# A Domain-Independent Facility Control Framework

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**Abstract:** The purpose of our built environment is to provide spaces in which human-designed activities may comfortably occur. An ever-increasing set of technical disciplines, economics, and societal norms place dynamic requirements on those who plan, design, construct, maintain, operate and manage our built environment. In this paper, a domain-independent framework to capture design requirements and then compare those requirements to the actual performance of a facility is presented. The foundations of this framework were five related Industry Foundation Class Model View Definitions that are partially implemented within commercial software and are being balloted within the United States National Building Information Model Standard (NBIMS-US V3). The application of this framework was tested using an algorithm that compares expected data with as-operated sensor telemetry. This algorithm was verified against simulated data and validated against sensor data. The sample models and tool kit developed for this project's experimental test bed has been adopted by industry and academia to support their missions of streamlining design and construction processes and educating future design and construction professionals. In addition, the initial application of this framework to support wider sustainability, engineering economics, and business process analysis goals is introduced. These applications demonstrate how small additions to standard building information model submission may quantitatively address current and future requirements placed on our engineered environment.

**CE Database subject headings**: Building information models; Design management; Construction management

**Author keywords:** Building information model; BIM; Model view definition; MVD; Industry foundation class; domain-independent; framework; life cycle; building control; control cycle; COBie; HVACie; Sparkie; WSie; BAMie; BPie; resource utilization

## INTRODUCTION

United States Department of Commerce information has for decades shown flat productivity in the construction sector, compared with more than 250% productivity increase over the same period in other business sectors (Teicholz 2004). Another widely cited study points to waste amounting to $15.8B per year USD resulting from failure to streamline work and information flows (Fallon 2006). Such findings were not, however, news to the research community. In

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1983, a blue-ribbon panel identified potential productivity gains achieved through the application of "personal computers" by capturing life cycle building information (BRB 1985). Despite 30 years of using computers in the design office and construction trailer, the production of paper (or e-paper) documents and use of databases for exception reporting remains the common level of use of these amazing machines with their now ubiquitous computer networks. Digitizing one small part of this process, the construction handover data, would have saved the United States over $2B USD per annum (Fallon 2007).

The design and construction industry's ability to implement new approaches and technologies comes at a time when owners and society are making increasing demands of our engineered environment. Examples of such criteria on U.S. Army Corps of Engineers' projects include the Americans' with Disability Act (starting in 1990), life cycle costing (starting in 2004), sustainability (starting in 2010), force protection (starting in 2011) and net-zero energy requirements (starting in 2012). In each case, practitioners have followed the well-worn path of waiting for guidance from technical experts who form organizations supporting each of these individual sets of requirements.

The necessary self-promotion of interest-group organizations has led each group to maximize its individual value, even when such behavior may actually decrease the groups' ability to meet the needs for which it was created. The most egregious of these efforts has focused on a domain currently receiving a high level of attention - energy modeling and sustainability. Leading researchers in the field of energy simulation have stated unequivocally that the results provided by energy simulation models are not reproducible and cannot be trusted due to "arbitrary decisions" made by the energy modeler and incorrect assumptions made by simulation tools (Bazjanac 2008). Other authors show a clear pattern of deviation between predicted energy use and actual performance of the constructed facility (Polly 2011). Practitioners have argued for years that complex energy models are too difficult to use, but more simplified methods, such as the Leadership in Energy and Environmental Design (LEED) design-by-checklist system, have also proven ineffective. Although tools such as LEED may have raised consciousness, their widespread application has created sufficient problems to generate lawsuits from owners claiming non-performance of highly rated facilities (McLellan 2011). Recognizing these problems, owners are beginning to pull back from LEED requirements. For example, in 2012 the United States Congress prohibited the Department of Defense to provide any funds for LEED certifications above Silver (USC 2012).

Lack of standardized performance measures to evaluate projects, and lack of strategic research direction, have been identified as essential causes of low construction industry productivity (NRC 2009). One reason for the inability to improve different aspects of building performance and information is the need for a common framework for building information modeling. Sacks (2010) outlines many potential benefits stemming from building information but indicates that, unless a holistic view of these disparate parts can be achieved, it will be difficult for building information technology to have a major impact. Forgues (2012) states that a unified framework is needed to guide the building industry to a more sustainable future. Jung (2011) argues that any such framework must consider both the technology to be used and the business activity being accomplished.

Regardless of the form of a framework, that framework must be clearly specified (London 2011). The lack of specificity in contract clauses that require building information deliverables demonstrates that unless the owner defines their requirements in the contract, then the models delivered will vary widely from project to project and even from modeler to modeler. Beyond the creation of a performance-based specification for building information deliverables, there is also a need for a methodology to establish the value of this building information to resolve disputes regarding errors or omissions in the specified deliverables (London 2011). This will inevitably lead to the development of a set of internally coordinated, but task-specific, specifications. In the context of the buildingSMART alliance, projects aimed at creating such specifications are called "information exchange" projects (East 2010b). A key motivation of information exchange projects is to ensure that efficiencies gained by streamlined business processes offset the cost of upgrading software and change management (Duarte 2012).

## OBJECTIVE AND APPROACH

While control cycles are the basis of virtually all industrial activities, the facility acquisition process differs significantly from most industrial processes in several ways. These include (1) the lag time between project phases, (2) the variety and number of stakeholders, (3) the variety of software tools used, and (4) the changes introduced throughout the process. This paper introduces a domain-independent framework for building control. This framework is composed of four parts: (1) documentation of design resource requirements, (2) capture of as-designed, as-built, and as-operated facility models, (3) comparison of the as-operated sensor information to the resources needed to operate the facility, and (4) identification of appropriate corrective action.

Effort on this program of work began in 2008 with the creation of a test bed to ensure that efforts on multiple individual projects could be coordinated. Next, projects documenting information exchanges for design processes affecting facility sustainability were conducted. The exchanges necessary to capture building automation and control systems data were defined. Next, the structures needed to compare facility requirements with actual performance were defined, and a prototype framework developed. Finally, a new data mining and clustering algorithm was developed and tested. This effort resulted in the creation of an adaptive building control and feedback system. Several tests of the extensibility of this framework were also conducted. Now that these projects have been concluded, this paper summarizes this program of work and introduces the overall facility control framework.

## TEST BED

A variety of commercial software is used to initiate, plan, design, build, maintain, manage, and operate facilities. The likelihood that proprietary information provided by one commercial software system will be available to any of the parties downstream is small. Proprietary information delivered during the course of a long-duration project may not even be supported by the time that the project has concluded. Therefore, the creation of a building control framework spanning the facility acquisition process requires the specification of open-standard data exchanges. As a result, the facility control framework was based on the Industry Foundation Class (IFC) Model (ISO 2013). Many commercial software systems currently support the exchange of information in IFC version "2x3". In 2013, the model was updated to version "2x4" or simply "IFC4."

### Building Models

Standardized data repositories, in fields of study other than building informatics, contain thousands of banks of scientific data sets and test cases (Marcial 2010). The first open repository for building information was established at the University of Auckland (Amor 2010). Much of the contribution to this initial repository came from buildingSMART international, whose sample models have traditionally focused on software unit testing for specific building information, such as the geometric representation of steel connection details. To support the development of an overall facility control framework, this project developed a new repository of building information models called the "Common BIM Files" (East 2012). For three buildings, a set of related model files were developed.

The three models correspond to facilities found in many residential, commercial, and campus settings (Johnson 2011). The smallest model was developed from a duplex apartment building design introduced to the United States in December 2009 (East 2012). The IFC 2x3 Coordination Model View Definition file for the duplex apartment building is shown in Figure 1. The second model was created from standard drawings and criteria for a two-story office building (USA 2013). The third model was created from a redacted set of construction drawings for a medical/dental clinic. Redacted operations and maintenance manuals are also provided with this clinic model.

The number of architectural elements in these three models is shown in Table 1. During this effort, some problems were encountered with inappropriate mapping of native authoring tool objects to higher-order objects in the IFC model. Some details of these issues, for readers familiar with IFC modeling, are addressed in the following paragraphs. For example, the count of IfcFurnishingElements contained both furniture and casework, which a typical designer, builder, or owner would consider to be different classes of object. Similarly, ifcFlowTerminals contained all plumbing model objects regardless of their capacity as actual flow terminals. For example, toilet grab bars and bathroom mirrors were incorrectly exported as ifcFlowTerminals by the commercial design software used to develop these models.

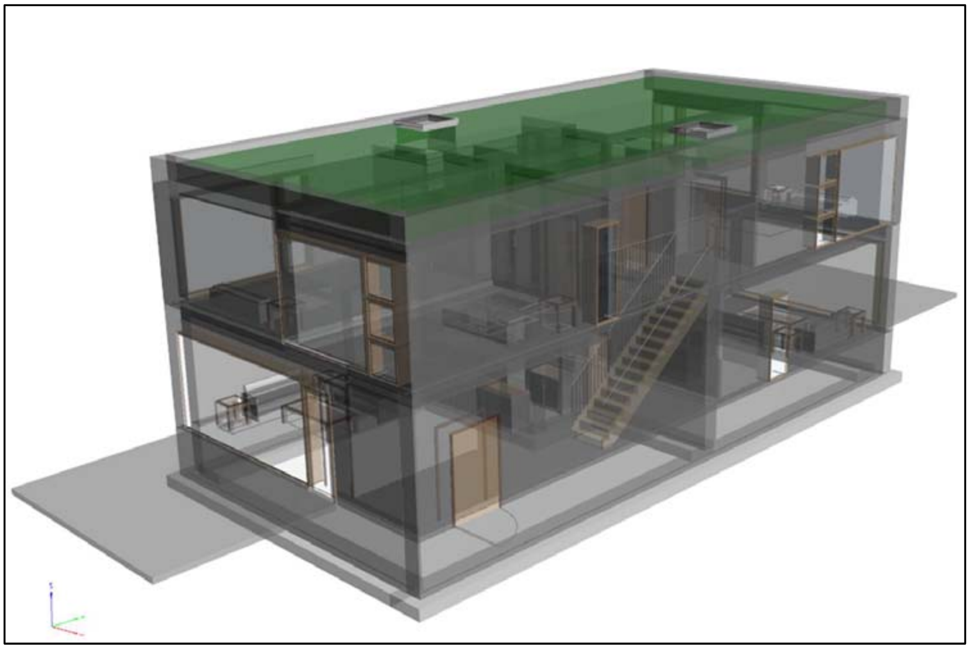

Figure 1. Duplex Architectural Model

Table 1. Count of Architectural Model Object Types

| | Duplex | Office | Clinic |
|---|---|---|---|
| ifcSpace | 22 | 99 | 269 |
| ifcDoor | 14 | 102 | 254 |
| ifcWindow | 22 | 69 | 71 |
| ifcFurnishingElement | 61 | 7 | 118 |
| ifcFlowTerminal | 105 | 31 | 3155 |

Table 2 summarizes the objects from the Mechanical-Electrical-Plumbing model files of the Duplex Apartment project. These models were also developed using IFC 2x3. Due to changes between IFC 2x3 and IFC4, several objects in the current model are mapped to entities depreciated in IFC4. For example, IfcEnergyConversionDevice includes both electrical transformers and air-cooled chillers. The more precise mapping in IFC4 would have required these objects to be exported as ifcTransformer and ifcChiller objects. Several other components that might have been better mapped to more precise object types are found under the depreciated IFC 2x3 object ifcFlowMovingDevice. These include Variable Air Volume (VAV) boxes, air handling units, and fans. Probably the most over-specified type in the IFC 2x3 models was

IfcFlowTerminal, which included air diffusers, electrical receptacles, fire sprinklers, and lights. Other objects were more appropriately mapped. For example, valves and strainers were both correctly mapped to ifcFlowController objects.

Table 2. Summary Content Count of MEP Models

| | Duplex | Office | Clinic |
|---|---|---|---|
| IfcEnergyConversionDevice | 16 | 3 | 16 |
| ifcFlowController | 6 | 12 | 173 |
| ifcDistributionControlElement | 2 | 0 | 5 |
| IfcFlowMovingDevice | 4 | 25 | 154 |
| IfcFlowStorageDevice | 0 | 1 | 3 |
| IfcFlowTerminal | 105 | 1456 | 3155 |

Since the initial publication of the models in 2010, progress has been made by software vendors to create models whose information matches that found on the equivalent contact drawings. This progress has been, in part, due to the publication of a series of these three models models. The improvements made to design software exports can be found in the sample files submitted by software vendors participating in annual buildingSMART alliance Challenges.

**Tool Kit**

In addition to having a common set of test models for this project, the team also developed a common software tool kit based upon bimserver.org (Beetz 2010). This tool kit meets several important criteria that promote its use as a research and practice instrument. First, the performance of the tool kit has been benchmarked against large building models. Thus, techniques developed for research purposes may scale to realistically sized projects. This is important since the underlying platforms of many research prototypes are unable to scale for production. Second, the tool has attracted talent from practitioners and researchers who want to use a building-information server without having to invest the time to develop underlying functionality that is typically outside their main research objectives. Next, an open-source development platform provides transparency and repeatability -- hallmarks of high-quality scientific research. Finally, the licensing of the bimserver.org allows the tool to be used for both research and commercial applications. Both the size of models allowed and the scope of server licensing may help research outputs to be more quickly used by their intended beneficiaries.

The first contribution to bimServer.org made during this project was to transform and test building information submitted against Construction Operations Building information exchange (COBie) specification (East 2013). The purpose of COBie is to exchange information about managed and maintained assets during the life of a project. Specific sets of building information, such as those needed for construction handover, are defined in the United States National Building Information Model Standard as subsets of the overall IFC standard. These

IFC subsets are called Model View Definitions (MVDs). All MVDs apply the same underlying IFC model representation to solve their specific problem. The difference between model views may be characterized by the list of included objects, their required level of detail, and business rules that enforce specific characteristics required by the associated business case.

Differences between MVDs may be found, for example, when comparing the Coordination Model View Definition and the MVD found in the COBie project (which will be referred to simply as COBie). These differences arise because the Coordination View contains information needed to detect geometric collisions while COBie contains information about managed assets. Clearly there are some aspects shared by both data sets. For example, concepts for facilities, floors, and equipment are shared. But there the similarity ends. The Coordination View includes structural elements, architectural walls and details, plumbing piping and fixtures, and Heating, Ventilating, and Air Conditioning (HVAC) piping, ducts, and equipment. Of all of those objects, only the spaces, plumbing fixtures, and HVAC equipment (and similar products) are necessary to catalog the managed assets required by COBie.

The level of detail in the Coordination View also differs from that needed in COBie. The Coordination View contains the detailed geometry of each item in its data set. Information about the geometry of material layers, such as insulation thickness on structural and fluid-distribution elements is also in the Coordination View. COBie, as a catalog of managed assets, does not require such specificity. The only geometric concept in COBie is that of spatial containment. Containment information in COBie is required to ensure that the building occupant is able to find the physical location from which each asset is maintained.

Finally, there are differences in the business rules that define the quality of the information in the two model views. The Coordination View only requires that there be a globally unique identifier for each object. COBie, on the other hand, is intended for human uses related to facility operations, maintenance, and asset management. As a result, the COBie business case requires the names of all COBie assets to be unique. Without such stringent requirement, a service order that says "Change the oil in Compressor-05 in Room 003" would be ambiguous.

MVDs specify the information content required to streamline a well defined business processes but do not, necessarily, mandate the physical format of how that information is delivered. The default format for an MVD is the IFC STEP Physical File Format (SPFF). Not all computer programmers and users will be interested in learning the details of SPFF. A key innovation of the United States National BIM Standard (NBIMS-US) is that formats other than SPFF are acceptable if non-ambiguous mappings can be defined. Given that the eXtinsible Markup Language (XML) is the cornerstone for the majority of current cloud computing applications, NBIMS-US has allowed mappings to a variety of XML-based schema. For example, COBie data may be prepared in any one of three XML-based schemas. ifcXML transforms STEP files directly to XML according to rules developed by the STEP community. While this format is recognized by buildingSMART international, it has not gained wide acceptance due to the size and complexity of the required schema. The next format is a National Information Exchange Model (NIEM) compliant XML schema suitable for programmers who may not want to learn the details of SPFF but who are eager to use facility asset information provided in a clean XML schema with an existing, United States user base. The simplicity of this XML schema led the authors to name this style of presentation "COBieLite."

Since COBie information needs to be verified and checked by people, a practitioner-accessible XML format for COBie data has also been provided. SpreadsheetML is an XML-based spreadsheet schema used by commercial spreadsheet software. It is often the case that those learning about COBie consider SpreadsheetML to be the standard, this is not the case. COBie is a specification of a required set of data about managed assets. Data meeting the COBie specification may be presented in SPFF, ifcXML, COBieLite, or SpreasdsheetML.

Regardless of the presentation format, the ERDC Tool kit is able to transform between these formats. The translation mappings are published both in the COBie Responsibility Matrix (East 2011) and the COBie ballot submitted to the NBIMS-US V3. These transformations ensure that SPFF files converted to other formats have zero loss of the information required by the COBie specification. This does not, however, mean that the files are perfectly the same. Small differences arise due to schema mapping rules because some schema contain information not needed by other schema. For example, in SPFF, the Globally Unique Identifiers' (GUID) of some linking objects are not maintained when that information is transferred to XML-based formats. Such differences are outside the scope of COBie requirements since the underlying asset information is not affected. Software vendors who have extended their Coordination View files to include COBie have also used the tool kit to filter out geometric information in the Coordination View that is not required in COBie. While it is possible to have COBie information transformed between XML-based and SPFF presentations, the contents of that transformation are based on the requirements of the COBie business case alone.

The tool kit's second application was to evaluate the format and referential integrity of files submitted for testing against the COBie specification. The tool kit has been used by over two-dozen commercial software systems to verify COBie compliance. Verification and validation rules in the tool kit are represented using the Schematron Definition Language (ISO 2006), a royalty-free standard from the International Organization for Standardization (ISO). Schema standardization efforts such as the US National Information Exchange Model (NIEM) use Schematron to represent complex validation rules for XML documents. Developing rules based on an established validation language, as opposed to hard-coding the rules into the toolkit applications, provides more opportunities for collaboration and extensibility.

With the development of a common set of building information models, and the tool kit as the basis for working with those models under way, the team set about defining the information needed to effectively manage the natural resources used in a facility. This effort began with the evaluation of the expected resources required for the facility to perform its mission. Systems supplying heating, cooling, electricity, and water were also defined. One final model view was also required to capture information generated by building automation and sensor systems. The paragraphs below describe these efforts.

## MODELING RESOURCE REQUIREMENTS

Building requirements are specified during the planning and architectural programming phase of a project. Discussions between owners, planners, and architects document the activities that are to take place within the facility. The architectural program is a set of information that describes one specific approach to meeting the needs of these activities. The most common artifact produced during the programming stage is the Room Data Sheet. The details provided with each room are, to a large degree, governed by the sophistication of the owner. Large owners will often have complete templates for the requirements of each type of space; smaller owners will not. The open standard specification of building programming (Jerving 2011) has been demonstrated in several public buildingSMART alliance meetings. The name of this specification is the Building Programming information exchange (BPie).

The typical set of programming information is not, however, sufficiently defined to describe the use of water, electricity, and other natural resources needed to enable the required activities. Additional necessary information includes the occupancy of the facility and parameters describing resource consumption (Chasey 2012). Occupancy information includes the building code classification of the facility, the various types of occupants using the space, and the expected and peak usage duration of these occupants. Parameters for required resources based on those occupancy levels were developed for water, electrical power, HVAC, and lighting. These parameters are applied based on relevant building codes and on the equipment installed in each building space. Properties mapping these parameters to specific equipment were identified in Kalin (2013) and (Fallon 2012).

## MODELING RESOURCE-INTENSIVE SYSTEMS

Given the widespread interest in issues related to sustainability and energy modeling, this project focused on design disciplines whose systems require the ongoing use of natural resources within the built environment. The systems selected for investigation under this project, therefore, were the HVAC system (Hitchcock 2012a), the domestic and waste water distribution systems (Chipman 2013b), and the interior electrical distribution system (Chipman 2013a). For each project, business-process models documented the information exchanges needed to support the coordinated design stage of a project. Teams of subject-matter experts and practitioners validated each result. These process models were developed using Business Process Modeling Notation (BPMN) (OMG 2011) to ensure that the resulting work would be compatible with requirements for submission of this information to the NBIMS-US. Each process model was organized into “swim lanes” according to responsible party. The owner, architect, design consultant, and product manufacturer each had its own swim lane. Within a given lane, the level of detail of the tasks differs from that of the level of definition in Critical Path Method (CPM) schedules. The level of detail required for these process models only defined activities that produced or required information to be consumed or produced by others in the process.

Figure 2 provides an example business process model describing the actions and information needed for HVAC schematic design. The overall project contained several such process models. For the HVAC schematic design process, three horizontal bands (swim lanes) were needed to model the business process at the appropriate level of detail. The bottom lane contains those activities accomplished by the architect. Of course, the architect does many other types of activities, but only the activities shown in Figure 2 are those related to the HVAC schematic design process. The top lane contains activities completed by the HVAC consulting engineer. To emphasize that the purpose of this business process model is to identify information flows, a middle lane modeling these information flows is added to the diagram. This middle lane explicitly names each set of information provided by the architect to the consultant and identifies those information objects that are required, or are produced as part of the HVAC schematic design process.

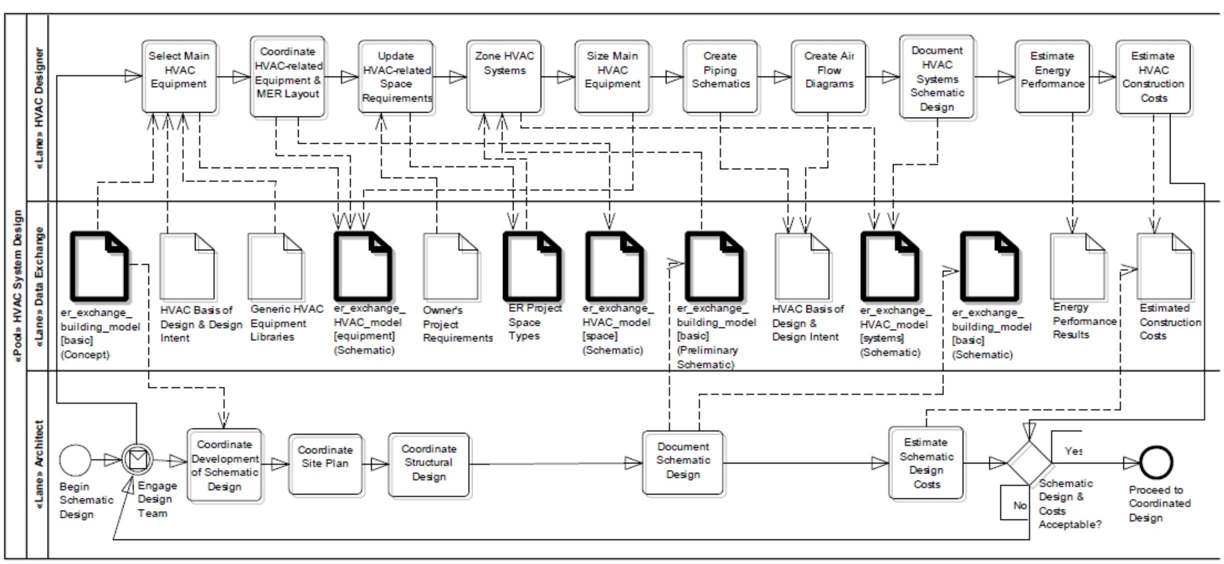

Figure 2. HVAC Schematic Design Process Model

The goal of the process-modeling effort is not to develop a comprehensive model of everything, but for subject-matter experts to articulate the minimum sets of information needed to achieve the specific objectives of the project at hand. In the case of the HVAC schematic design process, subject-matter experts identified seven of thirteen information exchanges as the minimum set of required information. Three of the omitted exchanges pertained to the documentation of design requirements and intent. The three other exchanges provide reports of HVAC design to other, related business processes.

Once a set of process models was complete, the contents of all information exchanges were documented and collated. For most exchanges, there are similar sets of information needed to support different processes. For example, information about name of the project and general layout of the building is a set of information created by an architect and then reused in many exchanges. For a given modeling project, the collated set of process models and exchange requirements is called, in the context of the buildingSMART, an Information Delivery Manual (IDM). The buildingSMART alliance does not currently maintain a master list of exchange requirements developed for multiple projects.

The next steps were to begin mapping these exchange requirements into the underlying IFC data model specification. The compiled set of these specifications for a given purpose is the MVD. Once the specifications were completed, a test of the ability of commercial software to produce conformant IFC files was accomplished for the HVAC (Hitchcock 2012b), water (Fallon 2013a), and electrical (Williams 2013) system. Illustrations of MVDs for Duplex Apartment Building are shown in Figures 3 through 5. An early-stage design, such as that found in Figure 1, will include both the architectural elements and the architect's expected placement of lighting, plumbing, and other products that provide the owner an idea of the final location of such products. The final placement of HVAC, water, and electrical components are, necessarily, updated by the specific design disciplines as the design progresses.

As the design passes from the architectural model to the coordinated design stage, additional models are created for each design discipline. The design for the heating and ventilation system of the duplex included the use of a combined hot water heater used for domestic and heating purposes. The HVAC model, Figure 3, illustrates (1) each components of the HVAC system, such as radiators and fans, (2) the assemblies of fans ducts and vents needed to provide proper ventilation in bathrooms, and (3) the connections that allow thermal transmission fluid to flow between the boiler and the radiators.

The duplex plumbing model, Figure 4, provides the detailed placement of each plumbing fixture, as well as each of the two combination hot water and heating boilers found in each of the two apartments. In addition to the placement of the equipment, the connections between those components are shown with one-inch water supply piping. The plumbing model provides a good example of the need for multiple model views. While the architectural model, Figure 1, is able to show a plumbing fixture as a single object, the model used for plumbing design requires more detail.  For example, the single model of a sink with a fixture and drain must be modeled as three distinct parts: hot and cold water supply valves (or combined valve) and waste drain. Such detailed modeling is required since the capacity of each supply and waste water line is used to support pipe sizing and gray water analysis.

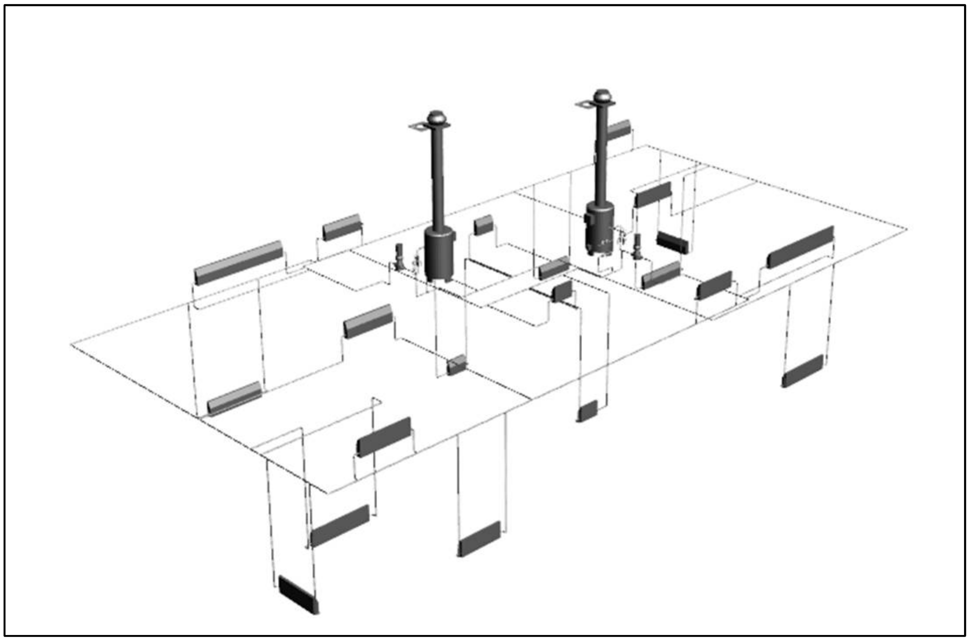

Figure 3. Duplex HVAC Model

The electrical model, Figure 5, provides the final location and properties of electrical components such as receptacles, lighting, and appliances.   As with the plumbing model, detailed information is required to allow design work to proceed.  An electrical distribution panel, for example, must be modeled as an enclosure box with individual circuit breakers.  Specific properties of the conduit and wiring that connects electrical devices is also required since, according to traditional design practice, electrical raceways are typically not shown on contract drawings.

While modeling the geometry of individual components has been implemented for many years in the Coordination View, modeling the connections between these components and assemblies, until recent updates to commercially available software, has not been practical.  This is because physical connections between pipes or ducts do not always close in actual design practice.  Even if all physical connections “touched,” the direction of flow could not be established with geometric information alone.   Connections in IFC are defined using ifcPort objects.  ifcPort explicitly identifies the upstream and downstream side of the connection.  The use of ports is required in each of the discipline MVDs.  In the HVAC MVD, ports are required on all equipment, valves, ductwork, and piping.  In the plumbing MVD, ports are required on all fixtures, valves, and piping.  In the electrical MVD, ports are required for all electrical devices.  Properties sets on these ports define the needed types of conduit and conductors for the circuit.

Analysis of the capacity of commercial software to support the requirements of these MVDs was also conducted as an additional part of this project.

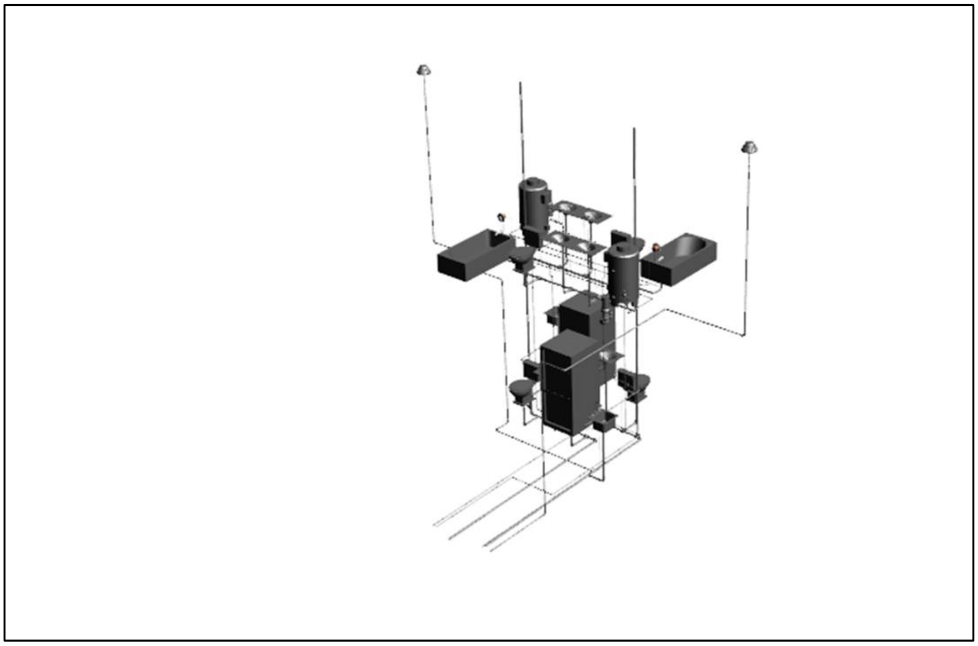

Figure 4. Duplex Plumbing Model

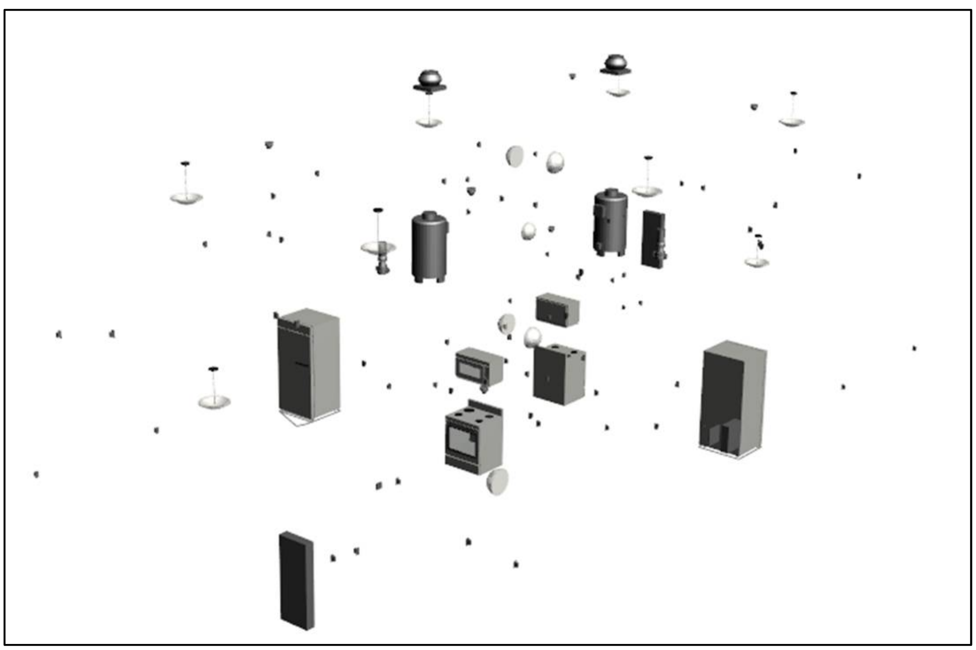

Figure 5. Duplex Electrical Model Example

## MODELING SENSOR SYSTEMS

In order to compare information about the actual behavior of a facility with its expected behavior, another information-exchange format and an open standard repository of sensor data needed to be created. The Building Automation Management information exchange (BAMie) was developed to link closed-loop control data points to assets being measured. BAMie defines the components, assemblies, and connections of a control system, and defines where sensor components (that publish sets of data at a specified frequency) can point to measurements of specific building components. BAMie does not specify the range of values, or associated units, but does specify the IFC representation for addressing in a variety of protocols such as the Open Building Information Exchange (oBIX) (OASIS 2006), LONWORKS, and BACNET.

## FACILITY CONTROL FRAMEWORK

When the project team stepped back from the discipline-specific details of each MVD, and that of the sensor system model, a pattern of information emerged that helped to guide the work that went forward. This pattern begins with the specification (BPie) of the expected minimum requirements that the finished facility must meet. Next, the components, assemblies of components, and systems that support services meeting those requirements may be specified (i.e. HVACie, Sparkie, and WSie). Finally, measurements about the performance of those services (BAMie) may be captured by extracting information trapped in closed-loop control systems. Table 3 summarizes the standards that comprise the Framework Model.

During the development of the Table 3 specifications, information from existing NBIMS-US was also re-used. The primary technical content of the NBIMS-US V2 was the Construction Operations Building information exchange (COBie) standard (East 2011). In the Building Programming information exchange (BPie) specification, information pertaining to room data sheets, spatial requirements, required equipment, and finishes are expressed in IFC format. Comparing COBie and BPie provides a good example how model views may be created from similar shared underlying concepts. Both COBie and BPie share ideas about spaces and equipment. BPie represents the plan for such assets. COBie provides the as-designed and as-built results. There are, however, some differences between COBie and BPie. One new modeling concept is required for BPie. That concept is “Space Type.” Concepts in COBie related to maintenance, warranties, and other handover information is also removed from COBie when creating BPie.

In the HVACie, Sparkie, WSie, and BAMie specifications, COBie MVD information may also found by extracting information about the managed assets found in each of these systems. For example, in HVACie information about a chiller can be exported into a COBie MVD. Information about the components in each of these systems, found in the COBie MVD, is a subset of the overall system model. The system MVD also includes the assemblies of component into assets such as chillers and electrical distribution boards. Also, the physical and logical connections between these assets are defined. The application of the system-specific MVDs within the context of both IFC 2x3 and IFC4 have been evaluated and examples provided through the buildingSMART alliance.

Table 3. Framework Model Specifications

| Content | HVAC | Electrical | Water | Sensor |
|---|---|---|---|---|
| Design Requirements | BPie | BPie | BPie | - |
| Components | HVACie | Sparkie | WSie | BAMie |
| Assemblies | | | | |
| Connections | | | | |

The use of the Framework Model specifications, shown in Table 3, may also be evaluated based on coverage of shared business process. An outline for life cycle facility asset-management business processes was initially developed in East 2010. A follow-on study further specified and documented these exchanges, and produced 25 exchanges that develop from owner's planning documents through to construction handover (Fallon 2013d). These exchanges were validated with a group of subject-matter experts. The coverage analysis is provided in Table 4. The first column of Table 4 provides this validated list of business processes. These processes begin with publication of an owner's standard room data sheets and product requirements (Phases 01-03). The programming phase of the project defines the requirements for the spatial and equipment assets to be delivered (Phases 04-07). The design phase creates the documents required for builders to meet those requirements (Phases 08-13). The construction phase completes the owner's requirements by the instantiation of the required engineered environments (Phases 14-25).

To compare the scope of each MVD, Table 4, in columns two through seven lists each MVD in the Framework Model and identifies those project phases addressed. BPie, in column two, covers information during the programming phase. The system specifications, in columns three through six, were developed based on the design phase only. The final project in the Framework Model, COBie, in column seven, is the most mature in terms of process coverage. This difference in coverage reflects the fact that COBie became a US National BIM standard in 2012. BPie, HVACie, WSie and Sparkie are being balloted in the NBIMS-US V3 round which is scheduled to be published in summer 2014. BAMie awaits vendor implementation, but is likely to be balloted in the NBIMS-US V4 round.

Table 4. Life cycle Phase Coverage

| Project Phase / MVD | BPie | HVACie | Wsie | Sparkie | BAMie | COBie |
|---|---|---|---|---|---|---|
| 01 - Facility Criteria | | | | | | |
| 02 - Design Specification | | | | | | |
| 03 - Feasibility Study | | | | | | |
| 04 - Project Definition | | | | | | |
| 05 - Space Program | X | | | | | X |
| 06 - Product Program | X | | | | | X |
| 07 - Request for Proposal | | | | | | |
| 08 - Design Early | | X | X | X | X | X |
| 09 - Design Schematic | | X | X | X | X | X |
| 10 -Design Coordinated | | X | X | X | X | X |
| 11 - Design Final | | X | X | X | X | X |
| 12 - Request for Proposal | | | | | | |
| 13 - Inquiry Issue | | | | | | X |
| 14 - Pre-Construction Plan | | | | | | |
| 15 - Inquiry Issue (RFI) | | | | | | X |
| 16 - Product Type Selection | | | | | | X |
| 17 - System Layout | | | | | | X |
| 18 - Submittal Package | | | | | | X |
| 19 - Submittal Issue | | | | | | X |
| 20 - Purchase Order | | | | | | |
| 21 - Product Installation | | | | | | X |
| 22 - Start-Up | | | | | | X |
| 23 - Product Inspection | | | | | | X |
| 24 - Punchlist Issue | | | | | | X |
| 25 - Turnover Package | | | | | | X |

## CREATING A CONTROL CYCLE

If the units of measure of planned facility performance, as defined in BPie, matched the units of measure of the sensor data, as captured through BAMie, then a cycle that allows management control is possible. While the units of measure (such as temperature, lumens, or occupancy) may match, the level of detail in the information provided does not allow easy comparison. Building programming specifications of building performance are based on blocks of time that represent periods of activity, such as a five-day, forty hour work week. For example, general overhead lighting in an interior office would be turned on at 0800 hours and turned off at 1630 hours Monday through Friday (assuming the facility is located in the United States). The actual information on lighting in that interior office may vary significantly from that idealized work time. For example if the workers in the office decided to come in at 0900 instead of 0800, but still work 8-hour days the pattern of work might be considered to be the same. Vacation days during the work week would also disrupt the expected sensor data stream, but not the pattern of use of that interior office.  Alternatively, if the lights in the office were on all day, every day, then this deviation from the expected pattern is likely to represent something other than the expected pattern of electrical use in that office.

The project team generalized three types of deviations in the patterns of signal data that must be resolved when closing the control cycle.  The team referred to these deviations as “noise.” compared to the clean “signal” provided by the more general pattern expressed in building programming data.  The first type of noise is a change in the intensity, or amplitude, of the sensor information when compared with the planned usage.  For example, the required temperature set-points in a room may be 68 degrees Fahrenheit during the cooling season, but the actual temperature measurement in the room will vary up and down.  The second type of noise is a shift in the start and end of the pattern.  For example, an office worker may start and end their day 15 minutes before or after scheduled duty hours.  The third type of noise is a change to the frequency of the signal.  This type of noise is most prevalent in building assets that are used for a short time by office occupants.  An example of the type of pattern that would generate frequency noise is the use of a microwave or coffee pot in an office kitchenette.

To determine if it was possible to compare the clean signal of expected resource use from the noisy information provided by sensor data, the team created a test bed to conduct the analysis. Starting from an example stream of sensor data that matches the expected data pattern perfectly, our team created simulated data streams spanning the entire solution space of signal-to-noise ratio.  A data-cleaning and pattern-detection algorithm was created to determine if it would be possible to evaluate the expected data stream when compared to that same data stream at different levels of noise.  This algorithm considers only individual sensor data; the resolution of multiple conflicting sensors across multiple building performance dimensions is not currently included in this analysis.

The algorithm contained four specific components:  noise reduction, data clustering, pattern classification, and anomaly detection (Bogen 2013).  Intensity noise reduction was accomplished through the application of Fourier transforms and spectral subtraction.  Frequency and shift noise were addressed through the application of an unsupervised k-means clustering algorithm. Pattern classification was accomplished through evaluating the difference between an incoming pattern and the current pattern.  The identification of differences was based on a root mean square analysis.  The threshold for identifying anomalous patterns was a compromise between precision and complexity.  As an example, assume an occupancy sensor expects someone working a fixed schedule.  If that person enters the room five minutes before the typical schedule that will likely not constitute a new pattern.  If, however, the person enters the room two hours after the expected arrival time, the detection of an anomaly should be expected.

This algorithm performed well on data streams representative of assets that use resources for an extended length of time, such as office lights. The algorithm also performed well on data streams that were representative of assets that were consistently turned on several times during the day for an extended period of time during each use, such as chillers and boilers. The algorithm did not perform well on data streams representing assets used frequently during the day but whose time of use is very short (Bogen 2013).

## DISCUSSION

Delivery of a Facility Control Framework, from the point of view of the facility user, should be as simple as providing the needed information and analysis routines on electronic storage media ready to be plugged into to the building sensor feeds defined in the model. At the start, the Framework would pre-populated with the signal analysis routines based on the expected patterns of occupancy defined during programming through commissioning. Once the occupants move in, the algorithm learns the actual behavior of the building occupants and learns these patterns. In operating such a facility, the facility manager would respond to changes between the expected and actual behavior of the facility and not alarms based on fixed sensor set-points.

The realization of such a vision requires that the information produced during the facility life cycle be compatible with the specifications identified in Table 3. To promote the ultimate creation of this framework, BPie, HVACie, Sparkie, and WSie formats have been submitted for consideration under balloting of the NBIMS-US V3. These specifications were balloted since implementation examples could be created, with a high degree of success, directly from existing design software (East 2012a).

One expected side-effect of creating a domain-independent facility control framework is that practitioners may look to use these new specifications to solve questions tangential to the designed scope of the framework's standards. Examples of such behavior can be found today for existing building information model standards. The Coordination View and the COBie standards have both been subject to out-of-scope use. For example, the "round-tripping" of Coordination View files goes beyond the scope of Coordination view, which was created to only export and compare building geometry. In the case of COBie, international examples that require asset geometry and pipes or ducts exceed the scope of COBie, which was created for the exchange of managed assets and spatial containment only.

Repurposing existing model standards may or may not be successful, depending on the amount of overlap between that specification and the practitioner's problem. Given that off-scope uses are to be expected, the authors conducted several studies to determine the brittleness of this framework. These studies were conducted concurrently with the development of the framework's standards. Since the full framework was not in place at the time these projects were undertaken, the analysis was limited to examples that evaluated the managed assets within the standards.

**Automated LEED Data Preparation**

The first of these studies investigated if a facility asset model compliant with the COBie standard could be augmented with information required to fill in LEED assessment checklists (Biswas 2012). Through a process of data mapping between the LEED data forms and the facility asset model specification, the additional information needed to meet LEED requirements was identified. The additional information needed constituted, with one exception, attributes related to the design of the facility that would not be expected in a simple model of building assets. For example, the COBie.Facility object is augmented with occupancy information as a COBie.Attribute object or, in terms of the IFC standard, the simple addition of a custom ifcPropertySet. COBie.Type objects were also augmented with information about recycled content. The conclusion of this project was that an analysis tool that determines the existing quality of data from a building information model, provided in COBie format, and allowed augmentation of that model to support LEED, would reduce the time required for LEED data collection by 45%. A similar study was also commissioned to successfully demonstrate the viability of using an IFC 2.3 Coordination View building model to create “green building XML” (gbXML) formatted data (Nisbet 2010).

**Automated Total Cost of Ownership Analysis**

The another study investigated the way in which a building-asset model compliant with the COBie standard could be augmented to evaluate Total Cost of Ownership calculations based on expected resource utilization (Florez 2011, Nisbet 2011). In this study, the heating and lighting system of the duplex apartment model were evaluated based on the expected utilization of the facility as either a residence or as an office. In these scenarios, differences in predicted space utilization were used to develop cost curves that predicted the annual operating expense of that system. A COBie file at handover will contain the location and count of all energy-conversion devices and identify the required maintenance for each type of device in the building. Additional information needed for each alternative type of product is (1) installation, replacement, and labor costs for maintenance, (2) product life expectancy, and (3) resource use efficiency. The detailed specification of such information across multiple product types is described in Chasey 2012. Contextual inputs included (1) planning horizon, (2) building use, (3) cost of power, (4) labor and material inflation rate, and (5) energy inflation rate. With this additional information, a new model or study was not needed; this supplement to the existing building asset model allowed a simple engineering economic calculation.

### Tenant Management

In many campus settings, organizational power is established by the number of facilities and or spaces under the control of a given department or business unit. While the needs of the overall organization may change over time, the precedence and prestige associated with managing a specific set of spaces may result in some groups needing more space and others needing less. Anecdotal evidence suggests that such behavior, without relevant controls, results in infrastructure overcapacity. This is because there is a limited ability of tenant managers to assess the actual usage of each assigned space. The framework described in this paper may be directly used to identify those spaces that are not being used as designed. Given common information about anomalous space utilization, management decisions about space reallocation may be rationalized.

### Critical Infrastructure Management

Closed-loop control systems incorporate alarms that trigger based on set-points established at system commissioning. Only during an extensive facility recommissioning process are these set points adjusted. As a result, many facility managers report frequent "false positive" alarms. Annoyance leads to habituation, with operators ultimately ignoring (or even disconnecting) these alarms (Reason 1990). Such natural human behavior is extremely dangerous in the management of critical infrastructure, as noted by the following example. For years, as many as 200 false-positive intrusion-detection alarms per day were encountered at a facility at the Oak Ridge National Laboratory. These alarms were the result of deer and squirrel activity on warning tracks outside and inside the facility's fence line. The case in question occurred when the alarms were sounded by three elderly protesters who cut through two security fences with bolt-cutters carrying banners and paint cans. These protesters proceeded to deface one of the most sensitive buildings in the United States Government facility inventory (Priest 2012). The proposed building-control framework, had it been in place, should have been able to learn the pattern of alarms from squirrels and deer over time and alarm on a new pattern: protesters with bolt cutters.

### Integrated Delivery Process

The validation of a new signal-processing algorithm (Bogen 2013) alone will be insufficient to motivate owners and practitioners to change software versions, and associated configuration and workflows, to provide the required standard facility information. While it is possible for large owners, such as government agencies, to mandate the delivery of such information, enforcement of such requirements is limited without an estimate of the impact of the process changes to deliver such information (London 2011). The author's efforts to apply lean methodology, using value-added analysis techniques for construction submittal processing (East 2011), have been applied more broadly through the development of a calculator to evaluate the delivery of asset information through the project life cycle (Fallon 2013).   The results of this COBie Calculator study indicated that over 90% of non-value-added costs related to facility asset information exchanges may be eliminated.

## CONCLUSIONS

Prevailing efforts related to building information modeling reflect the need to deliver facility information through a project's life cycle (East 2010).  Streamlining the delivery of discipline-specific building information alone is, however, insufficient to the support the increasing demands placed on our built environment.  This project has provided the framework for, and demonstration of, a domain-independent facility control framework that defines how resources required to support the mission of the facility compare with the actual behavior of the facility. The data-mining and pattern-matching algorithm developed in this project was demonstrated to be effective for the majority of fixed assets found in typical facilities.  This framework was also extended to demonstrate that additional types of building analysis, currently conducted in a stand-alone, stove-piped manner, can be conducted directly with virtually the same underlying building information.  If the proposed framework is available by the adoption of NBIMS-US V3, then the cost of adding new social and engineering considerations to the daily jobs of designers is simply the cost of adding new data to the framework, not the creation of new design disciplines.

In addition to the contribution made by the domain-independent facility framework introduced in this paper, the methodology used for this project has also become a contribution in its own right. The building information models produced as demonstrations of a facility's information life cycle are available through the buildingSMART alliance under Creative Commons License. These models have been directly used to evaluate the quality of commercial software compliance with the United States National Building Information Model Standard.   Educators have also used these models within their coursework.  The Tool Kit developed through this project has also become widely used to transform and check models submitted for testing as part of the United States National Building Information Model Standards.  Finally, the methodology used to predict the benefit of the life cycle delivery of building information model provides a validation methodology for projects whose benefits stem from process-based productivity improvements.

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