Bidirectional Interoperability Between CAD and Energy Performance Simulation Through Virtual Model System Framework

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Abstract

The paper describes a novel approach involving interoperability, data modeling technology, and application of the building information model (BIM) focused on sustainable architecture. They share relationships and multiple experiences that have existed for years but have never been proven. This interoperability of building performance simulation maps building information and parametric models with energy simulation models, establishing a seamless link between Computer Aided Design (CAD) and energy performance simulation software. During the last four decades, building designers have utilized information and communication technologies to create environmental representations to communicate spatial concepts or designs and to enhance spaces. Most architectural firms still rely on hand labor, drafted drawings, construction documents, specifications, schedules and work plans in traditional means. 3D modeling has been used primarily as a rendering tool, not as the actual representation of the project.

With this innovative digitally exchange technology, architects and building designers can visually analyze dynamic building energy performance in response to changes of climate and building parameters. This software interoperability provides full data exchange bidirectional capabilities, which significantly reduces time and effort in energy simulation and data regeneration. Data mapping and exchange are key requirements for building more powerful energy simulations. An effective data model is the bidirectional nucleus of a well-designed relational database, critical in making good choices in selecting design parameters and in gaining and expanding a comprehensive understanding of existing data flows throughout the simulation process, making data systems for simulation more powerful, which has never been done before. Despite the variety of energy simulation applications in the lifecycle of building design and construction projects, there is a need for a system of data integration to allow seamless sharing and bidirectional reuse of data.

Introduction

Millions of people and thousands of companies exchange information and communicate with computer networks. Within these complex innovations and networks, most software operates within its own unique language across various computer platforms. This can make it difficult to know how to send or share information. Fortunately, all software shares a common data language, which we call database. It has now become apparent that the AEC industry is adopting Building Information Model (BIM) as the next generation of CAD, and over standard computerized drafting generally known as CAD. Already many governments are adopting BIM technology. In the USA, the General Services Administration (GSA) and other agencies are embarking on initiatives that will require the use of BIM solutions for work done on their buildings and complexes. BIM is a different and
more productive way of working for all AEC professionals, from the architect or designer, through the structural and MEP engineers to the contractor, and finally to the owner.

Building model is a complete, integrated, digital representation of a project that can be used for many purposes and revenue streams while enabling design professionals to share data, allowing collaboration between architects, engineers, consultants, contractors, developers, and owners. All of these users benefit from many different aspects of data, which include different aspects of building design, concept, aesthetic, function, safety, energy performance and sustainability.

Lack of interoperability is a major obstacle that limits the workflow usability due to difficulty in acquiring information from building geometries, coordinates, climate location, thermal zones, construction and materials properties, etc. The following are descriptions of BIM:

- development of architectural detailing routines that support styles of detailing that can be easily customized;
- development of connection theory, allowing modules ranging from a piece of mechanical equipment to a prefabricated bathroom, to be interfaced with the rest of the building;
- development of new drawing representations to be used by construction and erection crews, eliminating the difficult to read current standards for construction documents;
- new ways to assess and evaluate buildings, regarding health, flexibility, and other factors;
- new representations that integrate architectural design and the construction process, so that design teams work out how a building is to be constructed as they design it; and
- new IT technologies for making buildings more responsive, adaptable, and healthful.

Literature review

Need for Interoperability

BIM and software interoperability have become increasingly important in facilitating information sharing and data integration. It helps to offer advanced building services through the use of tools in a collaborative project. It is inevitable in the traditional design process to recreate the same building model as much as seven or eight times (with modifications for architecture, structure, mechanical, electrical, plumbing, energy analysis and simulation, construction documents, lighting, code checking, cost estimation etc.). The largest portion of the effort to prepare building performance simulation input is absorbed by the definition of building geometry; that effort to comprehend and extract the pertinent information of 2D drawings to define 3D building geometry is required for carry out simulation. Traditional means of building performance simulation must be improved to level of automation in the acquisition of building geometry. It would be most desirable if the output data of CAD drawing can be directly imported into a simulation tool and converted into ready
to use graphic interface.

It is desirable that some absent aspects in those provided by Industrial Foundation Class (IFC) and leading software companies can be contributed by this research in the forms of the interchange data and the representation of the conflicts characteristic in the design collaborative.

**Industrial Foundation Class and leading software companies**

IFC is a data model developed by the International Alliance for Interoperability (IAI) in 1995 to provide data exchange capabilities for the AECFM industry. IFC represents the parts of buildings or elements of the processes; IAI defines IFC specifications and six releases have been published. IFC specifications provide common attributes and data structure of shared objects in various domains for modeling. IFC does not provide information exchange between software applications that have special conversion algorithm and process such as an energy software program that has an HVAC system and mechanical equipment programs. Many related software companies have planned or developed their products to share data objects with IFC or are based on IFC specifications and protocol. At the present time, there is no data exchange capabilities for building industry that can achieve the complexity of open system, multi-models, and bidirectional concepts of interoperability.

**Virtual Model System (VMS) framework**

VMS framework offers the innovative data collaboration, integration and sharing capabilities between CAD and software applications such as building code check, submission and compliance, energy performance simulation and prediction. It builds on a systematic framework or platform of BIM, which by facilitating information sharing and data integration, offer advanced building services through the use of tools in a collaborative project. It improves the traditional design process that has to recreate the same building model as much as seven or eight times (architecture, structure, mechanical, electrical, plumbing, energy analysis and simulation, construction documents, lighting, code checking, cost estimation etc.). It improves means of building performance simulation to the level of automation in the acquisition of building geometry. Output data of CAD drawing can be directly imported into a simulation tool and converted into ready to use graphic interface. Its automation to manipulate a program’s object model and database enables the users to reuse and update the data through editors.

The paper is intended to prove the VMS system can integrate disciplines and project phases and improve the effectiveness and efficiency of project operations. Integration or interoperability can come best when they are the objectives of VMS implementation and management using VMS method. The followings are the unique features of VMS:

- Builds on systematic framework or platform of BIM, which facilitating information sharing and data integration, offer advanced building services through the use of tools in a collaborative project.
• Offers data collaboration, integration and sharing capabilities and allows seamless sharing and bidirectional reuse of data, provides a new way to share information and collaborate on design data between applications through files, database, and software programs.

• Enables to quickly update and refines the design model easily even more accurate, reduce design errors, cost, time, while speed up project delivery.

• Maps CAD supporting design with energy simulation model, and downstream users who are doing 3D shop or mockup fabrication.

• Advances the techniques of a craft and practice of architecture by means of full interoperability through shared information models, data exchange and reuse.

• Addresses the quality and consistency of sustainability compliance information in 3D model, native 2D drawings, construction documents, specifications, scheduling, and shop model fabrication.

• Full-automated acquisition and expansion of building geometry through the commercial available CAD object model.

• Mapping engine provides translating of the commercial available CAD model. Data extracted of a CAD model and drawing such as geometries, coordinates, building materials and properties are directly imported. Data that beyond capabilities of the CAD shared object model to provide like climate and weather data, building operating schedule, HVAC systems have to go through data manipulation by database. Model calculating and editing engine provide automating calculation task through energy modeling, analysis and simulation program.

• Interactive and interfacing application provides user-friendly graphical interface over the internet. Data Model extends the capabilities of interoperability to any CAD, energy analysis program and other available software.

**Methodology**

The paper introduces methods to define, deliver, and operate the projects by using VMS method and technique to gain competitive advantage of sustainable architecture. The automation in VMS manipulates a program’s object model and database; enables the users to reuse and update the data through editors; and translates building elements, geometries, coordinate, location, orientation, area, zone, and space. Figure 1 shows the proven model of VMS framework that has been tested, specifically its data modeling concept and method. Figure 2 shows the VMS’s Integrated Development Environment (IDE)

**Database**

Databases enable the construction of information so that when the others retrieve the project data, they will be able to view it, no matter what kind of computer or application they are using. The followings are unique features of the
database systems:

- Automate bidirectional data mapping.
- Provide standard tool and analysis throughout lifecycle workflow.
- Enhance workflow from data regeneration to interface and presentation.
- Capture resource and incorporate into standards.

**Data Provider**

A data provider in the VMS framework serves as a bridge between an application and a data source. A data provider is used to retrieve data from a data source and to reconcile changes to that data back to the data source. Data provider provides functionality for connecting to a data source, executing commands, and retrieving results. Those results can be processed directly, or placed in a dataset for further processing while in a disconnected state. Data Provider in figure 2 extracts and retrieves data from building information 3D model, and provides full data exchange bidirectional capabilities between 3D models, 2D design drawings, construction documents and specifications, and energy analysis programs.

**Data Mapping**

Data mapping mapped the graphic and non-graphic information from BIM and stored in the database. Data Mapping allowed establishing a correspondence between data in CAD and data provider.

**Data Binding**

Data Binding uses information from BIM and creates data relationships by looking at related data.

**Data Relation**

Data Relation relates all the data table components and links them together. When the energy models or any software programs look up in one dataset, they can see another project’s database and get the data they need at the same time. Figure 3 shows a data table of the object model representations. Figure 4 shows the relationships of the data tables.

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Figure 1. Proven Model of Virtual Model System Framework.

Figure 2. Virtual Model System Framework IDE.
Interoperability Between CAD and Energy Performance Simulation through Virtual Model System Framework

Experiment

The proposed data mapping and exchange model has been developed within VMS framework to translate Autodesk® Revit® Building model to thermal-based DOE-2 model for energy simulation. VMS reads and extracts coordinates, geometries, thermal zones, and construction and material properties from Autodesk® Revit® Building, and translates them to create DOE-2 input files to perform energy analysis and calculation. Storing complete building information in a computer model and integrating all of the geometric model information requires the database system to hold geometrical data. The generation or extraction of data embedded in objects aims at generating floors, space, zones, walls, interior walls, roof, windows, doors, ceilings, and lists of building construction and materials to the thermal objects (zones and surfaces). Building geometry is essential to energy simulation engine such as DOE-2. The usability of DOE-2 performance simulation can be improved to its full capacity of acquiring bidirectional information.

Once the ASCII input file is created, it is possible to call and query DOE-2 as an operating command engine from VMS. DOE-2 then calculates the heating, cooling, and lighting loads necessary to maintain thermal and daylight control set points and conditions throughout the secondary HVAC system and coil loads, as well as the energy consumption of primary plant equipment and many other simulation details that are necessary to verify that the simulation is performing as the actual building would. The energy analysis and calculation results are sending to web browser for graphical user interface.

There are many benefits to using web browser graphic interface; they enable designers and building professional to collaborate, share and improve the relationships of building parametric.
elements and systems that affect energy efficiency and sustainability of a building design on the internet. Energy performances are displayed in easily well-defined graphical forms. They can effectively communicate, link and apply information, test options, compare the scenarios, make quick decisions, and determine the most efficient solutions in minutes. As a result, environmentally friendly and sustainability alternatives can be explored and better solutions for complex energy problems can be developed.

VMS framework established the following method and process and display energy performance viewer on the web browser:

- Created the project in AutoDesk’s Revit Building.
- Extracted data
- Design database system
- Created DOE-2 energy input files.
- Executed DOE-2 simulation.
- Displayed energy performance results as graphic viewer on the web browser
- Updated data bidirectional and linked data to the server.

Data Extraction through Object Model

Data mapping engine in VMS framework provides full capability of data extraction from CAD drawings, 3D model, schedule and attributes as shown in fig 5.

Project

The project establishes the context, including geometric representation context, for information to be exchanged or shared. There is only one shared project within the exchanged context. The project name is Chicago Center for Green Technology, which has received LEED Platinum award for her green building design.

Site

The site represents an area and comprises one or more building. The site location is determined by the project site, location, climate location and weather.
data to match with energy simulation weather data. Project site data provided for DOE-2 to generate building latitude (41.8), longitude (87.8), altitude (186 feet above sea level, time zone (6), and provide necessary weather data.

**Building**

Buildings comprise a basic element within the spatial structure hierarchy and number of stories.

**Building Envelope**

Building envelopes consist of a building level, area, area schemes, space or rooms, and thermal zones.

**Building Elevation and Level**

Building level comprises an elevation and represents a horizontal aggregation of space (Rooms) that are vertically bound.

**Building Area**

Area consists of building area and area schemes.

**Area schemes**

Area schemes define as a color fill diagram depicts function by programmatic area, with real time, automatically generated area tabulations.

**Rooms or Space**

Room or Space represents an area or volume bounded by surfaces.
The geometric representation of rooms or space is given by shape and placement allowing multiple geometric representations. The space boundary information can be acquired by space boundary.

**Walls**

Walls consist of exterior walls and interior walls. Walls are defined with certain constraints for the provision of parameters and geometric representation. The geometric representation of walls is given by shape and placement allowing multiple geometric representations.

**Windows**

Windows represents opening, recess, or chess, and reflecting void. There are two types of windows, opening and recess or niche, which are defined by attribute object-type. Windows have to be inserted into a wall element, which is part of the building elements and has the element relationship. The geometric representation of windows is given by shape and placement allowing multiple geometric representations.

**Doors**

Doors are defined as the opening elements, which are inserted into a wall element and become part of the building elements and have the element relationship. The geometric representation of doors is given by shape and placement allowing multiple geometric representations.
Floors, Ceilings, Roofs

There are the components that enclose room or space vertically. They can provide for lower support (Floor), upper support in the room (Ceiling), or upper construction in the building (Roof). The geometric representation of these components is given by shape and placement allowing multiple geometric representations.

Data Mapping of BIM to DOE-2 Simulation Model

A model is a representation of computer aided design information and how information relates to other information such as energy efficiency analysis and simulation like DOE-2. A model of computer aided design information is an object model; while a model of energy efficiency analysis and simulation information is a process model. An object model represents the information and structure of an object and its underlying components, which also are objects. A process model represents the information and structure of a workflow and its underlying processes. At the present time there is no technology or invention that can map through both object model and process model. This is making VMS framework challenging in providing a form of specification that can be used to create software application.

VMS framework uses DOE2.1E as the simulation engine to create the prototype interface and prepare in the format required by DOE2.1E input data file. The fundamental requirements for performing energy efficiency analysis and simulation with DOE-2 include:

- Climate and weather data describes the design climate and location for the city where the building is situated. The weather period is normally one year.
- Building operating schedule describes building use information to allow specification of the number of people, lighting, and equipment (either electric, gas, or other fuel types) in each thermal zones.
- Building thermostatic condition control schedule describes temperature control and thermal zone condition in each zone of the building.
- Geometric representation of the thermal zones and enclosure of heat transfer surfaces for each thermal zone.
- Geometric representation of the...
thermal surfaces, which converts from building elements such as walls, windows, doors, floors, ceilings, and roofs.

- Physical construction and thermal material properties of building elements describes specification of building geometry and surface materials and constructions.
- Building use information to allow specification of the lighting, equipment (electric, gas, or other fuel), and people in the building.
- HVAC system information to allow specification and scheduling of the system.
- Plant system information to allow specification and scheduling of the system.
- Economics of energy saving system information to allow specification and scheduling of the system.
- Thermal design parameters for specifying the intended simulation settings.

**Data mapping of Thermal Zones**

Thermal zone defines a thermal instead of architectural space, which is the basic information of simulation. The geometric representations of thermal zones may or may not be identical to architectural space in the CAD drawing. For each thermal zone, information regarding enclosure of heat transfer surfaces need to be obtained. A thermal zone requires parametric information of zone north axis, origin, type, ceiling height, zone volume, and convection algorithm.

**Data mapping of thermal surfaces**

Thermal surfaces refer to heat transfer surfaces to describe the thermal representations of building elements, such as walls, roof, windows, doors, ceiling, and floor. Each surface has some attributes to determine its interaction between internal and external environment. A surface may interact with another surface to represent inter zone heat transfer. Thermal surfaces are the basic ingredients of the thermal simulation.
Data mapping of building location and climate

The database server in VMS framework provides mapping for building location (Figure 18), climate (Figure 19), and weekly temperature (Figure 20).

One of the great capabilities of database in VMS framework is directly acquire building element construction and materials properties from Revit Building and export directly to DOE-2 INPUT files for energy simulation. Figure 21 show data mapping for wall construction and materials. Figure 22 show data mapping for window construction and materials.
Data mapping of coordinates and geometries

The database server in VMS framework provides 3D modeling engine for mapping of geometric, coordinate system and topological thermal object representation. Normally CAD information model performs calculation of 3D geometries, coordinates and topological model, which captured by mapping engine during exporting process. Figure 23 shows the mapping of floor plan coordinates and geometries captured from exporting Autodesk Revit Building.

Data mapping of artificial lighting

The database server in VMS framework provides mapping of artificial lighting, object representation of lighting types, quantities, power generated, and location of each room or architectural space in the building.

Relevant results

Thermal design software interface

Thermal design software interface is one of energy module interface that simulates the exchanges of heat through the outer skin of the building, and shows yearly estimates for the required heating and cooling energy, heat gain and heat loss through building components. The software provides the building energy performance and amount of energy electricity consumption (Kwh) and gas (Therm). Energy consumption is broken
down into lighting, equipment, space heating, space cooling, pump, and fans.

**Daylight factor software interface**

Day-lighting predicts the distribution of sunlight in the room, according to time of day and location, and calculates a yearlong average of the amount of daylight projected onto work surfaces in the room. Day lighting then offers an estimate of the amount of electrical lighting energy required to make up for the lack of natural daylight in certain areas of the room.

Since the software retains weather data for every hour of the year, in each of the cities where a user may situate his building, the modules are run on an hourly basis. Daylight factor result is plotted for each combination of window and reference point in a daylight space. The software interface provides daylight information for space, window, and reference point.

Daylight factor is calculated by preprocessor for 20 values of solar altitude and azimuth covering the annual range of sun position at the location being analyzed. The software projected the results on a space working plane between the elevation and floor plan. The window’s size, shape, and position are reflected from the CAD drawings and be able to updated both at the source or the interface program through editor.

**Scenarios: Options for Energy Efficiency Decisions**

VMS system can be used as a tool to provide the fast way and high accuracy to explore energy performance of building designs in real time, throughout the
building life cycle. This tool allows the design collaboration team to simulate, compare, and eventually making decisions. Real time calculations provide reliable results within minutes’ time. There are five scenarios that are set up for Chicago Center for Green Technology, 445 N. Sacramento, Chicago, Illinois, U.S.A., in order to compare the energy design decisions and perform simulation. The simulation results to be studied in this paper are electricity consumption for each category in this building.

**Scenario 1: Building Base line**

The case study modeled as a building baseline helps to ensure that the building meet a minimum standard of energy efficiency. The following are the basic descriptions of the base line properties:

- Indoor ventilation used purely mechanical system. The building has well-mixed indoor air flow and air infiltration.
- Walls materials have R-11 insulation.
- Windows used single glazed clear glass without blind.
- Windows area is approximately 60% of the room wall area that windows take up.
- Occupancy loads = 143 people/sq.ft.
- Lighting requirements = 1.3 watts/sq.ft.
- Equipment loads = 0.7 watts/sq.ft
- HVAC system and equipments were typical fan coil units to cool the zones and space.

**Results:**
The following are the energy consumed in kilowatts-hours for the whole year of 2006:

- Space Lighting = 133,109 kwh
- Equipment = 48,393 kwh
- Space Heating = 5,929 kwh
- Space Cooling = 44,095 kwh
- Fan Energy = 125,021 kwh
- Pump Energy = 49,060 kwh

![Figure 31. Scenario 1: Electric Energy Consumption for Each Category.](image)

**Scenario 2: Use of the Ground Loop Heat Pump**

This scenario substituted the use of typical fan coil units with the ground loop heat pump.

**Results:**
Fan and pump energy consumptions were reduced drastically with the same level of comfort. The reason that the space heating energy was higher is due to the fact that typical fan coil units consumed both electricity and gas energy, but ground loop heat pump consumed only electricity energy.

- Space Lighting = 133,109 kwh
- Equipment = 48,393 kwh
- Space Heating = 19,032 kwh
- Space Cooling = 44,021 kwh
- Fan Energy = 36,234 kwh
- Pump Energy = 29,754 kwh
Scenario 3: Use of Efficient Glass Types

This scenario replaced the single clear glass with low-E, double glazed glass types.

Results:
Space heating and lighting energy were reduced due to replacing low-E glass types.

- Space Lighting = 100,823 kwh
- Equipment = 48,393 kwh
- Space Heating = 13,156 kwh
- Space Cooling = 45,945 kwh
- Fan Energy = 35,575 kwh
- Pump Energy = 29,252 kwh

Scenario 4: Use of Natural Daylight and Efficient Glass Types

With the idea that day lighting can help not only in energy efficiency, but also the human comfort and space quality, this scenario brought in natural daylight and run the simulation to compare.

Results:
Daylight substituted the electricity lights in the building and reduced the energy consumptions

- Space Lighting = 84,982 kwh
- Equipment = 48,393 kwh
- Space Heating = 14,270 kwh
- Space Cooling = 44,574 kwh
- Fan Energy = 35,224 kwh
- Pump Energy = 28,913 kwh

Scenario 5: Use of Shading (Overhangs at the South facing façade, install window blinds)

This scenario installed the blinds for all South and West facing windows and overhangs on the South facing façade in order to study the effects of these shading devices, while preserve the human comfort from glare effect.

Results:
Space cooling and heating energy consumptions were slightly reduced.

- Space Lighting = 84,982 kwh
- Equipment = 48,393 kwh
- Space Heating = 13,645 kwh
- Space Cooling = 36,141 kwh
- Fan Energy = 35,224 kwh
- Pump Energy = 28,913 kwh

This paper aims to create an innovative tool and system between CAD information models, like Autodesk Revit Building, and thermal simulation model, like DOE-2.1E. Data modeling specifications for building geometry, thermal zone, construction and material properties, and thermal design parameters, were discussed. A data mapping engine in a VMS framework server has been developed to accomplish the task of fully converting CAD information models to energy performance models on the web with capabilities that never have been done before. The work flow and the implementation of model mapping were presented, and the process of data mapping was demonstrated with an illustrative example.

The research and development work can be further expanded to address the implementation issues of building and energy code checking and LEED certification building.

**Conclusions**

VMS framework is an enabling novel concept and unique AEC collaboration technology allowing full interoperability through shared information models and data modeling. The need for data interoperability and technological challenge to fully and bidirectional data sharing, updating, and reusing were reviewed. The innovative specifications and ability to link and share object-based models in CAD with performance-based model in energy simulation were introduced. The benefits of adopting VMS framework are the significant reduced time and effort spent in creating energy efficient building and sustainable design. A data model can be expanded to any other CAD application and energy simulation software.
Open BIM CAD Update

Plotted Graphs

Simulation

Mapping Building Model

Create Energy Input Files

Figure 36. Workflow in the Virtual Model System Framework.
References


