

DEVELOPMENT OF ENERGY SIMULATION USING BIM (BUILDING INFORMATION MODELING)

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ABSTRACT: This paper recognized a need in the architecture, engineering, and construction industry for new programs and methods of producing reliable energy simulations using BIM (Building Information Modeling) technology. Current methods and programs for running energy simulations are not very timely, difficult to understand, and lack high interoperability between the BIM software and energy simulation software. It is necessary to improve on these drawbacks as design decision are often made without the aid of energy modeling leading to the design and construction of non-optimized buildings with respect to energy efficiency. The goal of this research project is to develop a new methodology to produce energy estimates from a BIM model in a more timely fashion and to improve interoperability between the simulation engine and BIM software. In the proposed methodology, the extracted information from a BIM model is compiled into an INP file and run in a popular energy simulation program, DOE-2, on an hourly basis for a desired time period. Case study showed that the application of this methodology could be used to expediently provide energy simulations while at the same time reproducing the BIM in a more readably three dimensional modeling program. With the aid of an easy to run and easily understood energy simulation methodology, designers will be able to make more energy conscious decisions during the design phase and as changes in design requirements arise.

Keywords: Building Information Modeling; Energy Simulation; ifcXML; Interoperability, DOE-2, INP file

1. INTRODUCTION

While BIM technology allows designers to run energy simulations [1], there are limits on its usefulness in the current state of energy simulation programs. Academics have pointed out that there is a need for improved interoperability between energy simulation and building information modeling programs [2]. Construction practitioners have also identified that one of their greatest interests in the field of BIM is improving the interoperability between BIM and energy simulation programs [3]. The time required to read and reconstruct the geometry of a BIM file in an energy analysis program can amount up to 50% of the time required to run the energy simulation and because of this poor interoperability the usage of energy analysis during design is restricted [4]. Due to intense labor requirements in the energy modeling process design decisions are often made without the consultation of energy modeling [5].

The goal of this research project is to develop a new methodology to produce energy estimates from a BIM in a more timely fashion and to improve interoperability between the simulation engine and BIM software. In the case study applied in this paper a BIM is created using modern commercial building design software. Next the ifcXML file is read in a more commonly used modeling program that allows us to use the ruby programming language to extract the relevant from by the ifcXML. The geometric information regarding the building envelope is gathered and then used to recreate the BIM in this new interface. From there the extracted information

in conjunction with user entered data is compiled into an INP file and run in a popular energy simulation program, DOE-2, on an hourly basis for a desired time period. This then produces estimated energy requirement reports for the proposed structure based on the inputted conditions, duration, and location. The simulation results are then compared over various locations to the results from commercial energy simulation programs given the same conditions.

2. LITERATURE REVIEW

The Architecture/ Engineering/ and Construction industry is experiencing great change because of BIM and its increasing popularity (Eastman et al. 2008; Sacks et al. 2004). Many different energy modeling techniques have been applied to numerous studies in attempts to predict future energy usage over the years including: artificial neural networks, statistical analysis of building consumption data, decision trees, and computer simulations programs (DOE-2, eQuest, and EnergyPlus) [6], [7], [8], [9], [10]. Previous work has shown that using computer simulations takes a considerable amount of time to properly input data correctly, even for qualified practitioners [11], [12]. At the same time, DOE-2 specifically was applied in the study of predicting energy consumption in the building sectors of major U.S. cities to determine energy consumption profiles, but is very timely due to intensive labor requirements [9].

In hopes to alleviate some of the time requirements in this process several groups have begun creating new

methodologies for energy modeling using EnergyPlus [11].

3. RESEARCH METHODOLOGY

In process 1.1 (Figure 1) a model is first created using the Graphisoft three dimensional modeling program ArchiCAD 14.

The model is created with only the most basic of features: foundation, walls, windows, door(s), and a roof.

While this might not seem like very much information it is all that is required for running energy simulations. Interior walls and cosmetic designing is not required unless it is desired to have multiple heating ventilation and air conditioning (HVAC) zones for separate parts of the structure. This is because heat loss and gain through the interior walls are zero-sum products when considered in one zone. Once these basic parameters have been set and the geometry of the structure has been finalized the model is exported as an IFCXML file, process 2.1 (Figure 1). Process 1.2 (Figure 1) will be discussed later in the section on writing the INP file.

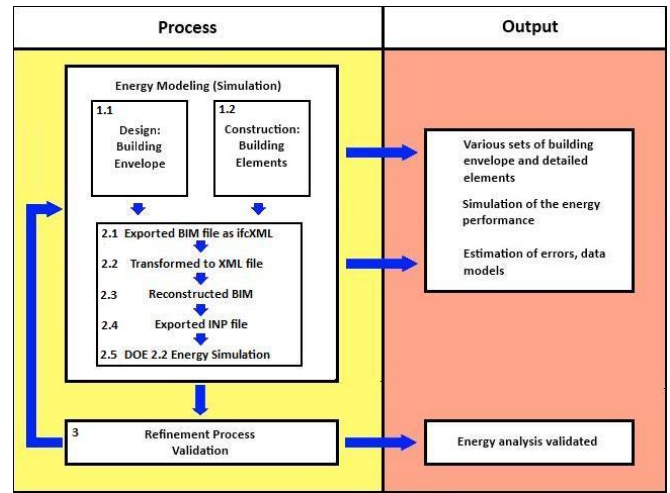


Figure 1 – Energy Simulation Methodology Flowchart

Before moving on to process 2.2 (Figure 1) it is necessary to better understand IFCXML files. The IFCXML file type was created by buildSMART (formerly the International Alliance for Interoperability). The goal of the file type is to, “promote open and interoperable IT standards to support the process change within the construction and facility management industries” [buildSMART 2008].

To better understand the information in IFCXML files, a complete view of how the IFCXML file is displayed in Excel in Figure 2.

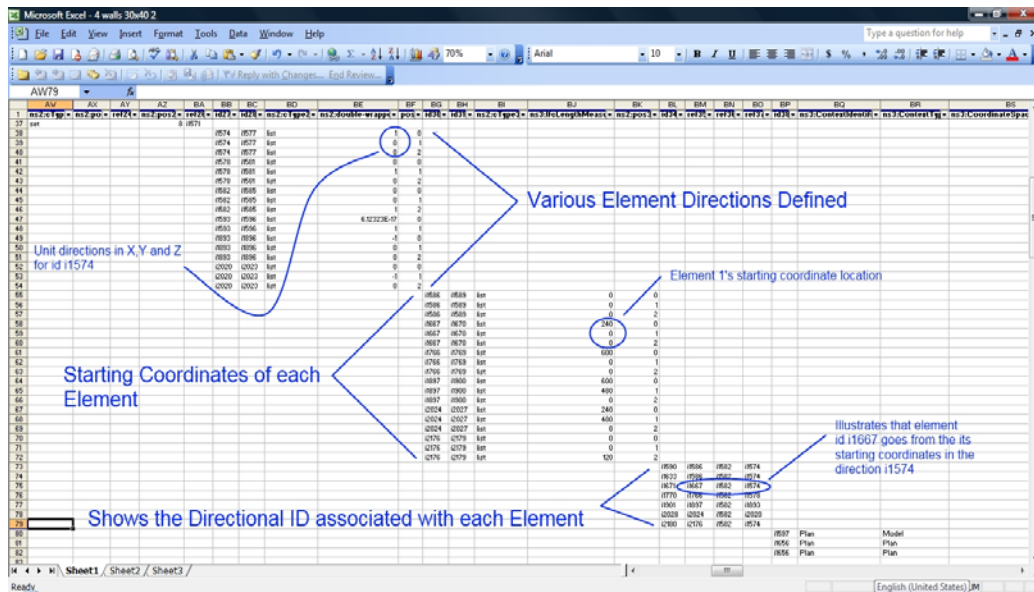


Figure 2 – Enhanced View of Box 1 of the IFCXML File in Excel with Descriptions

In Figure 2, we can see how the first section of important information is stored. There are three very important pieces of information in this section: directional element id definitions, starting coordinates of the various elements, and the direction each element is created in from its starting location. The directions are defined per unit of length in a three dimensional plane. The id i1574 that defined as (1, 0, 0) is one that moves from its starting location 1 unit in the x plane, 0 units in the y plane, and 0

units in the z plane. Lastly the direction of the element i1667 is defined. It can be seen in the figure that element 1, identified as i1667, moves from its starting coordinates with direction i1574. From above it can be seen that i1574 translates into (1, 0, 0) so this means that it moves to the right along the x plane. So using this information it is known that element 1 begins at location (240, 0, 0) and moves directly right its length. Every element created in the BIM is described in this manner.

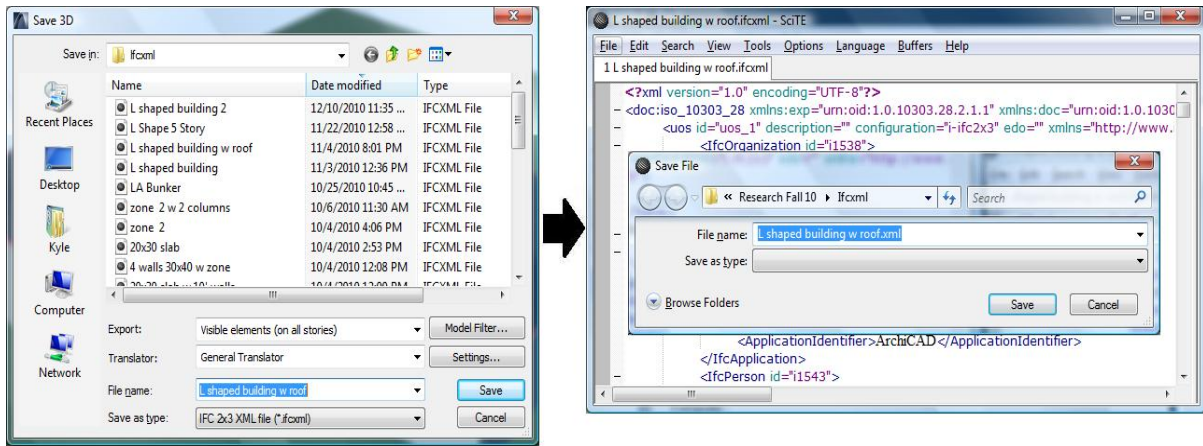


Figure 3 – Transforming the IFCXML File into a XML File

Process 2.2 (Figure 1) has the shortest duration of all, this is where the exported IFCXML file is resaved as an XML file manually. This is done as it is required to make the information in the file readable and able to be extracted later in the process (Figure 3), and can be done simply using most document editing software. SciTE was used to rename the file in this paper. Nothing changes about the file other than the name from filename.ifcxml to filename.xml.

Once the file has been transformed into an XML file it is now able to be read and reconstructed in a more readily available three dimension modeling program, process 2.3. Google SketchUp was chosen for this purpose because it allows the user to program customized applications in the program using the ruby programming language in their ruby console.

IFCXML files even for very simple BIM produce very long and complex files. The model used in this

paper consisted of only six walls, a door, a roof, and a slab, yet the IFCXML file was almost 8,000 lines of code.

Figure 4 below, is a very small excerpt from the IFCXML file created by the BIM used in this paper. This excerpt is describing the length in inches of the northern wall, or the second wall, based on order of construction in the BIM, as it is described in the file. To extract the information regarding the length of the wall we have to write the following ruby code:

```
target[IfcShapeRepresentation][‘i1803’][‘Items’][‘i1808’][IfcPolyline][‘i1799’][Points][‘i1802’][IfcCartesianPoint][1][‘Coordinates’][‘i1798’][IfcLengthMeasure][0]
```

The information is referenced by indexes essentially. The first thing that is called out is to find the first level of the index, IfcShapeRepresentation.

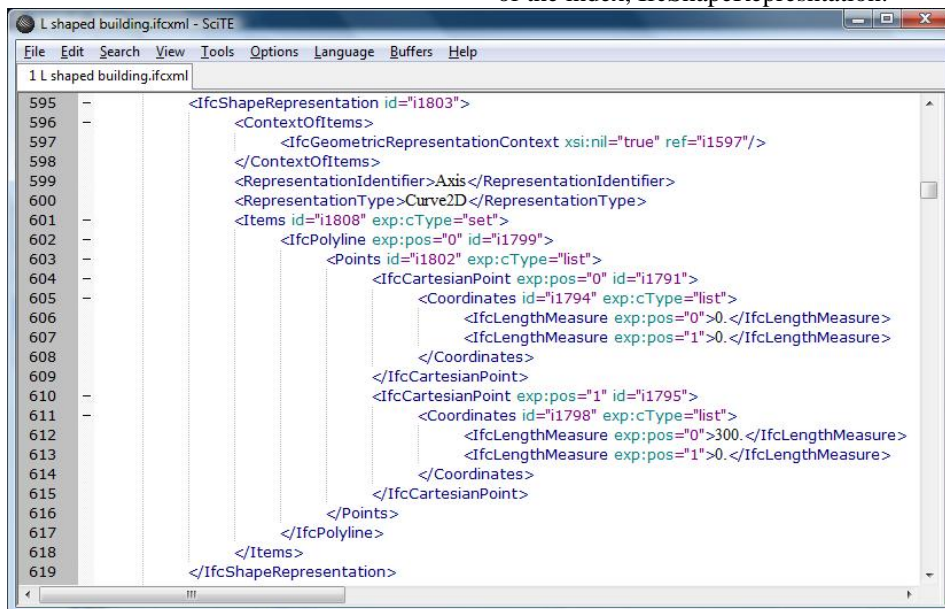


Figure 4 – Indexed wall length information about BIM in IFCXML file

Since there are multiple IfcShapeRepresentation throughout the file it is necessary to specify exactly which one we want, in this case we want the one with id = i1803. This is the second item in our code. The next level of the index on our way to grabbing the length dimension is Items. Even though it is obvious that in this particular subcategory there is only one

Items index, it is still necessary to call it out with the appropriate id, i1808. This works in exactly the same manner for IfcPolyline and Points. Once we reach IfcCartesianPoint the procedure slightly changes as there are multiple IfcCartesianPoint in this index location.

This procedure must then be replicated for every single piece of information that is needed to reconstruct the BIM, which includes: depth of each wall, length measurement of each wall, thickness of each wall, the starting coordinate for each wall, the direction of each wall. This is also done for the roof, location of the doors and windows, and the slab.

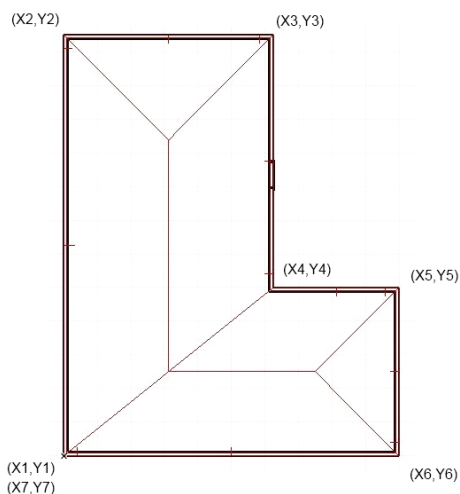


Figure 5 – BIM Coordinate System for Use in the Total Station Method Area Calculation

After all of the pertinent information about the structure has been extracted from the IFCXML file the internal area of the structure must be calculated for use in energy estimations in process 2.5 (Figure 1). This can be done in a variety of manners. If the shape of

the structure is known, such as a basic rectangular structure, simple geometric formulas can be applied, taking into consideration the wall lengths and thicknesses. With unknown shapes alternative methods need to be applied. The total station method was selected for use in calculating the area of the BIM in this paper. Using the formula:

$$A = \frac{1}{2} [X_1(Y_2 - Y_n) + X_2(Y_3 - Y_1) + X_3(Y_4 - Y_2) + \dots + X_n(Y_1 - Y_{n-1})]$$

With the extracted starting coordinate location, directional coordinate, and length of each wall, using this method we are able to correctly identify the values of the coordinates of the structure (Figure 5) and apply this method. Applying this formula to the coordinate system from the IFCXML file the area can be determined, and the volume can be determined applying the area to the depth of the walls. This approach does have limitations as it needs to be applied multiple times for more complex structures with interior elements such as columns, but the programming code could be adjusted to account for such instances.

Each IFCXML file is written in the same fashion when examined using a word editing program. In the first section the direction definitions are defined. The wall information is then stored in the order it was modeled in the BIM program. Two dimensional coordinates are listed for the starting and ending point of the wall, this is then followed in the next section by its thickness, and lastly its depth is listed. This then repeats for each wall item, then roof, then slab item.

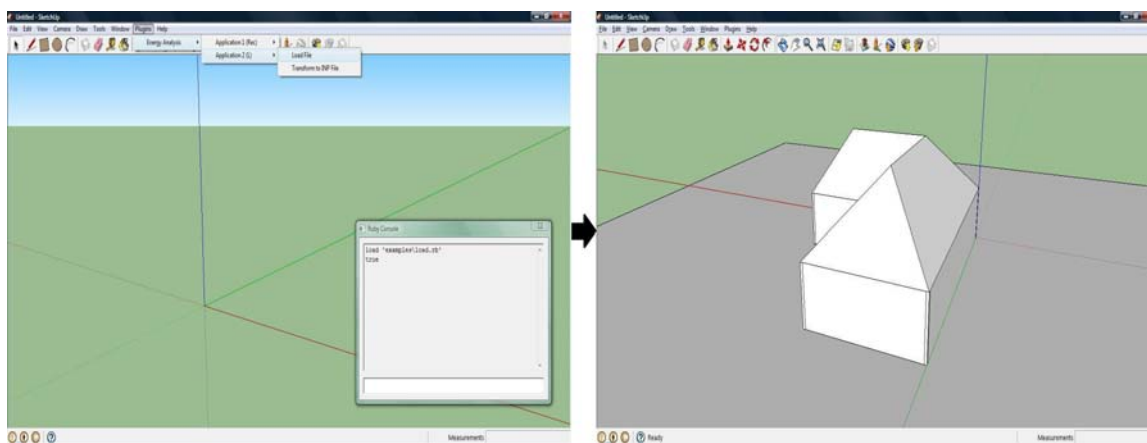


Figure 6 – Loading XML File in SketchUp Using the Ruby Console Interface

Now understanding how the information is gathered and area and volume are calculated the XML file can be loaded and read in SketchUp using the program written using the ruby programming language (Figure 6). The structure's area and volume are calculated using the total station method as mentioned above, while the structure is being reproduced in SketchUp. The program also prepares the INP file to be written by replacing variables in the code with the information from the XML file the beginning of process 2.4.

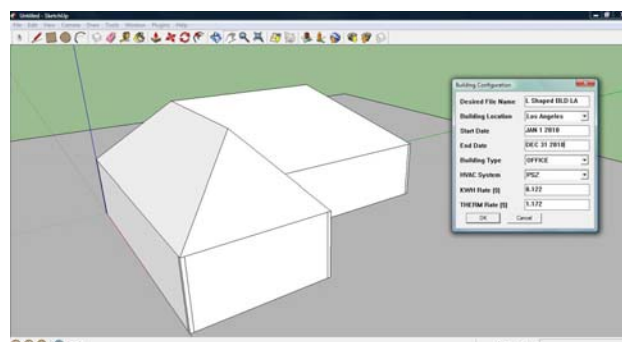


Figure 7 – User Input Interface for Exporting INP file in SketchUp

Figure 7 shows the user input interface for exporting INP file in SketchUp.

After the model has been recreated and the area and volume have been calculated, it is then almost ready to be transformed into an INP file and run in DOE-2.2. Then, the user must input at a minimum: desired run period (maximum of one calendar year), building occupancy type (i.e. office, warehouse, parking garage,

etcetera.), building location, proposed HVAC system, and applicable utility rates.

The heating and cooling points where either the heating or air conditioning engage have been set at below 70 degrees for heating and above 78 degrees for cooling, during occupancy. During non-working hours the systems have had the target points set so they essentially never run. With the combination of the user inputted information, the default information, and the geometric information extracted from the model an INP file is automatically written and saved.

Loads	Circulation Loops	Zones
TITLE RUN PERIOD DESIGN-DAY (for advanced users) SITE-PARAMETERS BUILD-PARAMETERS BUILDING-SHADES (for advanced users) MATERIALS, LAYERS and CONSTRUCTIONS GLASS-TYPES SCHEduLES (people, lighting, fans, temperatures, etc.) FLOOR (specifies different floor heights and geometries) SPACES Lighting, people, equipment, infiltration data EXTERIOR-WALLS WINDOWS INTERIOR-WALLS UNDERGROUND-WALLS	COOLING-WATER-1 = CIRCULATION-LOOP TYPE = CHW LOOP-PUMP = CHW-PUMP-1 .. TOWER-WATER-1 = CIRCULATION-LOOP TYPE = CW LOOP-PUMP = CW-PUMP-1 .. HOT-WATER-1 = CIRCULATION-LOOP TYPE = HW LOOP-PUMP = HW-PUMP-1 ..	ZONE-1 = ZONE DESIGN-HEAT-T = 72 DESIGN-COOL-T = 74 HEAT-TEMP-SCH = HT-SCH-1 COOL-TEMP-SCH = CT-SCH-1 OA-FLOW/PER = 15 SPACE = (Loads space U-name) ZONE-2 = ZONE LIKE ZONE-1 etc..
Meters	Plant Equipment	Additional Systems and Zones
ELEC-METER, FUEL-METER, etc	CHILLER-1 = CHILLER TYPE = ELEC-HERM-CENT CONDENSER-TYPE = WATER-COOLED CHW-LOOP = COOLING-WATER-1 CW-LOOP = TOWER-WATER-1 TOWER-1 = HEAT-REJECTION TYPE = COOLING-TWR CW-LOOP = TOWER-WATER-1 BOILER-1 = BOILER TYPE = HW-BOILER HW-LOOP = HOT-WATER-1 ..	SYS-2 = SYSTEM etc. ZONE-3 = ZONE
Pumps	Air Systems	Economics
CHW-PUMP-1 = PUMP \$CHW pump CAP-CTRL = VAR-SPEED-PUMP TWR-PUMP-1 = PUMP \$CW pump CAP-CTRL = ONE-SPEED-PUMP HW-PUMP-1 = PUMP \$HW pump CAP-CTRL = ONE-SPEED-PUMP ..	SYS1 = SYSTEM TYPE = SZRH CHW-LOOP = COOLING WTR-1 HEAT-SOURCE = HOT-WATER HW-LOOP = HEATING-WTR-1 MAX-SUPPLY-T = 105 MIN-SUPPLY-T = 55 TEMP = TEMP ECONO-LIMIT-T = 70 FAN-SCHEDULE = FAN-SCH-1 CONTROL-ZONE = ZONE-1 ..	BLOCK-CHARGES SCHEDULES UTILITY-RATES
		Reports
		LOADS-REPORT SYSTEMS-REPORT PLANT-REPORT ECONOMICS-REPORT END .. COMPUTE .. STOP ..

Figure 8 – Format of a Basic INP File (Hirsch 2004)

Before exploring how the DOE2 engine works it is important to understand the requirements of INP files. INP files are broken down into the following categories (Figure 8): loads, meters, pumps, circulation loops, plant equipment, air systems, zones, economics and reports. The loads category requires much of the basic information about the structure. This is where the duration of the simulation, site location in coordinates, material types and layer constructions are written.

A default unit is selected (PSZ system), temperature supply levels are set, occupancy type, and the heat sources are defined. The last step regarding the HVAC systems is defining the zone. The zone is

where the temperatures required to trigger the heating and air conditioning to turn on and off are entered. Once entered, the majority of the INP file has been written and all that remains is completing the economics and reports section. The only data needed for the economic section are the current utility rates for gas and electricity which the user entered earlier. Lastly the reports section is generally standard and concludes the file with default methods of reporting the information computed (Hirsch 2004). The INP file is now ready to be run in the DOE-2 simulator and estimate the proposed structure's utility bill.

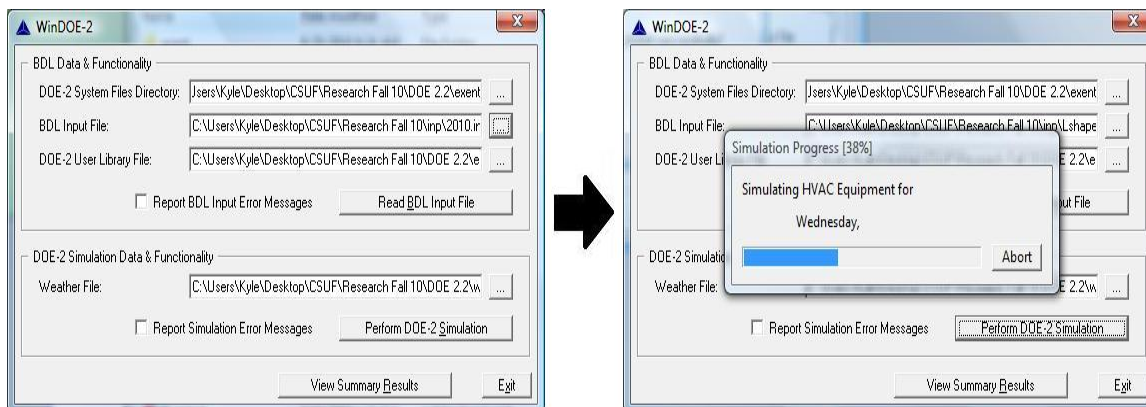


Figure 9 – DOE-2.2 Program Interface and Simulation of INP File

Now it is finally possible to calculate the structure's fuel and electrical demands. The economic analysis subprogram can now compute the expected energy costs applying the user inputted utility rates. The loads, HVAC, and economic subprograms are run on an hourly

basis for the defined duration (Figure 9) and produce the estimated utility bill of the proposed structure for the given time period with detailed analysis of the estimated energy consumption (Hirsch 2004).

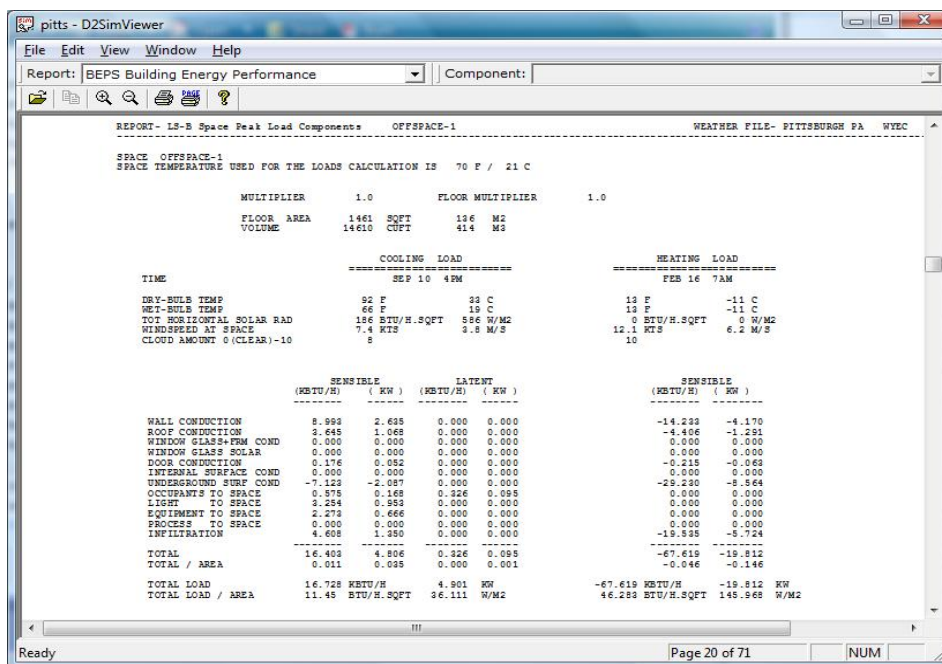


Figure 10 – DOE-2.2 SIM File Showing Peak Loading Conditions

DOE-2.2 produces a comprehensive breakdown of all of the energy costs for the corresponding energy simulations. A SIM file, energy simulation report, is created after each simulation (Figure 10). This report allows the user to read the explicit details of the simulation and verify that the proper conditions were tested. The file begins by stating the zone types of the building, location in coordinates, noting if there were any conflicts between the weather data and set location, and the area and volume of the structure which was run.

4. CASE STUDY

In this case study the proposed methodology was applied to a relatively simple one story L-shaped BIM with a net area of 1,461 interior square feet. The structure was designed with only basic features required for running energy simulations: exterior walls, flooring, roofing, and a door. The BIM transferred with little

effort into the SketchUp using the previously written Ruby code and was geometrically recreated. The BIM was exported as an INP for four separate tests in four separate cities, Los Angeles, Las Vegas, Chicago, and Pittsburgh with the following parameters for the ensuing energy simulation: the location of the building, one year duration for the simulation, office building scheduling and occupancy configuration, a packaged single zone heating ventilation and air conditioning system. All of the INP files were able to be read without error by DOE-2.2. The utility rates for each city varied slightly. For Los Angeles and Las Vegas \$0.122 per kilowatt hour and \$1.172 per THERM were used. In Chicago each kilowatt hour cost \$0.085 and each THERM cost \$1.172. In Pittsburgh each kilowatt hour of electricity cost \$0.096 and each THERM cost \$1.412. These utility rates were selected for uniformity with other simulation programs as they are the rates currently being used for the selected regions.

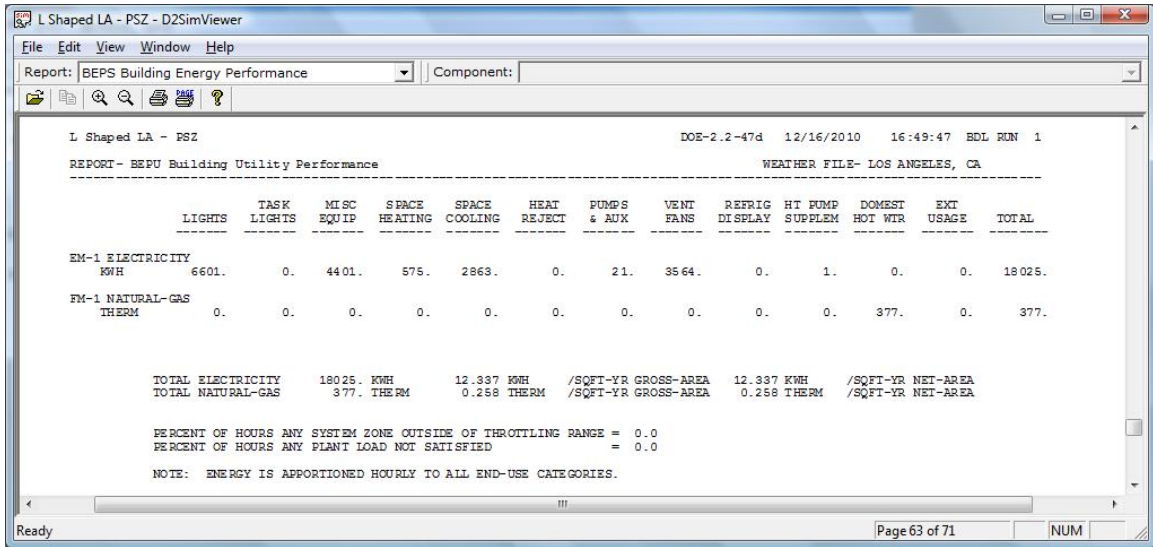


Figure 11 – Los Angeles Energy Simulation Consumption Breakdown

Inputting the INP file into the DOE-2.2 energy simulation program we were able to produce reasonable simulations. In Los Angeles the estimated kilowatt hours for the electrical components of the BIM was 18,025 and the estimated natural gas amounted to 377 THERM (Figure 11). On a per square foot basis this

amounted to an estimated 67.9 kilo BTU per square foot per year. Lastly, applying the aforementioned utility rates the structures annual estimated energy expenditure would be \$2,641 (Figure 16).

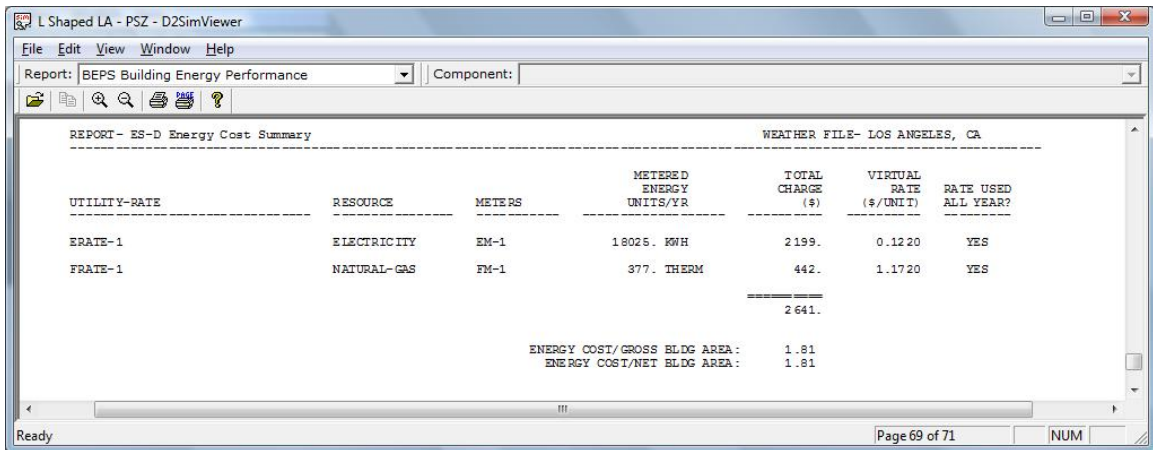


Figure 12 – Los Angeles Energy Simulation Expense Sheet

Chicago as could be expected due to the colder climate, produced energy estimates with a higher energy requirement. The estimated kilowatt hours and THERM were 24,307 and 259 respectively. When transformed into MBTU the electrical usage estimate became 82.9 and 25.9 for gas. Unlike Los Angeles in Chicago the largest electrical consumer was the heat pump supply closely followed by the space heating,

with the lighting power requirements being roughly 40% of each of those (Figure 12). This accounts for the larger ratio of electrical usage compared to the natural gas requirements. Applying Chicago's utility rates to these figures, the estimate for the annual energy expense here amounted to \$2,370.

Meter	Task	Misc	Space	Space	Heat	Pumps	Vent	Refrig	Ht Pmp	Domest	Ext	Total
Lights	Lights	Equip	Heating	Cooling	Reject	& Aux	Fans	Display	Suppl	Hot Wtr	Usage	
Total Site Energy: 108.83 MBTU 74.5 KBTU/SqFt-Yr Gross Area 74.5 KBTU/SqFt-Yr Net Area Total Source Energy: 274.75 MBTU 188.1 KBTU/SqFt-Yr Gross Area 188.1 KBTU/SqFt-Yr Net Area Percent of Hours Any System/Zone Outside of Throttling Range: 0.0 Percent of Hours Any Plant Load Not Satisfied: 0.0												
Electric Meters (kWh):												
EM-1												
3287	0	2191	8030	0	0	141	2177	0	8481	0	0	24307
3287	0	2191	8030	0	0	141	2177	0	8481	0	0	24307
Fuel Meters (Therms?):												
FM-1												
0	0	0	0	0	0	0	0	0	0	259	0	259
0	0	0	0	0	0	0	0	0	0	259	0	259

Figure 13 – DOE-2.2 Simulation Summary Results for Chicago, IL

Figure 13 shows the DOE 2-2 simulation summary results for Chicago. Of the four cities Las Vegas provided the estimate with the lowest energy requirements. The electrical and gas estimates were 21,830 kilowatt hours and 202 THERM. Converting these figures to MTBU they become 74.5 and 20.2 respectively. As could be expected being in the desert the one of the largest electrical consumers was the

space cooling requirements. This estimate could greatly change depending on the cooling set point, so if we were to lower the cooling set point for Las Vegas the electrical requirements could increase dramatically. Applying the rates to the estimated consumption Las Vegas tallied and estimated annual energy bill of \$2,900. The last city that the building was tested in was Pittsburgh. Much like Chicago, Pittsburgh was estimated to have relatively higher energy requirements.

General Information		Location Information	
Project Title: I shaped bld		Building: El Segundo, CA 90245	
Run Title: Revit L shaped 1 story bld.xml		Electric Cost: \$0.12 / kWh	
Building Type: Office		Fuel Cost: \$1.17 / Therm	
Floor Area: 1,461 ft²		Weather: Los Angeles, CA (TMY2)	
Estimated Energy & Cost Summary		Carbon Neutral Potential ¹ (CO ₂ Emissions)	
Annual Energy Cost	\$2,587	Base Run:	9.8 tons
Lifecycle* Cost	\$35,234	Onsite Renewable Potential:	-11.0 tons
Annual CO ₂ Emissions		Natural Ventilation Potential:	-2.3 tons
		Onsite Fuel Offset/Biofuel Use:	-1.1 tons
		Net CO₂ Emissions:	-4.7 tons
		Large SUV Equivalent:	-0.4 Large SUV's
Annual Energy		1. Carbon neutrality is defined here as eliminating or offsetting fossil based electricity and fuel use. For example, if the electricity grid is 60% fossil fuel and 40% hydroelectric, reducing grid electricity use by 60% and eliminating/offsetting on-site fuel use will make the project carbon neutral. Use any combination of efficiency, natural ventilation, renewable energy, carbon credits and biofuels to reach this goal. Renewable potential is the sum of photovoltaic and wind potential shown below.	
		Electric Power Plant Sources ²	
		Fossil:	61%
		Nuclear:	14%
		Hydroelectric:	15%
		Renewable:	10%
		Other:	0%

Figure 14 – GBS Simulation Report for Los Angeles, CA

5. VALIDATION

For validation of the results of our case study the results were then compared with a current commercial energy modeling program, process 3 (Figure 1). One popular commercial product for running energy simulations of BIM is Green Building Studio, GBS (Figure 14). GBS is an affiliate program of Autodesk Revit and runs simulations using their custom file type gbXML. The gbXML files are similar to the IFCXML and XML files in nature but are not interchangeable, so for comparison a replication of the model used in the case study had to be recreated using Autodesk Revit. Every detail from the original

BIM from ArchiCAD was recreated exactly the same in Revit, from building orientation to the slope of the roof. Once that model had been created, it was then exported from Revit as a gbXML file and uploaded into the GBS online program where the simulation is carried out. This is done using the GBS client interface.

The results produced in GBS were comparable to those produced using the methodology proposed in this paper. For Chicago GBS estimated an annual energy consumption of 124.4 MBTU compared to 108.8 MBTU produced in our estimate, a 12.5% difference. The cost estimate cost was \$2,293 compared to \$2,369, only a 3.23% difference. Los Angeles provided the largest difference in energy estimates at 14.32%. GBS

estimated 85 MBTU compared to 99.2 MBTU; however, produced the lowest cost difference at 2.04%

because of different natural gas and electrical proportions (Figure 15).

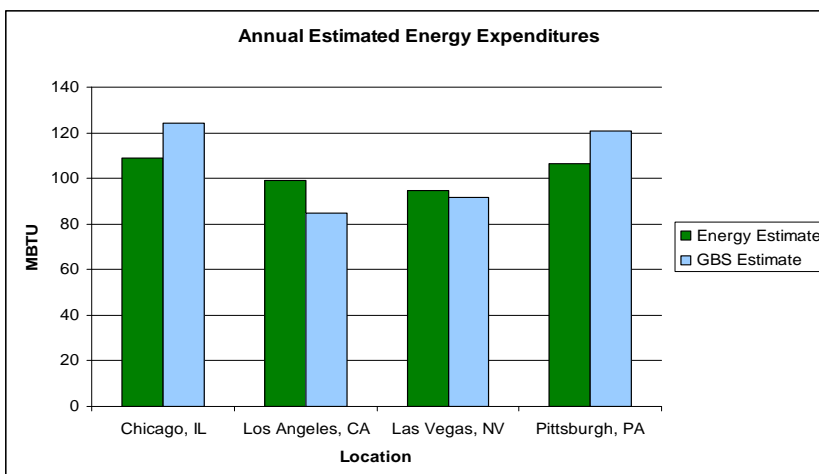


Figure 15 – Energy Usage Estimations Compared with GBS by Location

The estimates varied by \$54 with GBS at \$2,587. Las Vegas provided the closest energy estimate at only a 3.34% difference and only a 1 THERM difference on the natural gas requirements. Las Vegas was estimated to have an annual energy expense of \$2,785 by GBS a 3.94% difference. Lastly Pittsburgh had the lowest disparity in price with a 1.78% difference between the two estimation methods, and an 11.83% energy consumption difference. The similarity in estimation can be seen in Figure 16.

Across the four tests the differences in estimated expense and energy consumption are very comparable considering the multitude of possible variables affecting

each estimate. Without knowing the exact conditions used for the simulations run in GBS, i.e. the heating and cooling set points, the estimations can only be so closely grouped to those from GBS, as slightly different conditions were considered. A few degree differences in heating and cooling set points could mean hundreds or possibly even thousands of dollars difference in estimated energy costs. In total the average difference in energy estimates between the proposed methodology in this paper and GBS was 10.50%. The estimated annual expense difference between the two methodologies amounted to an average of only 2.76%.

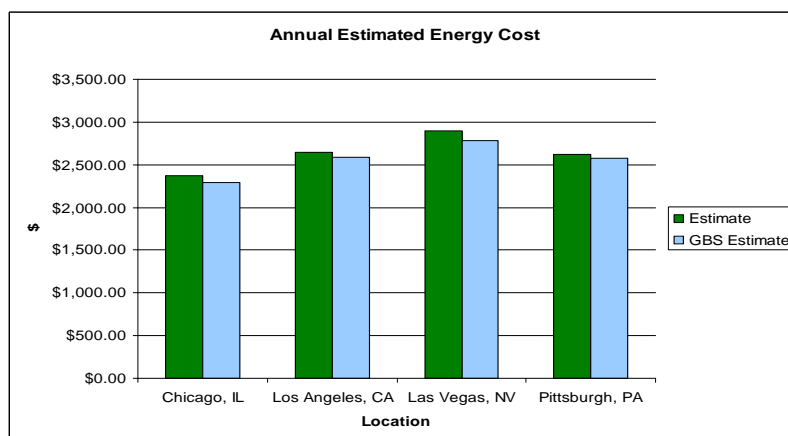


Figure 16 – Energy Cost Estimations Compared to GBS by Location

6. CONCLUSION

There is a great need in the architecture, engineering, and construction industry for new programs and methods of producing reliable energy simulations from BIM in an easily understood and prompt manner. Current methods and programs for running energy simulations are not very timely, difficult to understand, and lack high interoperability between the BIM software and energy simulation software. It is necessary to improve on these drawbacks as design decision are often made without the aid of energy modeling leading to the design and construction of non-

optimized buildings with respect to energy efficiency.

This paper presents a case study illustrating a new methodology for running energy simulations from a BIM in a straight forward and timely fashion. The results from the case study were very similar to those produced from current commercial energy simulation programs, with an average energy estimate variation of 10.5% and cost variation of less than 3%. The application of this methodology can be used to expediently provide energy simulations while at the same time reproducing the BIM in a more readably three dimensional modeling program. With the aid of an easy to run and easily understood energy simulation

methodology, designers will be able to make more energy conscious decisions during the design phase and as changes in design requirements arise.

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