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SmartBIM: *The Progression of Integrated Building Information Model over the Life-cycle of a Building*

Abstract:
Building information models (BIM) are changing the way building professionals work in building design, construction, and management. In a current research effort at Carnegie Mellon University, we are developing an integrated project model focusing on the construction phase. The premise of this work is that the continuous and immediate availability of the best possible information model provides significant advantage over traditional computer-aided drafting. This project model includes three-dimensional as-designed models, as-built information, and updated design information. The model is the most viable digital representation of a built environment, one that reflects a current status of the building over its lifecycle. We bring the BIM model (which has been updated through the design and construction phases) into the next phase of this building life-cycle, namely, management and operation phase.

Building state information is critical for the effective ongoing operation and maintenance of buildings. Through appropriate sensors, communication devices, and building information management strategies, life–cycle data about building components will be made available to the relevant actors for operation and performance analysis. Our research develops a methodology to create sensor–driven, high resolution building management system that use a BIM. We adopt the notion that a BIM represents the current state of the building, includes all collected information from the past, incorporates all future building status and, with respect to this paper, is a comprehensive and detailed representation of the operation and state of a facility through space and time over its life-cycle.

1. Introduction

We propose a framework for a "**Smart**" **B**uilding **I**nformation **M**odel (*SmartBIM*) for use in building management operation. From studies published in the literature one can claim that any database system suffices for a building information model; for our purposes here in this paper we use IFC as the *protocol* for a BIM. Such a model resolves data format incompatibility by supporting a syntactic and semantic convention necessary for automated data exchange and data sharing. The model integrates design specification, as-built information, occupant behavior as well as operational data. It is a representational schema that enables flexible decomposition (Stouffs and Krishnamurti 1997) of the building model according to various task specific views needed for the different building environment experts. Our focus in this paper is on the application of *SmartBIM* in the construction and operation / management phases of a building

1.1. Building Life Cycle

Design and construction projects proceed in phases from start to completion with variations that depend on a variety of factors — for example, the nature of the work, needs of the owner, type of contract, or delivery method. The explicit start and end of a constructed entity is uncertain and depends on the point of view from which it is defined. Ideally, the concept of the life-cycle of a constructed entity runs from the birth of an idea to the demolition of that built environment and the possible subsequent reuse of the site.

There are different ways of characterizing the building life-cycle. For instance, Gielingh (1988) structures it according to major transition phases, which he classifies as: feasibility study, design, construction planning, construction, operation, and demolition planning. Each phase involves a number of activities, each increasingly becoming more reliant on computer-based operations – for example, simple drafting and scheduling tools, applications for automatic detailing and fabrication of parts and, even, automatic monitoring of building plant operations. More complex tools include material procurement and tracking of use during construction, and equipment simulation for assessing equipment operation during the operation phase of a building.

At present, a serious obstacle to the use of multiple applications is the volume and nature of the information needed. These applications require data that defines specific contexts. Integration requires access, the incorporation of appropriate data, and interpretation of results with, possibly, iterative use and exchange between members of the building team.

In our research we focus on information related to construction, operation and management whether it be considered with planning and scheduling of activities, equipment mobilization, procurement, on and off-site constructions, component fabrication, contract administration, building system operation and maintenance or from exploring technological developments which offer new ways of capturing reality, thus providing information that improve the quality of the built environment — in a sense, one could say, of the overall architecture.

1.2. Building State Information

Building state information (as-built and as-used information) collected during the operation of the building is necessary for the effective operation and maintenance of a building. Buildings aggregate and integrate HVAC and lighting system components from multiple manufacturers and constructors. These systems are subject to change over time, and their controllers must respond to varying outdoor environments while maintaining specific indoor conditions. Dynamic change in a facility recorded systematically and in real-time, is of interest to designers, facility managers, occupants, and owners. Technological advances over time influence the composition and configuration of building systems. Buildings create technical challenges of providing individual comfort, organizational flexibility, technological adaptability, environmental sustainability, while at the same time minimizing energy consumption (Hartkopt and Loftness 2004). Conventional practice emphasizes "static" buildings and their conditioning by centralized bulk solutions. Sensing and control strategies favor centralized solutions that are inflexible. Moreover it is very difficult if not impossible to rely on such inflexible systems in a "one size fits all" manner. The current design of building management systems results in highly customized for individual buildings. This results in complex building operation and maintenance. For a fluid, flexible, and redistributable solution, some form of building information management is needed. Our research proposes a framework to collect such data using *SmartBIM*.

1.3. "Smart" Building Information Model (*SmartBIM*)

We develop a methodology to create integrated high resolution building information models that is capable of a comprehensive and detailed representation of the state and operation of a facility. In addition, these models are capable of supporting decision making — whence, *SmartBIM*.

We create a *SmartBIM* by using collected information that augments the BIM that collectively reflects the previous phases in the building life-cycle. In the building operation phase this *SmartBIM* will most accurately represent the current state of the building. The collected information includes data from sensors placed in the building, information about system maintenance, and occupant feedback. Addition there is also information about the space characteristics (geometry, material, space use etc.).

1.3.1. THE NEED FOR THE MODELS

Buildings tend to last longer than their original project team and owner(s). Phases in the building life-cycle rely on information generated in a previous phase. Standardization resolves data format incompatibility by supplying a syntactic and semantic convention necessary for automated data exchange and data sharing. Buildings are exposed to various agents of change, including humans, weather, depreciation, aging of materials and equipment and sensor failure. Methods are required to notify the building model of these changes and to adjust itself accordingly. This model will include monitoring occupant feedback and preference. Research and prototypical implementation are required to address the space–time resolutions for building models. These depend on information needs using the principle of multi-resolution models and mapping algorithms for the automated derivation of building models from sensor data. These also depend on a required model resolution, kind, quantity and placement of sensors. The building model stores the necessary information required to intelligently store/update sensor information and performance simulation results.

Advances in sensor hardware – sensor integration, electronic miniaturization (for example, commercial research in Micro-Electro-Mechanical Systems) (Technologies), and low power wireless communication have revolutionized the ability to collect building data. Stick on sensors discretely attached to walls, or embedded in floors and ceilings, active badges for users, sensors embedded in objects in a facility provide vast quantities of data. However, current building operation and management strategies lack sufficient ability for scaling and integrating diverse types of nodes (sensors and actuators) and the ability to support diverse operation applications. The *SmartBIM* framework simplifies this by providing a flexible mechanism to store information.

For building operation such information from *SmartBIMs* could be used for real-time fault detection at low-levels (individual sensors and clusters of sensors), and mid-level (building heating, cooling, and power generation system components such as control valves, pumps, fans, heat exchangers); performance monitoring at the individual room, zone, and building level as well as at the sub-system and system levels; intelligent decision making for building operations and maintenance. This would assist the creation of self aware sensors, self healing sensor networks and development of a framework to support automated calibrating of systems.

Buildings in the United States consumes 67% of all electricity, 40% of all primary energy (the Energy Information Administration, 2005). About half of this consumption is due to commercial building operations. Building state (as built and as operated) information is critical for the effective ongoing operation and maintenance of buildings. A hindrance in achieving better performance assessments over the building life-cycle is the inability to feed information in various forms to the relevant actors (facility managers, building owners) or agents (software tools that assist in data analysis). Such information is unavailable since as-built models do not reflect the as-used condition; as-used model are often not complete; changes that occur during the operation of a building are not reflected in as-used models; the framework for collecting and storing building operation data is not structured to allow easy analysis. Through appropriate sensors, communication devices, and information management strategies, as-used data regarding these components is available to the relevant actors for detailed performance analysis since the *SmartBIM* allows representational flexibility.

1.3.2. METHODOLOGY FOR BUILDING INFORMATION MODELS

Industry Foundation Classes (IFC)(IAI 2004) is one such industry-wide standard for the digital representation of building; in this paper, IFC is the protocol for the *SmartBIM*. IFC supports information sharing within the AEC/FM industry; an IFC data model facilitates the unambiguous transfer of information between computer systems. Using IFC schema definitions it should be possible to aggregate information from multiple sources for shared access and, possibly, provide a single entry-point to product information. The IFC platform specification, ISO/PAS 16739, defines data structures for representing building products and their information requirements in EXPRESS, a neutral modeling language (IAI 2004). Currently IFC is part of the Building Lifecycle Interoperable Software project (BLIS 2004) which coordinates the implementation efforts of several vendors and more importantly, supports the idea of an IFC file as the sharing/repository medium for the building life-cycle.

During building operation, environment sensors are installed and used to measure the current status of built environment. Following the IFC schema from IAI (IAI 2004), sensors can be defined by IfcSensor class (in IFC2x or earlier editions), and classified into the specific

IfcSensorTypeEnum type enumerations: HvacSensor, UserDefined, and NotDefined. The physical connectivity of the sensors to the model is through using IfcRelAssociates to one or more of IfcBuildingElement. A future development of our prototype will incorporate the IFC 2x2 schema into the model.

1.3.3. THE INTEGRATION OF BUILDING ENVIRONMENT SENSOR TO *SmartBIM*:
To ensure validity of the *SmartBIM* it is necessary to apply active and passive sensing techniques to evaluate actual conditions in the building and update the *SmartBIM*. It is proposed to use adaptive filter technology to process data and update building models. Sensor driven building models will be created by implementing non-linear parameter estimating schemes based on data obtained from sensors in a building. Such estimating schemes may be solved using the extended Kalman filter (Chen and Liu, 2000). The basic idea of the extended Kalman filter is to linearize the state-space model at each time instant around the most recent state estimate. Once a linear model is obtained, the standard Kalman filter equations are applied. The iterative application of the extended Kalman filter incorporating improved reference trajectories (obtained from sensed data) will further improve performance. This is based on the idea that once the filtered state is actually generated, that value would serve as a better state estimate than the predicted state for evaluating the measurement equation. The sensor driven building model thus generated would be integrated into and used to update the *SmartBIM*.

1.4. Representation Flexibility for *SmartBIM*

Design, construction, and operation activities rely on a restructuring of information that is not captured in the current information structure – that is, emergent information – as in the case of looking at a design that provide new insights leading to a new interpretation of the design elements. A conventional object-oriented approach requires a specification of design / construction / operation elements as objects that is maintained at all times, unless explicitly altered by the user. Then, any reinterpretation of the elements requires the specification of a (computational) change that not only fixes the source and destination object types beforehand, but also their numbers and mapping between properties.

Furthermore, a variety of design / construction / engineering problems requires diverse viewpoints each distinguished by particular interests and emphases. Standardization alone is not the solution to data exchange (Stouffs and Krishnamurti 2002). Any attempt to impose a common semantic model to which all adhere comes with attendant restrictions on possibly better solutions and may impede creatively new approaches to specific problems. If all adopt the same concepts, vocabulary and language, the view that data expressed within the language is accessible to each is challenged on the basis of practicality, representational flexibility and extensibility.

In this paper, we incorporate the representational flexibility of the model using *sorts* (Stouffs and Krishnamurti 2002; Stouffs and Krishnamurti 2004). *Sorts* presents a constructive approach to representations, based on an algebraic formalism and provides a uniform approach to handling various design data by means of behavioral specification, based on a partial order. Using this approach the model can be represented in multiple domains.

2. Case studies & Application of the Model

Our efforts in this paper are influenced by earlier work which we describe here.

2.1. The Building Construction Phase

In general, construction includes contractor planning and scheduling activities — for example, mobilization of equipment; material purchasing; on-site and off-site construction and fabrication of components by the contractor or subcontractors; contract administration by all parties (owner, architect, engineer, and contractor) concerned with specific rights thereof; and general implementation of contract document requirements through to project closeout (Hendrickson 2003). The contractor produces many documents such as progress schedules, shop drawings, payment applications, record documents, operation and maintenance data, and warranties. Some shop drawings, operation or maintenance data, and warranties may be prepared or submitted by manufacturers or their representatives for distribution by the contractor. These documents become part of the administrative records, and should be kept in the project file. The A/E may prepare contract modifications, such as change orders, as needed, to incorporate changes made in the project scope, time, or cost.

Here our focus was on the transformation of design, geared by new technology developments in reality capture, in detecting changes between a 'previous' as-designed condition to a 'current' as-built state. As part of this effort, we have so far conducted four test case studies (i) to measure the feasibility of our approach, and (ii) to discover problems. In the sequel, we discuss the overall project, work flow, integrated construction project model (to define and emphasize "changes" during construction), and describe the recording and representation of "changes".

2.1.1. REALITY CAPTURE DURING CONSTRUCTION

Recent advances in generating 3D environments using laser scanning technologies (Reinhart 2001), and in acquiring quality information about built environments using embedded and other advanced sensors (D. Sackin 2000; Foltz 2000) create an opportunity to explore the possibility of frequently gathering complete and accurate three-dimensional and quality related as-built data captured from a construction site. There are also commercially sponsored investigations in using laser scanning technology to produce 2D- and 3D-models of as-built conditions, for example, Leica Geosystems' case studies on suspension pipeline bridges using their commercial scanning package (LeicaGeosystemsHDS 2004). Current trends in the A/E/C industry for the use of integrated project models have shown that a semantically rich integrated project database combining multiple views of the project participants can support various project management and facility management during construction (Cleveland 1996; M. Fischer 1998; T. Froses 1999).

2.1.2. PROJECT WORKFLOW AND CASE STUDIES

Overall, the process for each construction case study starts with information gathering to build the continuously updated and maintained integrated construction project model, composed of a three-dimensional design model with specifications, a construction process model, and an as-built model of the condition at the construction site. The as-designed model should have a geometric level of detail that is useful for comparison, with features that are to be extracted from a current condition of construction. For non-geometric features, components must be presented with expected performance attributes that will correspond to the gathered data. The as-designed model, 3D design model with specification from construction documents, is obtained from commercial parametric design software as an IFC file for current protocol of BIM. Laser scanners provide accurate three-dimensional geometric as-built information (e.g., component identity); similarly, embedded sensors provide frequent quality related information (e.g., thermal expansion). This collection of as-built and continuously sensed information, its integration to the construction project model, the subsequent analysis of the construction project model for defects, and any consequent update of the design and schedule models enable project managers to manage defects actively. See Figure 1.

2.1.3. MODELING CHANGES DURING CONSTRUCTION PHASE

The construction project model is based on the architect's design, and contains geometric information and some, although not complete, attribute information in the form of IFCs. Changes are inevitable, and new entities can be triggered, by construction, into the project model. These new entities may be used only in the construction phase, or their usage may extend into the operation phase (for example, the uses of embedded sensors depend on their life span and/or any measurement goals set).

For the case studies, in an effort to capture the current condition on site, two new entities were added to the construction project model: embedded sensor data, and as-built geometric information from the laser scan. Entities are connected by way of their as-designed element identity. Embedded sensor entities have as substratum, an as-designed element and a location within that element. Sensor entities contain other attributes, such as type, usage, and time-stamped values. Each as-built geometry connects to an as-designed element. For the project, a new entity named "Defect" is added into the project model. The defect entity connects to both as-designed and as-built elements through their identities. It may also include one or both sensor entity and as-built geometry. After analysis, any newly discovered defect is submitted to a decision making process, involving stakeholders and supporting A/E/C personnel. A decision could result in: (i) a reconstruction of a part in the already built environment, (ii) a design change, or, (iii) by agreement, no further action. Furthermore, some decisions may cause other changes, such as a change in the construction schedule.

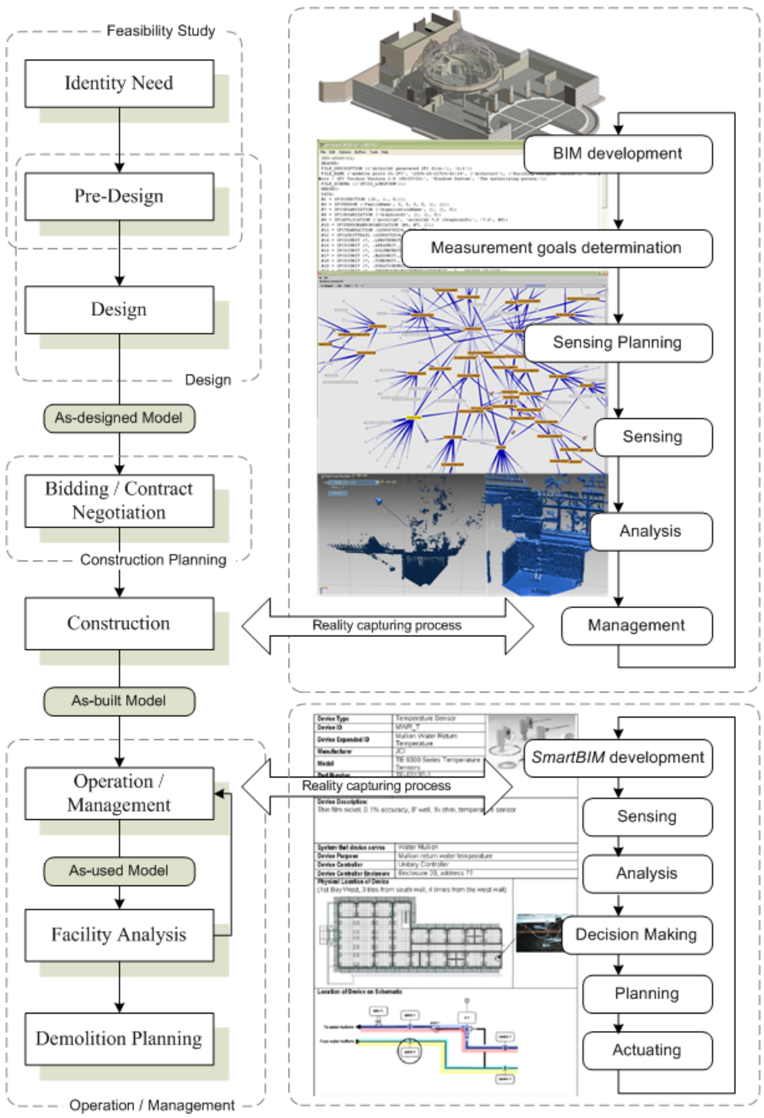

Figure 1: building life-cycle diagram of SmartBIM

Currently, our project model is designed to both capture changes in the drawings (as-designed), and changes on a given construction site (as-built). The as-designed model contains component geometry and attribute data, such as material, install-start time, install-end time, etc. Defect and sensor data are attached to related components in the as-designed model. Change in the drawings implies an update of the as-designed model. All attribute data and attached data are updated or copied component by component. The data of a new updated version of the as-designed model is recorded in a different subdirectory of the previous version. Consequently, our integrated construction project model contains all the history data (changes) in the construction documents. The as-built model records the data, which is scanned by a laser scanner periodically, and represents whatever has been built on the construction site. Each time the data is scanned, it is synthesized as a large point cloud data. It represents the latest recorded progress on the construction site, therefore records all the changes that have happened on the construction site since the last scan session. Similarly, a new scan session means an update of the as-built model, and the new scan session data is recorded in a subdirectory different from the previous scan session.

2.2. The Building Operation & Management Phase

Evaluation of facility state data for maintaining design specifications, monitoring of component performance over time, and operational process improvement is neither well structured nor well supported by technology today. With the merging of building technology and information technology, a systematic approach to facility state information is required throughout the life cycle of the facility (See Figure 1). To convert the data generated from sensors in the building into knowledge, for diagnostics and troubleshooting problems with building system components, and as an operational log to compute energy consumption, it is necessary to refer to the specifications and maintenance log of the sensor or actuator. Products are offered in the market place for mission or safety critical systems such as elevator, yet these efforts cover only a small fraction of the information that could be useful.

2.2.1 AUTOMATED DIAGNOSTICS AND IDENTIFICATION OF FAILURES

Currently simple rule based threshold algorithms such as minimum and maximum limits are used to trigger alarms. These are not sufficient to detect problems with building systems. The gradual lead up to building failures is often subtle. They are not as straightforward and obvious as major equipment but are of a transient nature affecting sections of users. Each individual piece of equipment may be functioning properly but the building system as a whole may not be delivering the expected performance.

Diagnostic algorithms typically examine single streams of data at any one time, such as the error between actual indoor air temperature and set point temperature, or the duty cycle of an actuator to determine the stability of control. Once a failure occurs in a building system data from multiple alternate streams is required to diagnose the failure. Building operators often use their experience in working with a particular building to diagnose building problems. However, in large facilities it is not possible to depend solely on human experience alone. For such systems to be effective they must provide a high quality of unattended operation. Increasing number of nodes in a system also results in a high susceptibility to failures. Sensor and sensor network failure detection algorithms are therefore required to better manage anomalous data.

Further research is proposed to develop methods to examine patterns and signatures across multiple systems. In an algorithm using a *SmartBIM*, streams of data obtained from sensors in a building could be considered to be the environmental signatures of that building under various criteria. Signatures will be correlated with user behavior to determine successes and failures. A self updating database of environmental signatures will be created to better detect problems. These algorithms will allow the operator to more easily see how a failure occurred rather than only providing information that a failure has occurred. This will increase the forensic capabilities available to building operators. This will also increase reliability of unattended systems and reduce operating costs. When additional devices are added or devices fail, device controllers will re-organize themselves to provide optimum performance.

3. Prototype Development

3.1. Flexible representation for *SmartBIM*

A building element may have multiple geometric and non-geometric representations. The participants during construction and operation, representationally, have their own aspect and scope. Figure 2 shows representation and user interaction structure of our prototype development.

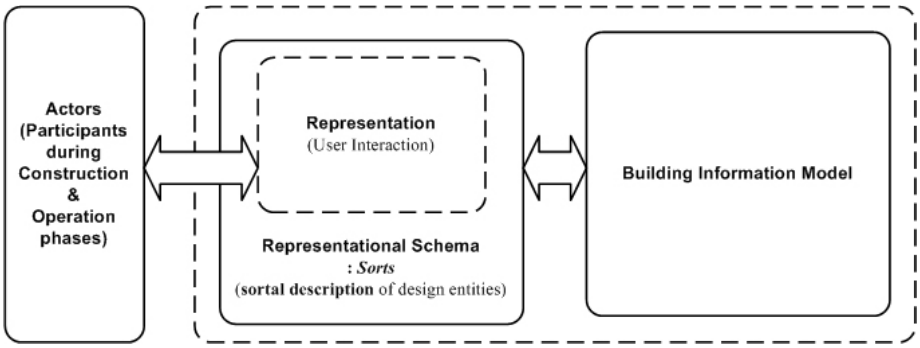

Figure 2: Representation structure diagram with Actors, Sorts and SmartBIM

The current prototype development consists of three spaces, namely general view space, *sortal* view editing space, and new view space. A general view of the *SmartBIM* is a dynamic graph representing the model and its component connectivity. From this general view, the *sorts* representational schema can generate a predefined *sortal description* (Stouffs and Krishnamurti 2002; Stouffs and Krishnamurti 2004) view of the model that is participant-specific. In order to increase the user interaction and the representational flexibility, dynamically defined views can be generated by combining components in the general view with specific functions (for example, relationship, volume calculation, surface generation, etc). Figure 3 shows a current prototype development.

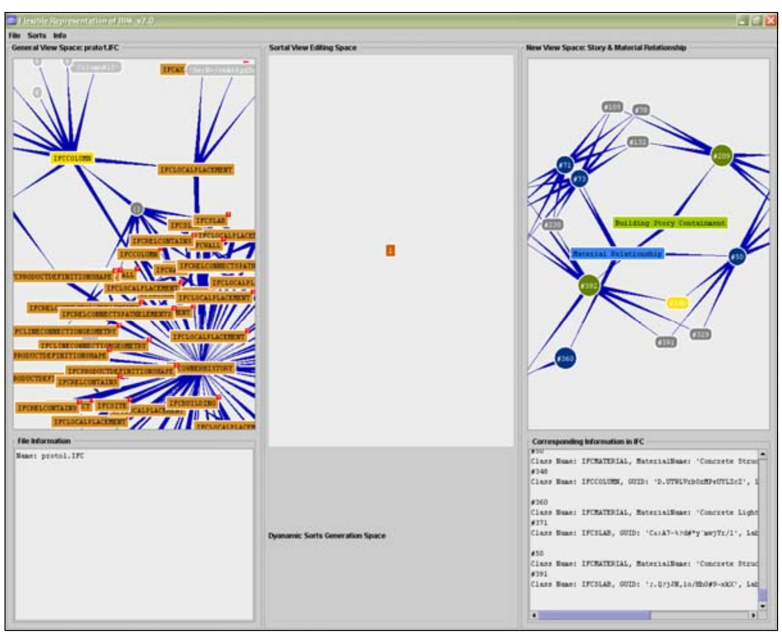

Figure 3: Current prototype development in representation

3.2. Restructuring of Information

Building elements have specific attributes. Some attributes are physical, such as geometry, materiality, building story containment, etc., and some are conceptual, such as project, space, construction time, etc. For our case studies, we derived the needs that were specific to the user(s) point of view in a specific time during construction and operation.

For example, the construction inspector needed a view that represented story containment and material use of building elements. In order to generate this specific view, we used the *sortal* approach to construct a new relationship from the model. We generate the *primitive* relationships that were embedded in the building information model, and then combined these *primitive* relationships to construct new relational structures. Figure 4 shows one such scenario.

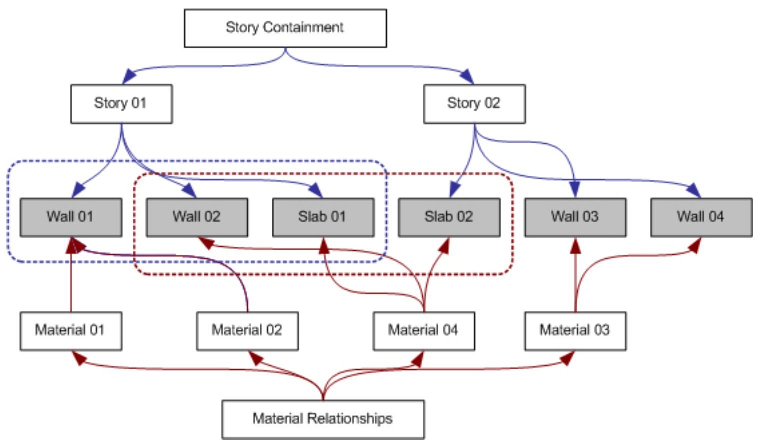

Figure 4: conceptual diagram of material and story containment relationship to building elements

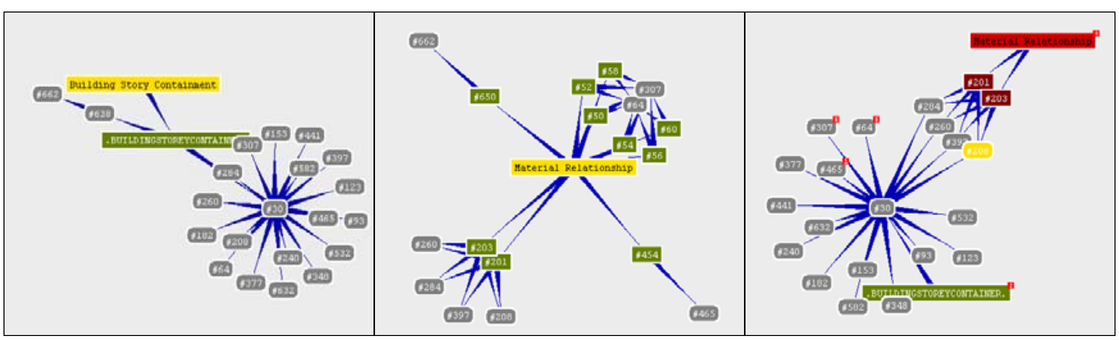

Figure 5: i) building story containment relationship to building elements, ii) material relationship to building elements, iii) combining two previous relationships into one representation

Note) Number node in the Figure 3, 5, 7 represents the line number in IFC file. The corresponding information from the IFC file is showing in the information window, also it can be synchronized into the node in general view space.

Figure 5 iii) depicts building elements relationship with material and building story containment in new view space. The representation clusters information which is not explicitly represented in current building information model.

In another case study we tested an office room with specific spatial conditions. The spatial requirements for this case study were: an office space with two walls facing outside, and two walls facing inside to different space definitions, with windows to outside, and with doors to inside and outside to different space definitions. Figure 6 shows the plan and rendered image of the case study.

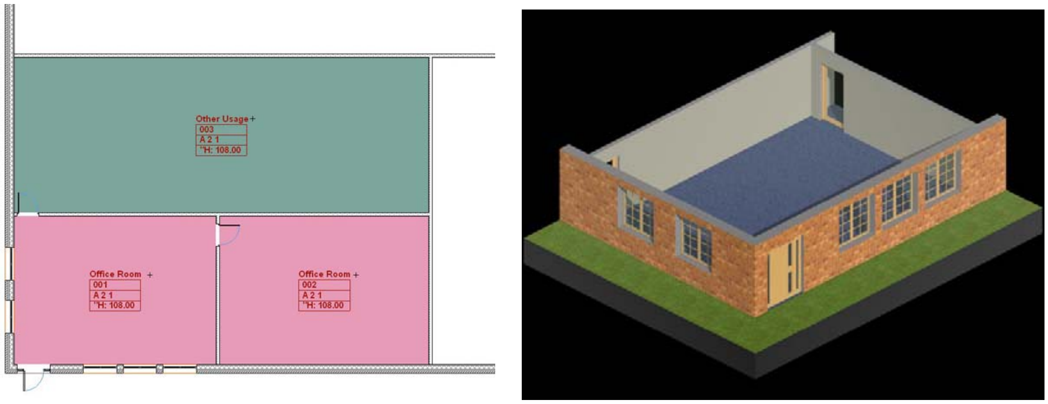

Figure 6: case study plan & rendered image

Here, the building operator needs the spatial relationship of the building elements and the locations of building environmental sensors within the building elements. Figure 7 illustrates such a spatial relationship.

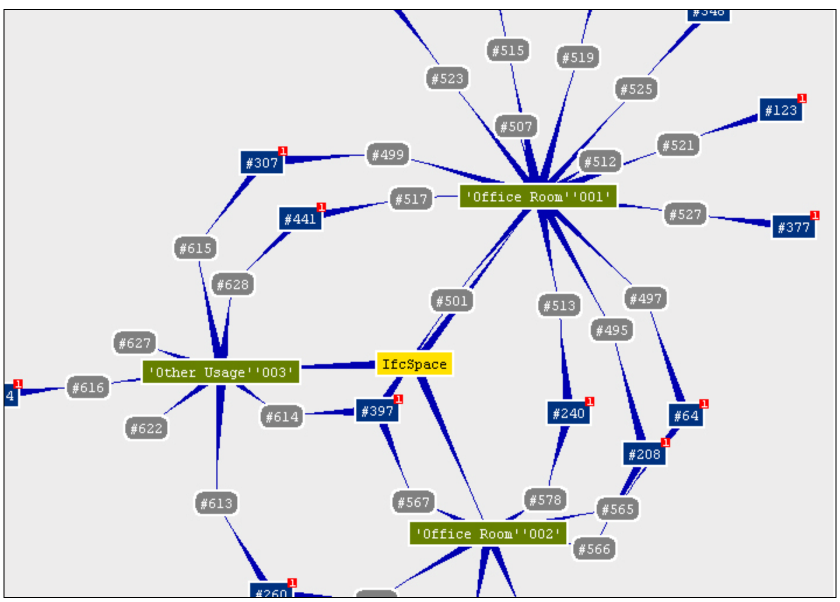

Figure 7: spatial relationship of building elements in the case study

4. Conclusions

Design, construction, and operation — all these activities in a building life-cycle could be considered as a mid-point of the cycle; this is especially true in our information technology age. A building, as a building information model, grows over time: how we see this vast storehouse of information; whether at any particular point in time, or in terms of the certainty and efficiency with which we can retrieve or piece together specific information; or, how we bring knowledge from the collected information are major issues.

Building control systems which rely on remote sensor–driven, high–resolution building models have the potential to significantly affect and enhance service quality and effectiveness in all relevant phases of a building life-cycle: from design to construction, commissioning, operation, and disposal or recycling. Furthermore, detailed real–time information about a facility's state serves as an invaluable resource for security and emergency services, and might enable novel kinds of services to become feasible, such as detailed life–cycle analysis of products on a large scale. Manufacturers can analyze data tracking of the performance of their products in various facility settings in order to develop better products, coordinate marketing efforts, and/or offer customized services related to their products. Databases containing detailed historical records of buildings could serve as a rich asset for collective learning by providing building practitioners, researchers, organizations, and manufacturers with feedback and a better understanding of the value and implications of their services and products.

SmartBIM could be the first steps towards these goals.

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Bibliography:

The Energy Information Administration, <http://www.eia.doe.gov>, Last Accessed: Mar 20, 2005

BLIS (2004). Building Lifecycle Interoperable Software.

Cleveland, A. B. (1996). "Integrating information with 3D models for facility life-cycle support." Analysis and Computation.

D. Sackin, e. a. (2000). "Embedded Micro devices for Infrastructure Monitoring." Congress of the International Association for Bridge and Structural Engineering (IABSE).

Foltz, B. (2000). 3D Laser Scanner Provides Benefits for PennDOT Bridge and Rockface Surveys.

Gielingh, W. (1988). General AEC Reference Model (GARM). CIB Conference on the Conceptual Modeling of Buildings, Lund, Sweden.

Hartkopt, V. and V. Loftness (2004). Architecture, the Workplace, and Environmnetal Policy. The Innovative University. D. P. Resnick and D. S. Scott. Pittsburgh, Carnegie Mellon University Press: 181-194.

Hendrickson, C. (2003). Project Management for Construction: fundamental concepts for owners, engineers, architects and builders.

IAI (2004). Schemas and Schema Documentations, International Alliance for Interoperability.

LeicaGeosystemsHDS (2004). Condition Assessment of Old Suspension Pipeline Bridge.

M. Fischer, F. A., and R. Akbas (1998). "Formalizing Product Model Transformations: Case Examples and Applications." Artificial Intelligence in Structural Engineering.

Stouffs, R. and R. Krishnamurti (1997). Sorts: A Concept for Representational Flexibility. CAADFuture, Kulwer Academic.

Stouffs, R. and R. Krishnamurti (2002). Representational Flexibility for Design. Artificial Intelligence in Design, University of Cambridge, UK, Kluwer Academic Publishers.

Stouffs, R. and R. Krishnamurti (2004). Data Views, Data Recognition, Design Queries and Design Rules. Design Computing + Cognition, MIT, Cambridge, Kluwer Academic Publishers.

T. Froses, e. a. (1999). "Industry Foundation Classes for Project Management." Electronic Journal of Information Technology in Construction 4: 17-36.

Siemens Building Technologies, <http://www.sbt.siemens.com/BAU/default.asp>, Last Accessed: Mar 20, 2005