing challenges posed by increasing number of large-scale construction projects.

Based on reviewing the prior research on the subject, the following conclusions may be made:

- Lack of digitization and adequate communication among the different systems used throughout the buildings lifecycles, and in particular during its operation and management, is significantly affecting the productivity and efficiency of the construction industry

- Although BIM has the potential to address this issue, no reliable way of integrating BIM with building performance M&M systems has been developed yet. Reasons are well documented in the references reviewed above. It should be noted that even large commercial organizations, such as Autodesk, have yet to introduce a viable way of such linkage. Autodesk project DASHER 360 https://dasher360.com is "…an ongoing project" for the past few years that aims to develop a standard commercial system that would see Revit™ connected to building performance sensors. Although there is no doubt that standardization of objects and information has tremendous value, it raises an important question: is standardization really necessary to integrate building performance sensors to BIM or is it just a means to establish a market dominance for those competing software organizations?
- The majority of the work done to date may be divided into two categories; first: research efforts using small scale or prototype demonstrations mainly focusing on integrating BIM with energy performance monitoring and measuring systems and second: representing visions of scholars and experts describing how BIM may be integrated with other systems, whether for commissioning or managing buildings.
- Aside from the technology challenges cited, other expected hurdles include need for education and training for all those involved in the process, whether engineers, technicians or facility managers.

These conclusions listed above present the contextual background for the proposed project as outlined in the following section.

3 Proposed Work & Methodology

The work proposed for this project is focussed on investigating the technical and economic challenges of integrating post occupancy tools such as sensors and metering devices with BIM so that information is entered once and then flows through the system in a seamless manner, which allows the BIM model to remain current all the time. Hypothetically, this would streamline the process of managing facilities and optimize resources needed for maintaining and operating a building throughout the remainder of its life.

Realizing the complexity of the work, it was decided to divide it into two parts; the first would include tasks related to proof of concept and prototype development, while the second would entail scaling up the prototype into a full scale application.

Proof of concept and prototype development work began in March 2017 and ended in January 2018. The work, which is the subject of this paper is summarized in the following sections.

4 Proof of Concept Work Description

The proof of concept and prototype development work made use of an existing BIM model developed for a small laboratory at Red River College (RRC) called the Experimental House. The building has a number of sensors and metering devices used to monitor and measure performance parameters such as: temperature, moisture, hydro consumption, and indoor environmental qualities. Different options for integrations were investigated and assessed before selecting the most cost effective option.

The following sections describe the selected facility and work performed.

4.1 The Experimental House

The Experimental House was built at RRC in 2016 to monitor and analyze the long term performance of Tire Derived Aggregate (TDA), processed from old car tires, when used as a "Green Building Material" to replace Natural Material (NM) in backfilling walls and underneath floor slabs of home basements. The building, shown in Figure 1, includes a typical home basement and a makeshift top for weather protection. The basement was divided into two identical sides where TDA is used on one side and NM used on the other in backfilling the walls and underneath the slab. Since the methodology used for that research project was based on comparing the performances of the two materials, identical sets of sensors and measuring devices were installed on each side. Figure 1 shows the different types of M&M systems used and the locations of these systems.

Figure 1: The Experimental House at RRC

The original Revit™ based BIM model developed by the architect during the design stage did not include the sensors. However, due to the uniqueness (non-standardized) of many sensors used, they were all added to the model at the start of this investigation, as general sensing objects using available Revit™ libraries. An example of such a custom system is the strain gauge device shown in Figure 1 that is used for monitoring and measuring lateral pressure against the basement walls. This factor, namely the use of non-standardized M&M systems, has somewhat influenced the decision to select the integration platform, as described in the following section.

4.2 The Selection of the Integration Platform – The Host

Based on prior work in this area, three general ideas for integrating M&M systems with BIM were reviewed and assessed. The first entails bringing all M&M systems into the BIM model. However, this option was found to have a significant challenge, that is: no current facility/feature exists yet in Revit™ that allows for real time information from sensors to be streamed in a cost-effective manner. The second option calls for bringing the BIM model to the M&M platforms. The main challenge with this option is that there may be more systems in any building that belong to different proprietary/commercial vendors that require replicating the model's entries as well as managing risks associated with model changes or a vendor's own system troubles. The third option was found to be, from the investigators' point of view, the most practical and cost-effective one. The option calls for creating a platform that hosts the BIM model, or a stripped down version of it, as well as the data from all M&M systems that exist in the building. A number of custom developed tools and processes were added to the platform to streamline the uploading and analysis of the data.

4.3 Development and Content of the Host

At the start of the project, a Linux server owned by RRC was used for hosting the platform. The server was configured as an archetypal LAMP environment that includes the Linux operating system, an Apache web server, a Mysql database, and the PHP programming language for custom coding.

The investigation began by looking at visualization of a BIM model within a browser environment. The 3D view of the Experimental House was produced by converting the original Revit™ file to an IFC (Industry Foundation Class) file and then using the xBIM toolkit to generate a browser compatible view of the model. The xBIM toolkit reduced architectural details to minimize the computing power required for utilizing the BIM model, while still being able to represent the necessary elements of the building for effective visualization within standard browsers across a variety of devices (including tablets).

As the requirements and complexity of the initial investigation grew, CodeIgniter was introduced as a PHP web development framework to engineer the platform within a Model-View-Controller (MVC) architecture. CodeIgniter provided functions and libraries needed to manage a database, process data, generate dynamic web pages, send requests to other servers, and reduce the repetitive work of developers.

Another technology shift happened when we discovered that modifications to the IFC file could be handled using an available .NET-based API (Application Programming Interface). This API allowed us to perform basic modifications to the IFC file, such as removing sensors or appliances from the model, and bringing the changes forward into the viewer thru the xBIM toolkit, allowing for real time BIM editing. To use the .NET API effectively, we shifted the entire Host platform from Linux to a cloud hosted Windows Server 2016 environment. We re-established the entire LAMP and CodeIgnitor environments on the Windows server and added an Internet Information Services (IIS) private site to receive and process the .NET API requests for modifying the IFC file.

Finally, the Host platform incorporated data from a select number of M&M systems within the building. The selected systems were all proprietary technologies produced by different vendors for different purposes. The main purpose of selecting those different M&M systems described below was to identify the difficulties associated with integrating those and other similar systems with BIM. The systems included:

a) **Building structural health (BSH) monitoring sensors**: 36 sensors used for measuring the temperature and moisture of backfills and 24 sensors for measuring lateral pressure of the backfills on basement walls were selected for this investigation. The sensors were installed at different locations, as shown in Figure 1, but distributed equally and identically at both sides of the basement walls to measure the differences in moisture, temperature, and lateral pressure of each type of backfill, i.e. the tire derived aggregate (TDA) vs natural material (NM). The raw data (signals), produced by these sensors, were uploaded to the vendor’s server to be processed and then both the raw data and the processed data were downloaded as an XML file.

b) **Building energy consumption (BEC) meters**: the commercial device selected for this investigation was used to measure the power consumption of a typical home appliance, specifically a dehumidifier. The device resembles smart meters where consumption data produced were recorded directly on a computer in the Experimental House.

   The recorded data were formatted as an XML file through a special software, developed by the device’s vendor, for the transfer of data between different devices. However, because there was no web API or other means of delivery over the Internet, a “linkage” computer program was developed specifically for this investigation to allow transfer of the XML file to the Host cloud platform where it was processed, and the sensor readings were extracted and inserted into the master database.

c) **Indoor environmental quality (IEQ) monitoring & measuring systems**: two systems were used in this investigation, the first is an “off-the-shelf” device that measures parameters such as temperature, humidity, CO, CO_2, and contaminant levels inside the building. The second system was used to measure radon levels in the basement when subjected to different ventilation conditions.

Readings from the first system were downloaded via a web API provided by the vendor. The radon monitoring and measuring system was perhaps the hardest to deal with since it has no web API and its raw signals were only readily accessible by the proprietary software of the vendor. However, the research team was able to develop another "linkage" computer program to copy and transfer its measurements to the Host platform where they were extracted and inserted into the database.

4.4 Demonstration of the developed prototype

The M&M systems selected for this investigation were grouped into three categories that are likely needed to manage any facility performance. As mentioned above, these categories are: building energy consumption (**BEC**), indoor environmental quality (**IEQ**) and building structural health (**BSH**).

The developed prototype was used to demonstrate how live data from these different M&M systems can be integrated into the BIM model of the Experimental House and to ultimately address the three main objectives for the investigations namely: first: what are the challenges faced in connecting different M&M platforms to a BIM model and how to mitigate these challenges, second: how to transform data generated by these different systems into a "useful-for-analysis" format and third: how to perform changes in the BIM model, if analysis necessitates, and propagate these changes back to keep it current. The following sections summarize how these three objectives were addressed:

4.4.1 Challenges of integration

As indicated in section 4.3; a primary challenge was in retrieving data from different M&M systems. Many M&M systems' vendors provide web Application Program Interfaces (APIs) that allow users to download data over the internet. However, there were some challenges in retrieving data via the different unique APIs types of files provided by some of those various vendors. To handle different file types, a corresponding import module was developed for each format. For instance, XML files were used by the **BSH** sensors to transfer data, so an XMLREADER was used to parse the content of the files. To download data from this vendor's server, the Host first logs into the manufacturer's server and then a request to retrieve data for a specific time period is issued and the downloading process begins. The **BEC** measuring device did not provide an API, so its data could only be transferred and stored through custom developed import modules where an onsite computer initiates data transfers to the Host on a daily basis. One of the **IEQ** systems has a web API which provides CSV text and JSON file types. CSV text is plain Comma Separated Value text, whereas JSON is Object-Structured text. Both file types required custom import modules on the Host to transform and insert the different sensor readings into the master database. The download process of the **IEQ** system was similar to the **BSH** sensors data download process, except that a secure connection to the **IEQ** system vendor's server was supported through the use of generated API keys instead of logging in with a username and password as was done with the **BSH** vendor.

Date and time stamps of each M&M system was another challenge due to the individual system's formatting and set-up protocols. Before retrieving data from the APIs, all date & times were formatted differently based on the sensor vendors' specific format. These dates and times were normalized into a system-wide standard format on the Host platform across all sensor readings, regardless of the source vendor. This provided a better basis for time-variant data analysis and visualization.

Another challenge faced was how to standardize the different names and formats as well as types of readings that make up the data retrieved from each vendor's system before uploading into the Host database. For example; some vendors use different names to indicate a same reading whether these readings were raw signals or processed values. The Host database tables were therefore designed to record the intended name of each retrieved reading and which sensor the reading corresponds to.

One of the significant challenges faced was managing the growth of communication between vendor APIs and the host platform when transferring potentially large amounts of sensor readings. After creating the initial function for retrieving sensor readings from M&M systems, it was decided that due to the amount of data that was being handled, optimization of the retrieval process was needed. The optimization process entailed first retrieving local data available from the host database, and then once the server receives results from the database it queues the date ranges of the missing data. The host platform then runs two parallel asynchronous processes. First, the queried local data is immediately rendered to the user for visualization, while the second process attempts to download the missing data using the remotely accessed API provided by the sensor vendors. Before displaying the remotely retrieved data, it is cached into the host database for faster results during future inquiries.

Visualizing data was another challenge. In order to visualize data for analytical purposes; e.g. energy consumption vs time, the user would select a sensor and the date range. When the request was submitted, Google Charts, selected for this application, uses the given date range to determine the time scale of the chart. When the server passes the data from the database to the user's browser, Google Charts plots the data as a line chart. The server also would send the missing date range, if any, that would help the browser plot initial data from the server and show gaps for any missing data until they had been received. This was done to show the user results while the data was being retrieved and transferred. Whenever the browser received all data, Google Charts redrew the chart for a complete view of the entire date range. The challenge with visualization was that Google Charts also needs to consider the time zone offset when determining the time scale. Unlike many of the different M&M systems, Google Charts used minutes instead of hours as the default unit. To resolve these time formatting problems, some prototype functions were created to normalize the date & time strings of the different retrieved datasets.

Another hurdle was to modify the IFC file. The xBIM toolkit was used to visualize the 3D model in the main web page of the Host by dynamically generating a .wexbim file from the IFC file of the BIM model. We discovered API libraries based on .NET technology to make changes to the IFC model. We tried to create a .NET Core-based web API on the original Linux server, but ran into many problems with driver version contradictions. The API development on the Linux environment was able to successfully modify the IFC file, but it failed in visualizing the changes, so that API development was discarded. In order to correctly modify and visualize IFC files, a .NET Framework based web API was deployed on a Windows Server 2016 environment along with migrating all our Linux work over to Windows. The API development on Windows not only successfully modified the IFC file but also correctly visualized it. This API was published on the Windows Host within a private Internet Information Services (IIS) web site and could be called whenever changes were requested by the user. Once the 3D model was modified, a new IFC file and a new .wexbim file were created for version control. The original file was reserved for rollback when needed.

4.4.2 Transforming data into "fit-for-analysis" form:

There are generally two necessary steps required to make use of data generated from building M&M systems. The first entails making sure that individual readings are correct and complete while the second step involves performing statistical operations, e.g. averaging, correlating, and normalizing etc., which may be necessary to allow users to conduct useful and effective analysis of their building's performance.

To address the issue of data correctness and completeness, reasonable tolerance limits were selected for the individual readings; e.g. temperature or humidity values, and a simple "if-then" operation was used in the Host database to weed out unrealistic and incorrect values produced by a particular sensor and replace them with averages of the closest sensors' correct readings.

The second step was addressed through simple correlations of actual values vs industry limits; just to demonstrate the Host platform capabilities of performing these types of tasks. Figure 2 shows examples of these comparisons as well as the 3D views of the Experimental House as it appears in the application page.

It should be noted, however, that advanced "Machine Learning" techniques will be implemented in the next Phase of the project to illustrate the how a facility's current performance may influence its management, even though such performance may deviate from design projections.

4.4.3 Keeping BIM model current all the time:

One of the main objectives of this investigation was to demonstrate how changes; called for through analysis, can be made to the facility and can be simply and simultaneously incorporated into the BIM model so that the model is current all the time; regardless of the facility's age. A simple process was introduced in this investigation, as summarized in section 4.4.1, which enabled a user to remove an appliance (dehumidifier in this case) and save the change made to the IFC file to the corresponding Revit™ file.

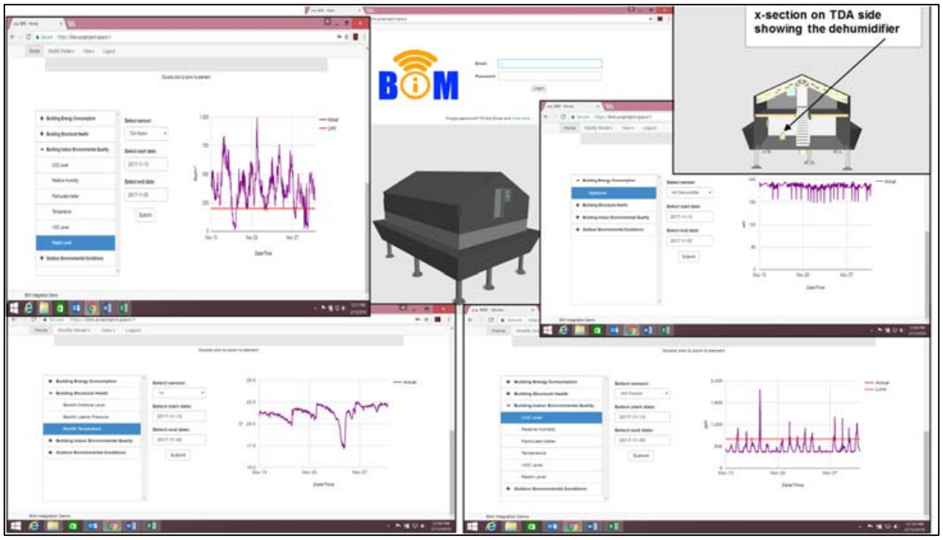

Figure 2: The Host page showing 3D views of the Experimental House and graphical representations for some building's M&M performance parameters

4.5 Summary conclusions and next step

The work summarized in this paper is the first part of a larger project targeting the integration of building performance monitoring and measuring (M&M) systems into building information modeling (BIM) for the ultimate use of managing facilities throughout the remainder of their lives after completing construction.

The work began by assessing different options for integration which led to developing a platform to host representations from BIM and M&M systems. Three objectives were identified for the investigation. First: what are the challenges faced in connecting different M&M platforms to a BIM model and how to mitigate these challenges; second: how to transform data generated by these different systems into a "useful-for-analysis" format; and third: how to perform changes in the BIM model, if analysis necessitates, and propagate these changes back to the model to keep it current.

The investigation showed that a number of challenges were met throughout the integration process the most significant of which continues to be the lack of interoperability among the different digital systems. Although these types of challenges may support the views that industry-wide standardization is essential to resolve them; it is believed that simple operations may be sufficient to achieve integration, particularly in cases where custom sensors may be needed to perform unique functions. Nevertheless, more investigation of this issue will be conducted during the next phase of the project.

Transforming readings collected from M&M systems into useful data followed methodical steps common for this type of work. First, simple algorithms were developed and included in the platform database to ensure accuracy and completeness of the data. Second, analytical tools and functions were used to organize the data in a format that is clear and helpful for facility managers. Finally, a process was developed to allow facility managers to perform simple changes to the model so that the implemented changes in the platform would propagate to the BIM model and hence keep it current all the times.

The proof-of-concept phase is now complete and future work will focus on scaling up the developed system and integrating facility management performance data generated from all the M&M systems installed within the newly constructed Skilled Trade and Technology Centre (STTC) http://blogs.rrc.ca/development/sttc/ located on the main campus of RRC. This facility is expected to be completed in the fall of 2018 and is envisioned to be a living lab and an innovation hub to students attending trade and technology programs at the college. The facility is equipped with significant networks of sensors dedicated to measure building performance that will serve two main purposes: 1) to help with commissioning and managing the facility and 2) as an educational tool. It is therefore believed that introducing the proposed integration between BIM and those building performance M&M systems will streamline those tasks undertaken for commissioning and managing the facility over its lifecycle.

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