COURTHOUSE ENERGY EVALUATION: BIM AND SIMULATION MODEL INTEROPERABILITY IN CONCEPT DESIGN

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ABSTRACT

This paper presents the development of an automated energy analysis for GSA and the results of a case study comparing two courthouse design options in the Preliminary Concept Design stage. The purpose of this study is to understand the issues around a BIM-driven concept design process that integrates building simulation for design evaluation. The study is developed in two phases: 1) generating a Building Simulation Model (BSM) based on a Building Information Model (BIM); 2) conducting sensitivity analyses to evaluate variability when comparing two design options using building simulation.

NOMENCLATURE

BIM: Building Information Model
BSM: Building Simulation Model
GSA: General Services Administration
IDF: Input Data File for Energy Plus
IFC: Industry Foundation Classes – export file format for a BIM application
SMC: Solibri Model Checker

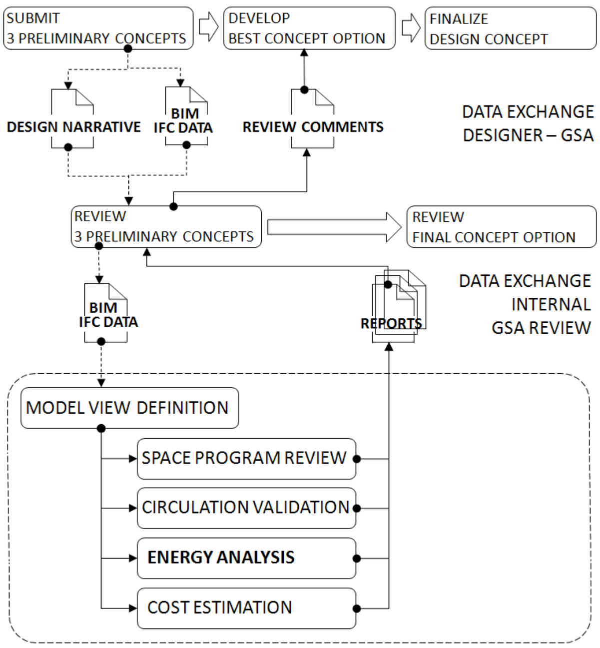

Figure 1 Automated assessment of preliminary concepts for US courthouses

INTRODUCTION

In an effort to improve the performance of federal buildings, the General Services Administration (GSA) has committed to the implementation of integrated planning and design processes to "verify the performance of building components and systems, and help ensure that design requirements are met". As an extension of this initiative, GSA has funded the AEC Integration Lab at Georgia Institute of Technology to automate the reviews of preliminary design concepts for new courthouses in the United States. At this stage of federal building procurement, designers are required to provide preliminary options toward the selection of a final concept to be further developed. The GSA evaluates these options based on compliance the US Courts design guidelines, and specific project requirements, including preliminary cost estimation and energy performance assessment.

Concept design is the stage in current architectural practice where building location, orientation, general massing of the building, and floorplan layout are generally determined. This research focuses on the BIM-driven exchange of information for the assessment of the different alternatives. This paper describes the development of an automated energy analysis tool to support this phase of the decision-making process. The paper presents the results of a case study comparing two courthouse options in the Preliminary Concept Design stage. The purpose is to understand the issues around a BIM-driven concept design process that integrates building simulation for design evaluation. The study is developed in two phases: 1) generating a Building Simulation Model (BSM) based on a Building Information Model (BIM); 2) conducting sensitivity analyses to evaluate variability when comparing two design options using building simulation.

In the first phase, our objective is to identify the available information that can be directly mapped to the BSM and how to include the other necessary input. Our goal is to test the flexibility of the interface to handle models with varying degrees of resolution. In the second phase, we study the impact of competing design options on energy performance, acknowledging that certain parameters in the energy model are unknown at the stage of the comparisons and thus have to be asumed. This leads to uncertainties in the inputs and thus to uncertainties in the simulated energy performance. It is hypothesized that two types of uncertainties need to be incorporated in the BSM. Uncertainty typically found in simulation models developed for engineering analysis (i.e. irreducible uncertainties in the physical parameters) and a different type of uncertainty associated to the design variants that are being compared, leading to certain variability of design parameters, which are consequently translated into probability distributions of the input parameters of the simulation.

BACKGROUND: INTEROPERABILITY BETWEEN DESIGN AND ANALYSIS

Previous studies have focused on two factors affecting the communication between architectural designers and building simulation experts: data exchange between the design and analysis models, and the aggregation of the simulation results to achieve transparency in the design evaluation process. Eastman et al (2008) suggest that with BIM, interoperability encompasses both, the integration the tools for design and analysis, and the early integration of multiple domains of expertise in the building lifecycle process. BIM interoperability is rooted in the concept that all the data associated to a building can be managed in one repository. The goal is to facilitate the exchanges between various domains in the Architecture, Engineering, and Construction (AEC) industry, by having a centralized data model accessible to various domain applications (Eastman, 1999).

Interoperability framework

Developments in interoperability have evolved from structuring simple data exchanges to structuring the process of data exchange in building design. The following aspects of interoperability have been identified:

- Subsets of data, or views, are needed by different domain applications
- The data model needs to be managed to make sure the correct version of the data is being used
- The overall data exchange process also needs to be managed to ensure the complete set of data is available to the domain application

Because the building information model is continuously changing during the building lifecycle process, interoperability is facilitated through structured data exchanges, requiring pre-conditioned scenarios. In a recent study, van Treeck and Rank (2005) describe the integration of building information model, a thermal multi-zone model, and a CFD mesh model. In this study, a product model is imported from an architectural design tool into an energy simulation domain and a mesh is automatically generated for CFD. The BIM is mapped into a boundary representation using a graph structure to decompose the building information model into set of required building objects.

Armor and Augenbroe (1995) propose an approach to interoperability based on the concept of "project windows". Project windows are subsets of data, used by "clusters" of related domains. An application of this concept is presented in the DAI prototype, conceived as dialogue between the design and analysis domains (Augenbroe & de Wilde, 2003):

- Four layers are used to view data across domains, levels of granularity, and applications.
- The analysis scenario layer structures the dialogue using a process model.
- Tasks in the process model are associated to analysis functions

Here, the design-analysis process is represented as tasks linked to a set of analysis functions, with the intelligence to request data from the design information layer, and connect to a tool selected for the building analysis model. At the core of this concept is the need for expertise to acertain the types of analyses that can be performed based on the data available.

Uncertainty as feedback

Other resarch efforts on interoperability focus on sensitivity and uncertainty analyses to provide meaningful feedback to the designer (MacDonald et al, 1999). The underlying argument is that at this early stage of design, it is more appropriate for the decision-making process to communicate "performance values against the probability of their occurrence" rather than to compare a set of a simulation results to a benchmark value (DeWit, 2004). The use of uncertainty analysis is part of a cycle, beginning with a coarse model that is subsequently refined, using sensitivity analysis to identify the parameters with greater uncertainty. Morris (1991) first proposed a method to evaluate uncertainty by isolating a single parameter at a time. DeWit and Augenbroe (2002) propose a method to quantify uncertainty in the evaluation of thermal performance, to support rational decision-making. Four types of uncertainties are identified:

- *Specification uncertainties* arise from incomplete specification in the design such as materials information, thermal zoning or other system design aspects or properties.
- *Modeling uncertainties* are rooted in the assumptions made in the simulation model.
- *Numerical uncertainties* can occur if an inappropriate time-step is selected for a particular simulation, or more generally the uncertainty in the approximation scheme of a stochastic differential equation.
- *Scenario uncertainties* are experiment uncertainties, specifically weather conditions and occupancy patterns.

In a recent study, Struck and Hensen, (2007) focus on two types of specification uncertainties, physical and design-related, as having the greatest uncertainty in the concept design phase. They propose a combined representation of quantitative and qualitative results to enhance communication between designers and simulation experts. The goal is to aid practitioners in early design decisions, and "make explicit" the use of uncertainty and sensitivity analysis by providing "quantitative prediction of performance indicators".

COURTHOUSE CASE STUDY

This case study explores these two aspects of interoperability: data exchange and data uncertainty. The first part of the methodology outlines the strategy to generate a BSM from a BIM in the automation process of the design guidelines for the US Courts. The second part compares two design options using sensitivity analysis.

State of the BIM

A preliminary concept model is a BIM containing information of both the building envelope and the internal layout of spaces which are labelled to comply with the design US Courts departmental organization. This information is represented geometrically using walls, slabs, roofs, and spaces (Figure 2). As stipulated in the GSA guidelines, the BIM is supplemented with a written narrative including other aspects of the design, such as the intended percentage of glazing and the materials of the building envelope. Architectural designers provide the BIM in the form of an IFC data file (Figure 3).

In order to proceed with the four types of automated assessments of the preliminary design options, a model view is used in SMC, the Solibri Model Checker application (Solibri). Our energy evaluation module is implemented as a plug-in in this application (Figure 4). SMC imports the building information model in the form of an IFC data file, collects the BIM data and represents it as Solibri_Wall, Solibri_Slab, Solibri_Space, Solibri_Roof, etc. SMC provides a plug-in interface to execute three basic steps:

- Visualize the thermal zones for the BSM by selecting perimeter and core zones or zoning based on a zone per department space (Figure 5)
- Input the parameters for percentage fenestration and exterior shading elements
- Generate the Input Data File (IDF) to run in Energy Plus

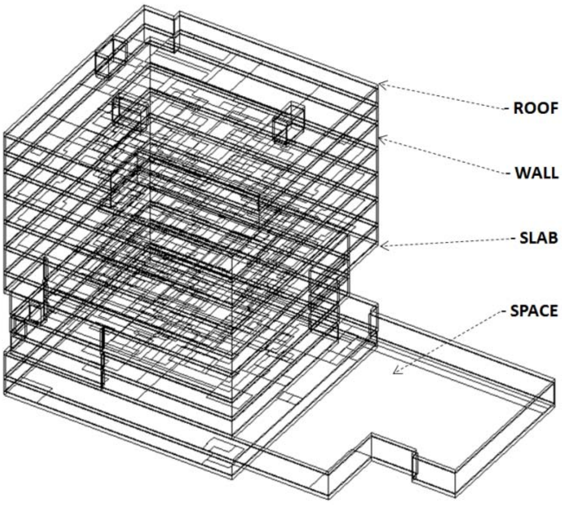

Figure 2 Geometric components of a Building Information Model for a courthouse concept design

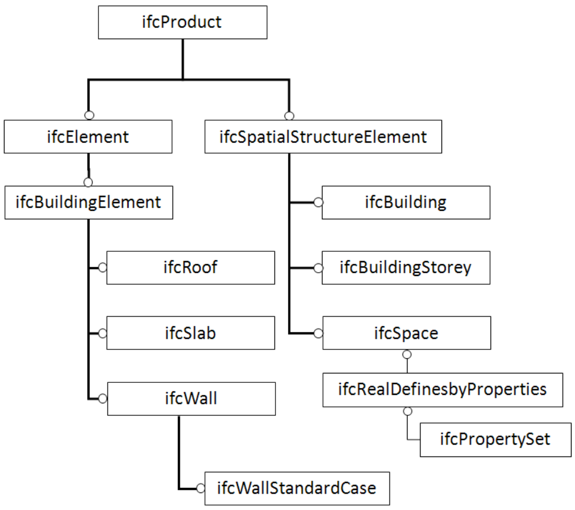

Figure 3 Diagram of the IFC data structure for a Courthouse BIM (simplified to show relevant components for BSM)

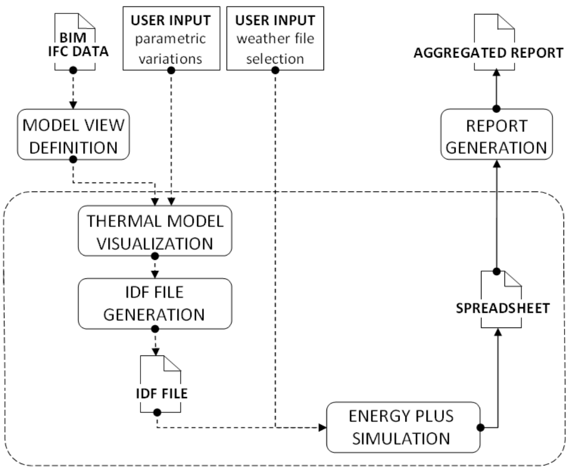

Figure 4 Automated energy analysis

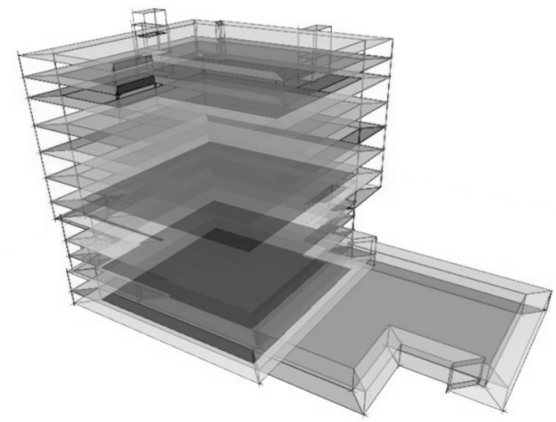

Figure 5 Visualization of the courthouse thermal (perimeter & core) zones generated in the system

Mapping process

Data mapping includes translating the BIM data components and the additional user input into the input necessary for the BSM. Three types of BSM parameters are identified.

- BIM-derived parameters
- User-defined parameters (design intent)
- Default parameters

These parameters are transposed to the simulation entities of BSM at various levels.

- *Thermal zones and Heat-transfer Surfaces* are derived from the geometric information of the building components. An algorithm is created to calculate the volume of the zone based on the space area, the adjacent walls, and the distance between floor slabs. The coordinates for the zone surfaces are then calculated and stored in a string for the generation of the IDF for Energy Plus.
- *Construction types* are derived from the BIM, and then mapped to default parameters. Based on the thickness of the wall component, an ASHRAE light, medium, or heavy construction type is selected and associated to a set of default materials with embedded defaults such as U-value. These defaults are stored as strings and collected in the IDF file generation process (Figure 4).
- *Window sub-surfaces* are defined by the user. The user can change the default 30% fenestration value (based on GSA's minimum overall window to wall ratio), and this value is parameterized to generate the window geometry.
- *Attached Shading surfaces* are also defined by the user as an additional option. (Currently IFC does not support the definition of shading devices such as vertical fins.)
- *Internal Heat gains for occuppancy, equipment, lighting for each zone* are associated to schedules of occupancy and operation. First each thermal zone is given a name based on the BIM's space and the departmental name in the ifc.property set for that space. Second the name of the zone is mapped to occupancy types in California's energy standard, and the corresponding loads. (California Code).
- *HVAC and thermostat* are a default setting. HVAC is idealized as Compact PurchasedAir. Thermostatic control is based on a default schedule based on office use.

Additional input data required for the BSM, such as simulation parameters and report calls for output variables, are also set as default. Weather data is selected in the Energy Plus interface.

State of the BSM

A BSM consists of a vector of inputs, x, a simulator, f, and a vector of outputs, y. Sources of specification uncertainty in the inputs can be linked directly to a) the set x_{design},of parameters specific to a design option, either derived from the BIM or defined in the plug-in interface; or b) the set $x_{default}$, of default values assigned the BSM parameters in the mapping process. We can represent the BSM as:

$$y= f(x)$$

where, $x = x_{design}+ x_{default}$

The set of parameters, x_{design}, includes the geometric description of the model, internal load distribution, and attributes of the building envelope. The set of default parameters, $x_{default}$, refers to the physical properties of design specifications such as the conductivity of a material layer, or simulation specific requirements such as the type of calculation used in the simulation. We therefore propose that in the preliminary concept design stage, the set of default parameters is larger than the set of design parameters.

$$x_{design} \leq x_{default}$$

Analysis process

We compare two design options for a courthouse in downtown Salt-Lake City. In Option A the building envelope has 30% fenestration which is the default setting in the GSA energy assessment module. Option B has been varied to reflect an alternative design option where 80% of the envelope surface is glass. In order to study the potential impact of different sources of uncertainty on option A-B comparison, a coarse preliminary uncertainty analysis is performed. We assume for simplicity that the envelope is the only source of physical as well as design uncertainty. Six parameters (Table 1) associated to the building envelope, x_1, x_2, x_3, x_4, x_5, x_6, are identified as uncertain parameters for this study:

$$\{ x_2, x_3, x_4, x_5 \} \in x_{default}$$

$$\{x_1, x_6 \} \in x_{design}$$

For the purpose of this study, two physical properties of of the building envelope are varied to explore uncertainty introduced by design specifications. The conductivity of the cladding surface, x_1, is given a wider range of possible values to explore the probability of having cladding surfaces ranging from metal to brick. The shadowing transmittance coefficient of the exterior shading surface, x_6, is varied to study the probability of having shading in one of the outcomes of the options.

Table 1

Building envelope parameter and their expected mean values- source: Energy Plus data sets based on ASHRAE Fundamentals, 2005, Chapter 30

		Expected value	unit
OPAQUE SURFACE			
X1	Thermal Conductivity Cladding layer	45.280	W/m-K
X2	Thermal Conductivity Insulation layer	0.030	W/m-K
X3	Thickness Insulation layer	0.051	m
TRANSPARENT SURFACE			
X4	Solar Transmittance	0.552	
X5	Thermal Conductivity	0.900	W/m-K
SHADING SURFACE			
X6	Shadowing Transmittance	0.0	

The thing to observe is that parameter x6 has been added to reflect a design uncertainty rather than a physical uncertainty. x6 can take a value between 1 (fully opaque shading) and 0 (fully transparent, i.e. no shading). The value is unknown as it is yet undecided whether a shading device will be part of the envelope, and if so to what extent the shading will be effective The design uncertainty can be treated in different ways. One could assume total ignorance or one could assume a certain bias towards no shading when the glazing percentage decreases and full shading when the glazing percentage increases. These variations in assumptions and their affect on the outcome of the decision between option A and B will be studied in the following cases.

Three types of comparisons are established to examine the sensitivity of these parameters in the simulation output.

- *Case 1- Single parameter analysis*. Parameter samples for each option are generated using a uniform distribution for the Shadowing Transmittance parameter x6 (Table 2). The other 5 parameters are treated as deterministic variables.

Table 2

Shadowing Transmittance parameter range

PARAMETER	RANGE		distribution
X6	0.0	1.0	uniform

- *Case 2- Physical uncertainty analysis with 5 parameters*. Design uncertainty is removed by assuming a deterministic link between the glazing percentage and X6. Parameter samples are generated for each option using a normal distribution for the opaque and transparent surface parameters. Option A is assigned a fixed shadowing transmittance value of 1.0, to represent 100% transparency (no shading is present) and Option B, a fixed value of 0.0, to represent 100% opacity (Table 3).

Table 3

Building envelope parameter ranges

	μ	σ	unit	distribution
X1	65.385	50.960	W/m-K	normal
X2	0.030	0.002	W/m-K	normal
X3	0.053	0.015	m	normal
X4	0.579	0.100		normal
X5	0.907	0.057	W/m-K	normal
	Option A		**Option B**	
X6	1.0		0.0	

- *Case 3- 6-parameter analysis.* This is a combination of physical and design uncertainty in a way that reflects the glazing percentage-x6 bias. Parameter samples for each option are generated using a normal distribution for the set of parameters associated to the opaque and transparent surfaces. A pert distribution is used for the Shadowing Transmittance, giving Option A a tendency toward 1.0 (no shading), and option B toward 0.0 (full shading) (Table 4).

Table 4

Building envelope parameter ranges

	μ	σ	unit	distribution
X1	65.385	50.960	W/m-K	normal
X2	0.030	0.002	W/m-K	normal
X3	0.053	0.015	m	normal
X4	0.579	0.100		normal
X5	0.907	0.057	W/m-K	normal
	RANGE		**distribution**	
X6	0.0	1.0	pert	

The Monte Carlo method is used to analyze the uncertainty propagation. RiskAmp plug-in for Excel generated samples using the Latin Hypercube Sampling technique. All simulations calculate the cooling load for the month of July. The output variable observed is the total zone/system sensible cooling energy. Scatter plots were generated to evaluate individual input variables and output results. (plots are omitted from this paper for brevity.) Summary statistics were prepared for the output of the three cases. Probability density functions and cumulative density distributions were used to compare option A and B in each case.

RESULTS

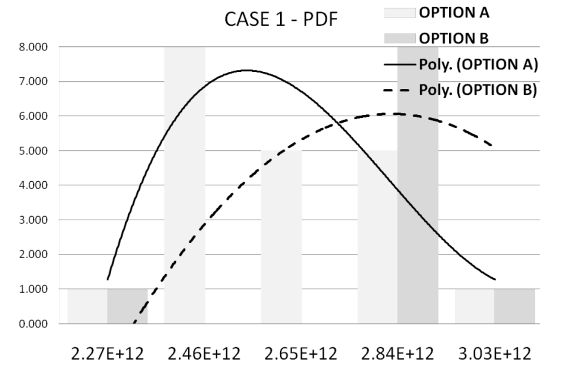

Figure 6 Case 1 Comparison using Probability Density Function. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

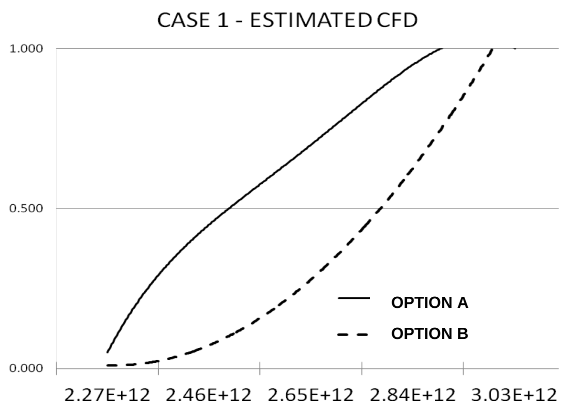

Figure 7 Case 1 Comparison using Cumulative Probability Distribution. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

Table 5

Case 2 Summary Statistics

Units in Joules

	OPTION A	OPTION B
SAMPLE SIZE	20	19
SAMPLE MEAN	2.27E+12	2.75E+12
STANDARD ERROR	5.84E+09	2.86E+10
STANDARD DEVIATION	2.61E+10	1.25E+11
MEDIAN	2.27E+12	2.78E+12
SKEWNESS (ASYMMETRY)	5.26E-01	-3.51E+00
KURTOSIS (FLATNESS)	-1.42E+00	1.39E+01
MEAN 90% CONFIDENCE INTERVAL		
UPPER LIMIT	2.28E+12	2.80E+12
LOWER LIMIT	2.26E+12	2.71E+12

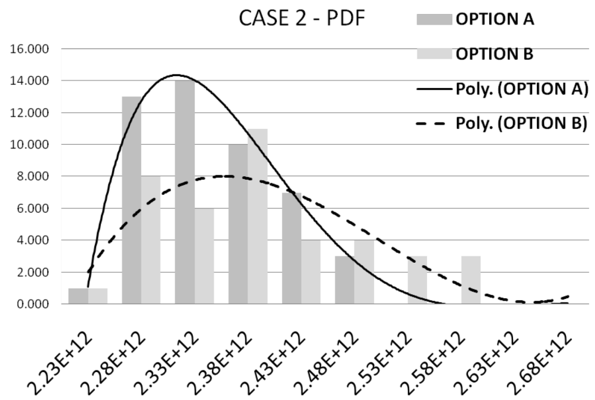

Figure 8 Case 2 Comparison using Probability Density Function. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

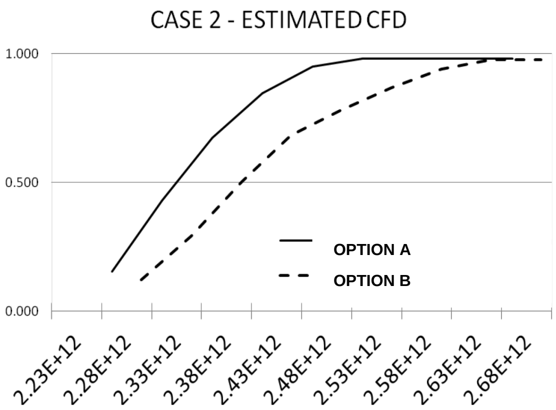

Figure 9 Case 2 Comparison using Cumulative Probability Distribution. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

Table 6

Case 2 Summary Statistics

Units in Joules

	OPTION A	OPTION B
SAMPLE SIZE	49	41
SAMPLE MEAN	2.33E+12	2.68E+12
STANDARD ERROR	1.16E+10	1.97E+10
STANDARD DEVIATION	8.11E+10	1.26E+11
MEDIAN	2.33E+12	2.64E+12
SKEWNESS (ASYMMETRY)	2.50E+00	1.10E+00
KURTOSIS (FLATNESS)	1.07E+01	1.47E+00
MEAN 90% CONFIDENCE INTERVAL		
UPPER LIMIT	2.35E+12	2.71E+12
LOWER LIMIT	2.31E+12	2.64E+12

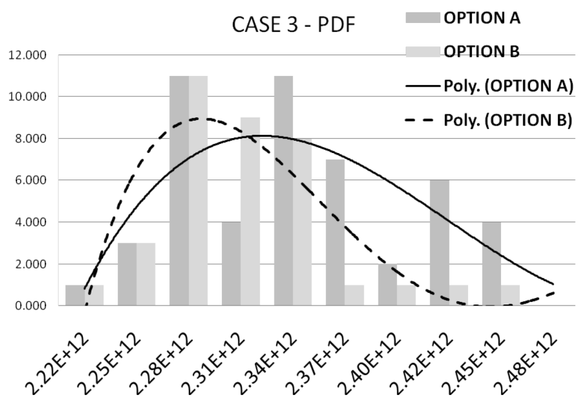

Figure 10 Case 3 Comparison using Probability Density Function. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

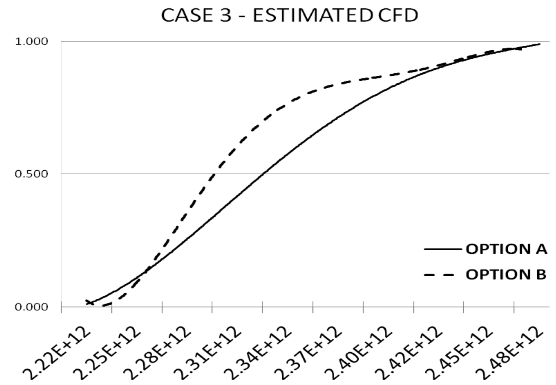

Figure 11 Case 3 Comparison using Cumulative Probability Distribution. Solid line, Option A; dashed line, Option B. Horizontal axis in Joules

Table 7

Case 3 Summary Statistics

Units in Joules

	OPTION A	OPTION B
SAMPLE SIZE	50	42
SAMPLE MEAN	2.33E+12	2.78E+12
STANDARD ERROR	9.21E+09	2.28E+10
STANDARD DEVIATION	6.51E+10	1.48E+11
MEDIAN	2.32E+12	2.73E+12
SKEWNESS (ASYMMETRY)	5.97E-01	1.44E+00
KURTOSIS (FLATNESS)	-2.51E-01	1.75E+00
MEAN 90% CONFIDENCE INTERVAL		
UPPER LIMIT	2.35E+12	2.82E+12
LOWER LIMIT	2.32E+12	2.75E+12

DISCUSSION: RANGES OF UNCERTAINTY IN PRELIMINARY CONCEPT DESIGN

Interoperability is possible when the building information model can represent, structure, and share the data needed by the design and the analysis domains. However, in a preliminary concept design, the designer's model is a sketch usually lacking detailed information required for many types of evaluation. In this study we examine how, at this early design stage, many aspects of the designer's intent can indeed be represented in a BIM. The property sets of the BIM's components enable the exchange of information that can be mapped to the entities of the simulation model, including the specification of the building envelope and internal heat gains. The results of the first phase of this study show that information on the design parameters can be exchanged. However, these parameters have embedded lower level physical parameters that are set as defaults in the preliminary concept phase and are deep sources of uncertainty.

Exploring the potential of uncertainty analysis

In the second phase of this study we propose that evaluations can be conducted if the proper uncertainties are defined and propagated to the outcome. If the outcomes show one option to be dominant over the other in spite of the uncertainties (i.e. with a high enough confidence interval), it is warranted to declare one of the options the preferred one. We identify two sources of uncertainty in the preliminary concept stage: physical uncertainties and design uncertainties. Physical uncertainties are irreducible but quantifiable as Gaussian probability distributions. We explore three cases to study of design uncertainty, uniform distribution, pert distribution, and deterministic assumption.

In case 1, a uniform variation of the shading parameter shows that the use of shading elements in Option B would not significantly mitigate the impact of 80% glazing on the cooling demand, as compared to Option A with a 30% window-to-wall ratio. In case 2, it is confirmed that a larger number of outcomes associated to option A would probably perform better than option B, but it is also shown that in many instances the options would have similar outcomes. In case 3, the spread changes and a larger number of outcomes associated with Option B would perform better. (A qualitative examination of scatter plots, omitted for brevity, shows that the glazing coefficient is the dominant parameter in this subgroup of 6 parameters observed.)

Improving the dialogue between the design and analysis domain

Within the concept of a design-analysis dialogue, it is important for the designer to understand what is required in an analysis request, as well as for the building technologist to provide feedback that is more meaningful. In addition, there seems to be an unrealistic expectation from designers that the simulation results will directly point to a component of the building to adjust for a better result. In this study, we examine a particular case where the use of shading devices in a courthouse is a design parameter evaluated for its impact on the cooling demand. Uncertainty analysis proves to be a useful tool to shed light in the dominance of a particular parameter or set of parameters. The study also confirms that variation of a design parameter such as shading, would also require changes in the glazing properties and the conductivity of the opaque surfaces for a better performance.

In our scenario, the choice to use shading devices may be considered an evident choice, based on its relationship to the fenestration ratio of the building envelope. We propose that there may be other interrelated design parameters not so easily identified. Within a design option, variability deals with a single subset of parameters and can be studied as parameter uncertainty. However, in a choice of among design options, we need a different approach to uncertainty analysis, where variability could be a measure of the tendency of different subsets of parameters.

The use of uncertainty and sensitivity analysis in concept design, as the main feedback in a design-analysis dialogue, could have an impact on the entire building lifecycle. What are the expected levels of uncertainty in concept design, design development, or building operation? Are there ways of categorizing uncertainty based on the different types of design evaluations? This will require a clear communication of how uncertainty propagates from the BIM to the BSM. To provide a meaningful feedback, the next step in interoperability is to improve the study of uncertainty associated to design intent whether it is considered unknown and unquantifiable or random and irreducible.

CONCLUSION

The early integration of energy simulation as a mode of design assessment reveals how information can be made explicit in a BIM in order to support design evaluation and decision-making in concept design. The research focuses on the most problematic aspect of concept design: the design model is a representation of intent rather than a complete solution. We use sensitivity analysis to study a scenario where design parameters lead to a wide spectrum of uncertainty in the BSM, based on the granularity of the designer's BIM model. The results of the second phase show that to ascertain a clear choice between two design options requires a strategy to address design uncertainties. The direct conclusion of this study is that improving building energy performance cannot be directly linked to the integration of a single design component such as shading because design parameters and their associated uncertainties are option-dependent. If indeterminacy is inherent in models and data exchanged between design and analysis, more research is needed to improve the dialogue and the use of uncertainty analysis to support design decisions.

ACKNOWLEDGEMENT

Thanks: Professor Ruchi Choudhary for all her mentoring in EnergyPlus; P. Pasiala of Solibri for the close collaboration in the implementation; M. Swarts in setting up the simulation farm; H. Hu for helpful suggestions in the sensitivity analysis.

Special thanks to the research team, under Professor Eastman: Y-S. Jeon, J-M. Lee, J-K. Lee, H. Sheward, S. Abdelmohsen, M.G. Zapata.

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