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ThermalOpt: A Methodology for Automated BIM-Based Multidisciplinary Thermal Simulation for use in Optimization Environments

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ABSTRACT:
This paper describes ThermalOpt - a methodology for automated BIM-based multidisciplinary thermal simulation intended for use in multidisciplinary design optimization (MDO) environments. ThermalOpt mitigates several technical barriers to BIM-based multidisciplinary thermal simulation found in practice today while integrating and automating commercially available technologies into a workflow from a parametric BIM model (Digital Project) to an energy simulation engine (EnergyPlus) and a daylighting simulation engine (Radiance) using a middleware based on the open data model Industry Foundation Classes (IFC). Details are discussed including methods for: automatically converting architectural models into multiple consistent thermal analytical models; integration/coordination of analysis inputs and outputs between multiple thermal analyses; reducing simulation times; and generating consistent annual metrics for energy and daylighting performance. We explain how ThermalOpt can improve design process speed, accuracy, and consistency, and can enable designers to explore orders of magnitude larger design spaces using MDO environments to better understand the complex tradeoffs required to achieve zero energy buildings.

KEYWORDS:
multidisciplinary design optimization (MDO); conceptual building design; energy simulation; daylighting simulation; interoperability; process integration; design automation

1. INTRODUCTION

Reducing the environmental impacts of buildings is urgently important. The American Institute of Architects (AIA) in the Architecture 2030 Challenge (AIA 2011) and the Federal Government in the Energy Independence and Security Act (FEMP 2007) both call for net-zero energy (NZE) consumption for new building designs by the year 2030. Maximizing energy performance, however, has proven elusive to industry for many years. The greatest opportunity to reduce energy consumption lies in the concept design phase, when orientation, massing, materials, components, and systems and their properties are defined.

Thermal design processes are complex multi-criteria problems that require structured and systematic definition and exploration of design spaces (Ross and Hastings 2005, Lewis et al. 2007, Bazjanac 2008, Papamichael et al. 1997). Performance-based design (Becker 2008, Oxman 2008) requires that designers possess information about the performance trends and interactions of the potential design spaces available to them (Mourshed et al. 2003). However, according to surveys of AEC design firms, architects and engineers generally take over one month to generate and analyze a design alternative. Due to the limited time available for design, each project often achieves as few as three such iterations. The majority of professionals surveyed indicated that they spend less than half of their time doing 'value-adding' design and analytic work, and used simulation tools primarily to validate a chosen design alternative, not to explore multiple alternatives (Gane and Haymaker 2010, Clevenger and Haymaker 2011). Designers typically vary multiple parameters at one time in an unsystematic manner resulting in difficultly isolating impacts of individual design parameters (Wang et al. 2005b), and operate with small and under-explored alternative and impact spaces that do not meet NZE requirements (Watson and Perera 1997, Lazzara 2008). A number of tool and process limitations in current practice result in narrow explorations of design spaces. For example, designers' tools usually generate static design alternatives and are not intended to help define and explore design spaces (Shea et al. 2005, Mora et al. 2008), and do not produce information that is represented in a form that facilitates multidisciplinary analysis (Gallaher et al. 2004, Holzer et al. 2007, Wang et al. 2005a). However, even when these limitations are overcome, designers must tread carefully, as design spaces quickly become unwieldy (Woodbury and Burrow 2006).

1.1. Multidisciplinary Design Optimization (MDO)

To improve design space exploration, researchers developed a class of formal methods to as multidisciplinary design optimization (MDO). MDO is a growing engineering discipline concerned with the formalization of iteration and coordination between groups working on the design of complex engineering systems and with creating an environment conducive to these formal methods (AIAA 1991). At its core is the notion that design is a goal oriented decision-making process driven by performance feedback (Malkawi 2004).

Prior research compared design processes in the AEC and aerospace industries based on a series of directed interviews and case study data gathered in each industry (Flager and Haymaker 2007). The research showed that aerospace designers, once they adopted MDO methods, were able to dramatically improve process efficiency, design knowledge, and product performance. The application of MDO methods to support thorough investigation of design spaces in AEC holds much promise (Geyer 2009, Caldas 2008, Shea et al. 2005, Diakaki et al. 2008).

Process Integration and Design Optimization (PIDO) is an MDO framework that comprises software and design techniques intended to help engineers and analysts manage the setup and execution of simulation and analysis tools, integrate and synthesize results from multiple domain applications, and optimize one or more aspects of a product design. PIDO environments enable the integration of commercial or proprietary software tools into a common environment using software “wrappers” or “plugins” which interface with the tools to be automated. Once an integrated model has been built, design exploration and optimization tools can be used to perform various trade studies such as parameter scans, optimizations using formal optimization algorithms (e.g. genetic algorithm (GA) or gradient optimizer), and Design of Experiments (DoE). The data generated with these tools provide the information necessary to employ advanced visualization and post-processing/analysis techniques that assist designers with better understanding the design space.

1.2. BIM-Based Multidisciplinary Thermal Simulation

Performance-based design supported by product models is becoming state-of-the-art practice for an expanding number of design disciplines (Fischer 2006). Product models are now being applied to all phases of the design process, from the generation of design concepts through preliminary and detailed design. The use of these models, also called building information models (BIM) (Eastman et al. 2008), allows practitioners to flexibly and efficiently generate and modify geometric and semantic models. There is widespread support for a product model centric approach to MDO in literature (Mourshed et al. 2003, Lazzara 2008, Crawford and Haimes 2004, Townsend et al. 1998). Today’s emphasis on high-performance buildings makes it important to leverage BIM-based thermal analyses during design, in particular multidisciplinary analysis using daylighting and whole-building energy simulation analysis tools.

1.3. Technical Barriers for BIM-Based Multidisciplinary Thermal Simulation and MDO

In order to use a BIM-based multidisciplinary thermal simulation process in an MDO environment, the entire process must be able to be executed in a fully-automated and efficient manner once initialized. The tool and process limitations in current practice described earlier manifest themselves in a range of technical barriers that exist for this goal to be achieved. Fig. 1 illustrates a typical design process implemented in practice and highlights several of these technical barriers. The primary author constructed a simple building in Revit Architecture (Autodesk 2011b), and evaluated the design for energy performance using eQUEST (DOE 2011b) and Integrated Environmental Solutions (IES) (IES 2011) and for daylighting performance using Ecotect (Autodesk 2011a). The two energy models demonstrate one application that cannot import 3D geometry from a BIM (eQUEST) and one that can (IES). EnergyPlus was not used as most practitioners don't use it due to a lack of a comprehensive graphical user interface (GUI).

After finishing the Revit model, the first author re-created the geometry in eQUEST and imported the geometry into IES and Ecotect using green building extensible markup language (gbXML 2010). Data import issues occurred with the window overhangs in both applications, and in many instances it was not possible to assign parameters consistently in the three analytical models due to differences in model granularity, libraries, and GUIs. Revit successfully transferred construction thermal properties to IES, but not to Ecotect. While eQUEST and IES simulated annual energy use, the Ecotect interface to Radiance (DOE 2011c) calculated illuminance profiles for several design days. It was therefore not possible to integrate the results of the daylighting analysis into the energy analyses due to the differing time scales and output data format. The first author manually input results into Excel for post-processing. Each new iteration in the process required manual modifications to the Revit, eQUEST, IES, and Excel models. Time requirements for each step are shown below.

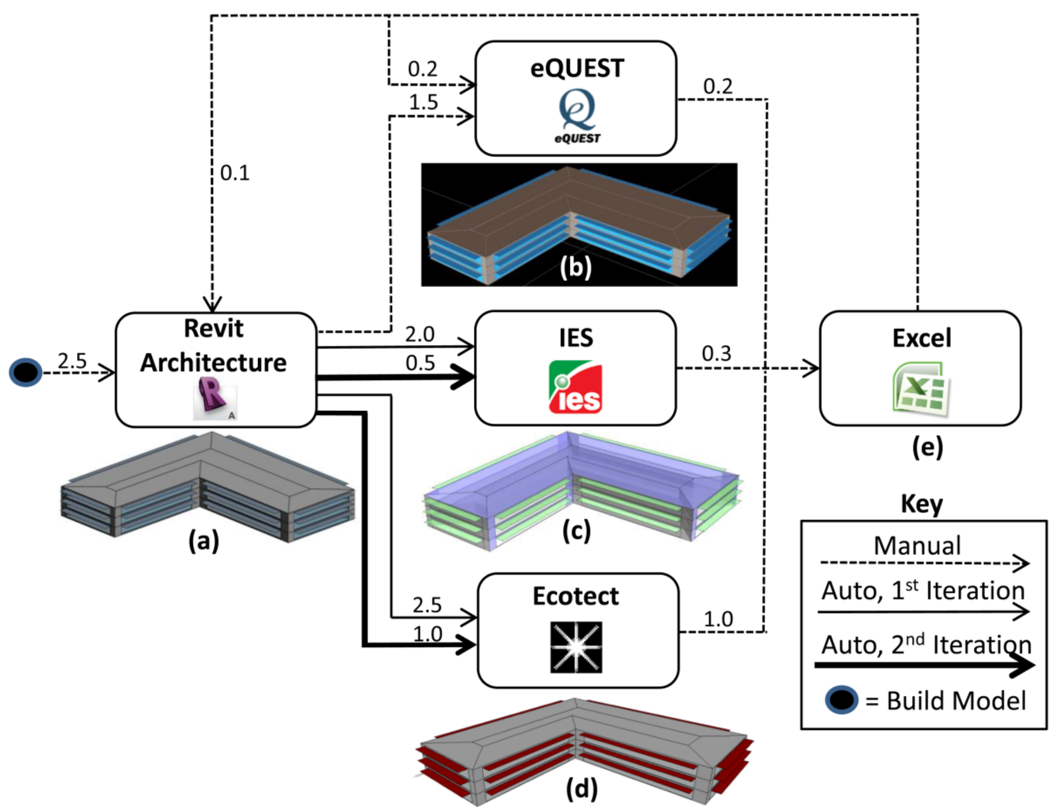

Fig. 1 A simple model was built in Revit (a) and analyzed in eQUEST (b), IES (c), and Ecotect (d). The results were manually post-processed in Excel (e). Time requirements (hours) for each step are labeled on the arrows. While time requirements decreased for the second iteration in all instances, several preparatory steps had to be repeated.

This example demonstrates several technical barriers faced in BIM-based multidisciplinary thermal simulation today that must be addressed to successfully automate a process for use in MDO environments. The most significant challenges are:

a) *Long Analytical Model Preparation Times:* Preparation of the required input files for simulation is a time-consuming process, particularly with limited or no GUI functionality.
b) Inaccurate Conversion of Architectural Model to Analytical Model: Data transfer from a BIM to a thermal analysis application is typically hindered by interoperability issues (Bazjanac 2001, Bazjanac and Kiviniemi 2007). This hindrance results in manual or semi-manual replication of existing information, resulting in errors, omissions, misunderstandings, and misinterpretations (Bazjanac and Crawley 1997).
c) *Inconsistent Conversion of Architectural Model to Analytical Model:* These same interoperability issues result in a lack of consistency in the conversion of architectural to thermal models. The same architectural model, if given to five different designers, typically will result in five different thermal models. This lack of consistency, and therefore repeatability, limits the integrity of the energy simulation process.
d) *Missing or Invalid Data in Architectural Model:* Missing or invalid data from the BIM model frequently compromises the integrity of the analysis and must be managed in a reasonable manner that itself does not compromise the integrity of the analysis (Bazjanac et al. 2011).
e) *Inconsistent Analytical Models for Multidisciplinary Analysis:* Energy and daylighting simulations are typically conducted with two different tools that require specialized skills, frequently by two different people in two different firms. This segmentation results in inconsistent analytical models and analysis results.
f) Long Analytical Model Simulation Times: Time-consuming simulations for both energy and daylighting limit the ability of the designer to evaluate a large number of design options within the time constraints of conceptual design (Hong et al. 2008).
g) *Poor Coordination of Analytical Model Outputs/Inputs:* Energy and daylighting simulation engines both model the same set of solar thermal processes, and therefore necessitate the integration of analysis outputs and inputs. This integration frequently does not take place, resulting in conflicting output results.
h) Inconsistent Performance Metrics: Performance metrics for energy and daylighting simulations frequently are generated on different time scales. For example, long simulation times for daylighting frequently result in analyses for just a few select times throughout the year (e.g. mid-winter, mid-summer, spring/fall equinoxes). These differences prevent legitimate integration and comparison between the two analyses.

This paper introduces a methodology called ThermalOpt that mitigates these technical barriers and may be used in an MDO environment. Section 2 provides an overview of ThermalOpt and the overall MDO process used for this research. Section 3 presents the results of the applying ThermalOpt within an MDO environment to an implementation test case, as well two industry case studies. The former includes some preliminary results from a trade study, including some analysis visualizations, to give readers a sense of the type of information ThermalOpt can enable. However, accuracy of EnergyPlus and Radiance thermal simulations, and a discussion on optimization strategies, their effectiveness for evaluating thermal simulation, and an evaluation of trade study visualization methods is beyond the scope of this research. Conclusions and future research are discussed in Section 4, with acknowledgements in Section 5.

2. THERMALOPT: AUTOMATED BIM-BASED MULTIDISCIPLINARY THERMAL SIMULATION METHODOLOGY

ThermalOpt enables an automated methodology to pre-process, configure, execute, and post-process a BIM-based multidisciplinary thermal simulation process that may be used during early design. This method is faster, more accurate, and more consistent than conventional methods. A faster BIM-to-simulation process will enable a larger number of design alternatives to be explored. Research suggests that improved design process accuracy and consistency also result in improved design exploration (Young et al. 2007, Gallaher et al. 2004), and that this improvement increases the chance of discovering higher performance designs (Akin 2001, Ipek et al. 2006, Krishnamurti 2006). With the process automated, it may also be used in MDO environments introduced in Section 1.1. This capability enables designers to conduct advanced trade studies and leverage their advanced design space exploration and visualization capabilities.

The ThermalOpt methodology and the overall MDO process it was used with for this research are shown in Fig. 2. ThermalOpt has been implemented via four different components: (1) an IFC2ThermalSim Plugin; (2) a ThermalSim Plugin; (3) an EnergyPlus Wrapper; and (4) a Radiance Wrapper. The IFC2ThermalSimPlugin is custom software that utilizes the commercial software BSPro by Olof Granlund Oy (Granlund 2011) for several steps. The ThermalSim Plugin is custom software. The EnergyPlus and Radiance Wrappers are custom software that utilize the commercial energy simulation engine EnergyPlus (DOE 2011a) and daylighting simulation engine Radiance, respectively. The contribution of the ThermalOpt methodology consists of a suite of methods that reside within the custom software of these four components, and not in the commercial applications themselves. As was the case in a previous classroom case study (Flager et al. 2009b), the MDO environment selected is ModelCenter (Phoenix Integration 2004) and the parametric BIM application is Digital Project (Gehry 2011). Data is transferred to ThermalOpt from Digital Project via the interoperable data model Industry Foundation Classes (IFC) (buildingSMART 2011).

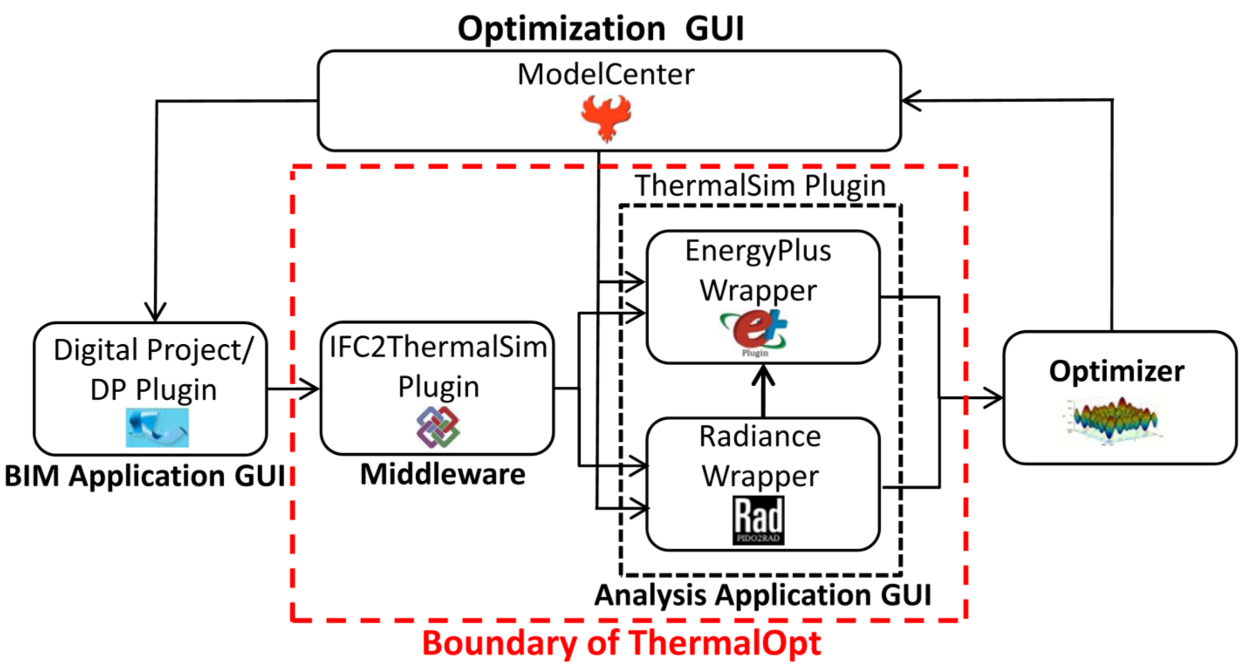

Fig. 2 The user starts the overall MDO process by building a parametric BIM model and assigning analysis information using the BIM Application GUI (Digital Project) and the Analysis Application GUI (ThermalSim Plugin). When the user initializes the trade study, in this case an optimization, the BIM information is passed via IFC (DP Plugin) to a middleware (IFC2ThermalSim Plugin) for preprocessing, then to an energy simulation

environment (EnergyPlus Wrapper) and a daylighting simulation environment (Radiance Wrapper) for analysis. The boundary of the ThermalOpt methodology is shown in red.

Fig. 3 shows a more detailed overview of ThermalOpt and the overall MDO process. The IFC2ThermalSim Plugin converts the Digital Project IFC file into an intermediary output text file that is formatted for the EnergyPlus and Radiance Wrappers. The designer defines the trade study strategy within Model Center. Once the process is executed, the Wrappers generate the appropriate input files for analysis and run the simulations. An optimizer, such as a GA or gradient optimizer, evaluates the results against user-defined design constraints and objectives, and determines the next design iteration to be evaluated.

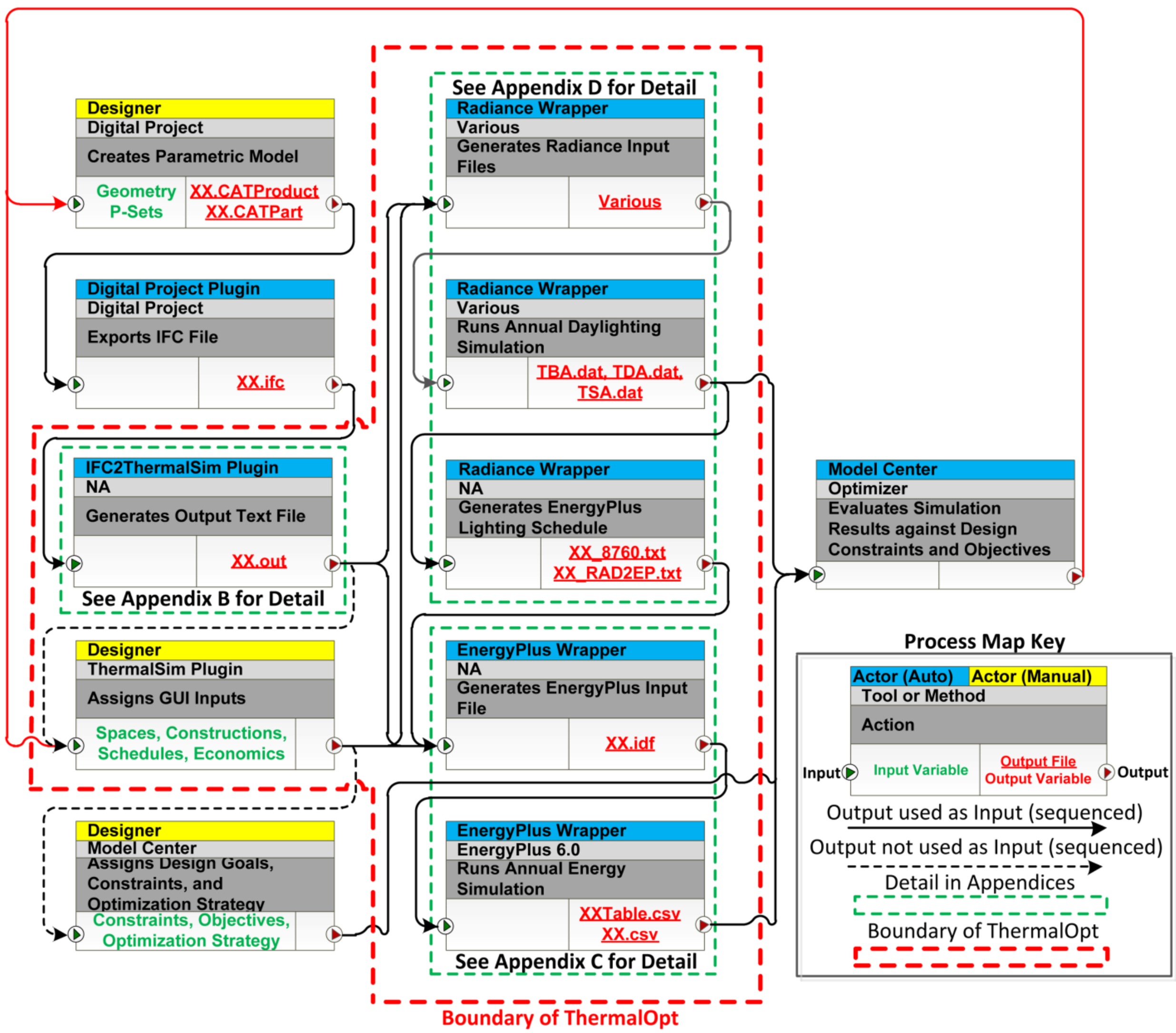

Fig. 3 High-level process map of ThermalOpt. Detailed process maps can be found in Appendices B-D.

The steps for low energy design in order of importance are to: (1) reduce thermal loads; (2) meet thermal loads with the most efficient HVAC equipment possible; and (3) meet the remaining demand with renewable energy (Bradshaw 2006, Lechner 2009, Kwok and Grondzik 2007, Mendler et al. 2006, Givoni

1994). Therefore, passive thermal performance, or all non-mechanical energy flows in a building, is the most critical component. For this reason, the authors chose to limit the scope of ThermalOpt's simulation capabilities to passive thermal design (PTD) strategies during conceptual design. Appendix A lists the PTD strategies that may be evaluated by EnergyPlus and/or Radiance, and those that ThermalOpt currently supports. Cost and time constraints prevented the remaining PTD strategies from being implemented during this first phase of research.

Table 1 summarizes the suite of methods that constitute the overall ThermalOpt methodology, and the technical barriers from Section 1.3 that each method mitigates. There exists a wide range of additional methods that may be implemented to further mitigate these technical barriers.

Table 1 ThermalOpt methods for automated BIM-based multidisciplinary thermal simulation and how they mitigate the technical barriers presented in Section 1.3.

ThermalOpt Methods	**a**	**b**	**c**	**d**	**e**	**f**	**g**	**h**
IFC2ThermalSim Plugin								
Conversion of Architectural Space Boundaries (SBs) to Thermal SBs (2.2.1)	x	x	x					
Conversion of Column Objects to Shading Surfaces (2.2.2)	x	x	x					
Splitting of Window Objects with Lightshelves (2.2.3)	x	x	x					
Geometric Translation of Shading Surfaces for Non-Planar Walls (2.2.4)	x							
Post-Processing of Object P-Sets (2.3.5)	x			x				
ThermalSim Plugin								
Common Input File for EnergyPlus and Radiance (2.3.1)	x				x			
Common GUI for EnergyPlus and Radiance (2.3.2)	x				x			
EnergyPlus Wrapper								
Generation of IDF using Template Files (2.4.1)	x							
Post-Processing of EnergyPlus Outputs (2.4.2)	x							
Radiance Wrapper								
Methods for Simulated Space Selection (2.5.1)	x					x		
Automatic Daylighting Sensor Grid Generation (2.5.2)	x							
Conversion of EnergyPlus Geometry to Radiance Geometry (2.5.3)	x				x			
Calculation of Annual Whole-Building Daylighting Performance Metrics (2.5.4)	x							x
Scaling of Annual Daylighting Performance Metrics (2.5.5)						x		
Generation of EnergyPlus Lighting Schedule using Radiance Output (2.5.6)	x				x		x	

Key: **a**=Long Analytical Model Preparation Times, **b**=Inaccurate Conversion of Architectural Model to Analytical Model, **c**=Inconsistent Conversion of Architectural Model to Analytical Model, **d**=Missing or Invalid Data in BIM Model, **e**=Inconsistent Analytical Models for Multidisciplinary Analysis, **f**=Long Analytical Model Simulation Times, **g**=Poor Coordination of Analytical Model Outputs/Inputs, **h**=Inconsistent Performance Metrics

Section 2.1 provides an overview of the steps in Digital Project the designer must undertake for ThermalOpt. Sections 2.2-2.5 discuss each of the ThermalOpt methods introduced in Table 1.

2.1. Digital Project/DP Plugin

Digital Project is built on top of CATIA for which ModelCenter already had a plugin (herein called the Digital Project Plugin, or DP Plugin). No modifications were required for this research. The Plugin allows ModelCenter to communicate with Digital Project via a COM link, enabling direct manipulation of design parameters in the parametric model. The designer builds a parametric BIM model using the Architecture and Structures (A&S) Workbench (Gehry 2011) in Digital Project. The following objects are supported:

slabs (base slabs, floors, and roofs; vertical or tilted), walls (internal and external; vertical or tilted), windows (internal and external; vertical or tilted), doors (internal or external; vertical or tilted), spaces (occupied and plenum), columns, overhangs, fins, lightshelves, adjacent buildings, daylighting sensors, rooftop photovoltaic panels (PV), and building integrated photovoltaic panels (BIPV). Appendix B lists the object properties available. The objects themselves may be parameterized in any way available in Digital Project. While building the model, the designer must assign custom property sets (p-sets) to all the objects in the model for use during the analysis. When the designer finishes, the DP Plugin searches for all the exposed independent and dependent parameters and exposes these to the designer for inclusion in trade studies (Fig. 4). After selecting the desired parameters, the designer loads a CATIA script to automatically export an IFC file. Once a trade study has commenced, the Plugin automatically changes the selected parameters to the desired value and updates the geometry accordingly.

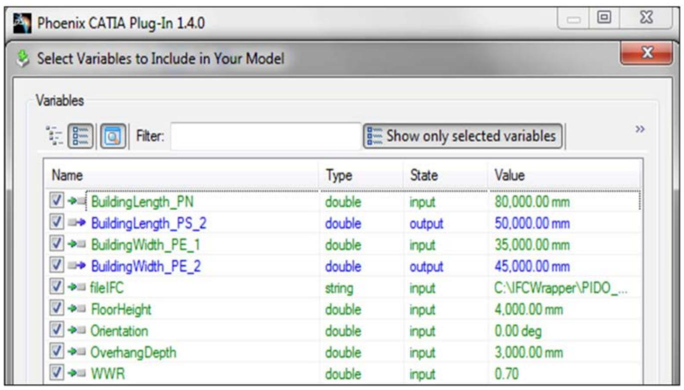

Fig. 4 The DP Plugin allows users to select which design variables to include in the trade study. Green variables are independent, and blue are dependent.

2.1.1. Digital Project Modeling Requirements

While middleware or other pre-processing techniques may allow for the reduction, simplification, transformation, and interpretation of data from the BIM tool to meet specific analysis requirements in a fully or semi-automated design process, BIM-based analysis still requires some forethought by the designer as to specific modeling requirements to adhere to in order to successfully leverage the BIM data for the downstream analysis using these methods (Bazjanac and Kiviniemi 2007). Failure to do so typically results in an interoperability interruption and the designer must go back to the BIM tool, troubleshoot, and modify the geometry to resolve the issues (Bazjanac 2008). The modeling requirements for ThermalOpt are the following:

- *Co-planar surfaces cannot be used as bounding elements of a space*. This requirement is due to limitations of Digital Project. Failure to adhere to these requirements will result in incorrect definition of space boundaries upon export of the IFC file.
- *A single wall object may not serve as both an interior and exterior wall.* Same as above.
- *Multi-story spaces cannot use vertically stacked walls as bounding elements.* Same as above.
- *Single-story spaces cannot be "stacked" to create multi-story spaces.* Same as above.
- *Columns, overhangs, and lightshelves must be rectangular (fins may be triangular).* This requirement is due to limitations of EnergyPlus.
- *Adjacent buildings must be modeled as shading surfaces with glazing.* This requirement is due to limitations of Digital Project. Modeling adjacent buildings for shading purposes in DP using

conventional A&S objects (e.g. walls, slabs, spaces, etc.) will result in an IFC export that does not allow for the distinction between simulated and non-simulated buildings.

- *Each object requires that a predefined p-set be assigned.* Custom p-sets are required as the native p-sets assigned by the BIM-tool contain only a small fraction of the properties required for a BIM-based thermal analysis.

If the designer meets all these requirements, the IFC2ThermalSim Plugin, ThermalSim Plugin, and EnergyPlus/Radiance Wrappers will accept the model with any possible configuration of walls, slabs, windows, spaces, overhangs, fins, lightshelves, columns, adjacent buildings, and daylighting sensors.

2.1.2. IFC Export

Gehry Technologies enhanced the quality of the IFC export in Digital Project to support the requirements of the IFC2ThermalSim Plugin. Two types of IFC files may be exported: surfacic or detailed. The surfacic export exports analytical spaces using the centerline of the bounding objects (Fig. 5b). The detailed export outputs architectural spaces based on the inner surfaces of the bounding objects (Fig. 5c). Designer requirements and the existing objects in the model determine which export method to use. If construction thickness may be ignored, then designers use the surfacic export. If the construction thicknesses cannot be ignored, or the model contains columns, the designer uses the detailed export.

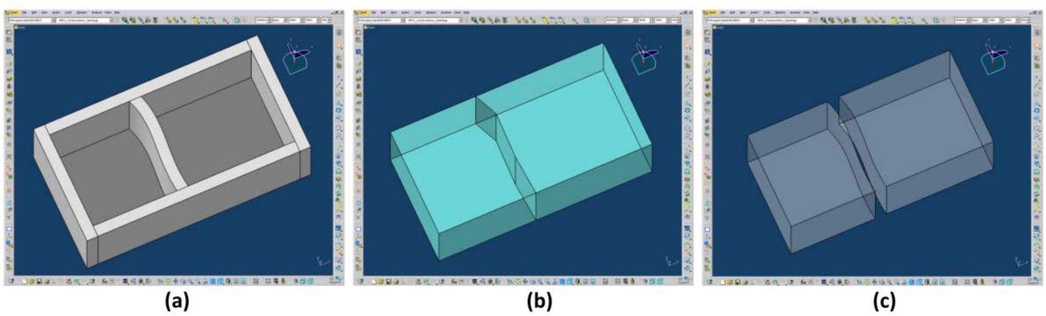

Fig. 5 When the surfacic export is used for the example building (a), the space limits are determined by the wall centerlines (b). When the detailed export is used, the space limits are determined by the inner surfaces of the bounding walls (c).

2.2. IFC2ThermalSim Plugin

The IFC2ThermalSim Plugin, is coded in C++, executes a series of processes to filter, translate, and transform the data in the imported IFC2x3 file to a text file formatted based on the requirements of EnergyPlus. IFC enables the use of a variety of BIM tools (e.g. Revit and ArchiCAD). The output file contains new space boundary geometry and existing object properties from the IFC file. The Plugin executes a number of processes including: calculation of thermal space boundaries from architectural space boundaries; conversion of column objects into shading surfaces; splitting of window objects with lightshelves; re-positioning of overhangs and fins for non-planar walls and windows, and post-processing of object p-sets. Appendix B shows a detailed diagram of the IFC2ThermalSim Plugin.

2.2.1. Conversion of Architectural Space Boundaries to Thermal Space Boundaries

The effective conversion of the architectural BIM to the thermal analytical model is one of the most challenging, time consuming, and often poorly executed steps in practice. Space boundaries define spaces and their relationships to the enclosing building elements, and may be either architectural or thermal in nature. Thermal space boundaries may be categorized as 1st level space boundaries (1LSBs), 2nd level space boundaries (2LSBs), and 3rd level space boundaries (3LSBs) (Weise et al. 2011). 1LSBs are the boundaries of a space defined by the surfaces of building elements bounding the space (physical space boundaries) or by virtual surfaces provided by an adjacent space with no dividing wall. They form a closed shell around the space and include overlapping boundaries representing openings (filled or not) in the building elements. 2LSBs still represent building elements that bound the space, but are more granular than 1LSBs. 2LSBs are subdivided when they contain: openings (with or without fillings like doors and windows); differences in materials and/or material assemblies; and differences in spaces or zones on the other side of the building element represented by the space boundary (e.g. two different spaces on the other side of a wall). 2LSBs represent both sides of a heat transfer surface separated by the thickness of the building element. They can be used by thermal analysis software, but require that the two adjacent surfaces are found and combined to form a single heat transfer surface. 3LSBs consist of all remaining space boundaries that have an opaque building element behind the boundary. For example, the end of a wall (wall butt) that divides two spaces on the other side of a wall. When 2LSBs and 3LSBs are combined, they form a closed shell around the space. Fig. 6 shows the three primary types of space boundaries.

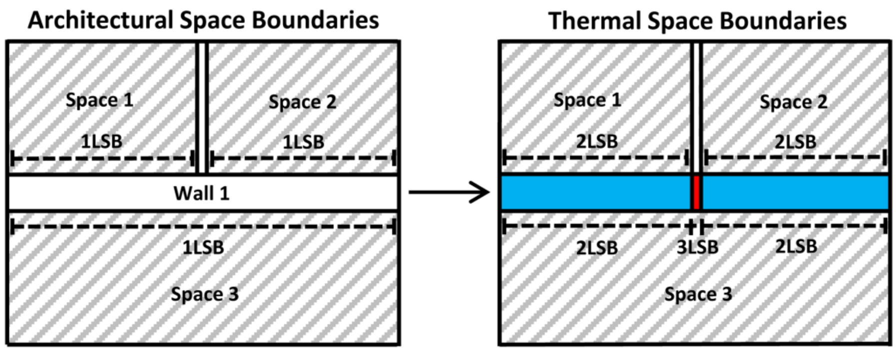

Fig. 6 1LSBs (architectural) vs. 2LSB and 3LSB (thermal).

The Plugin uses a middleware called BSPro to automatically split 1LSBs into 2LSBs and 3LSBs. Once the IFC file with valid 1LSBs is imported, BSPro executes a series of geometric algorithms to split them into the appropriate heat transfer surfaces, rename them, and provide their geometry (all vertex points of each space boundary polyloop), orientation, and relationships to adjacent spaces, opaque constructions, and opening constructions.

The Plugin executes a number of additional processes to assure accurate space boundary information and calculate additional space boundary information not provided by BSPro including: converting relative geometric coordinates from BSPro to global coordinates; identifying space boundary "pairs" by comparing the polygon coordinates of potentially matching space boundaries; correcting polygon orientation for slabs and walls so the first vertex of a space boundary is the same as the last vertex of the paired space boundary; matching the starting vertex of skylight windows to the host roof; correcting the polygon coordinate ordering for vertical surfaces following the "upper left-hand, counterclockwise" requirement of EnergyPlus; and checking each space boundary for inner space boundaries as inner space boundaries are related to the host space boundary and not the space in BSPro.

2.2.2. Conversion of Column Objects to Shading Surfaces

The Plugin converts column objects into shading surfaces expected by EnergyPlus and Radiance. The IFC2ThermalSim Plugin converts each column into four vertical shading surfaces as defined by the column footprint profile and the extrusion length (or column height), shown in Fig. 7.

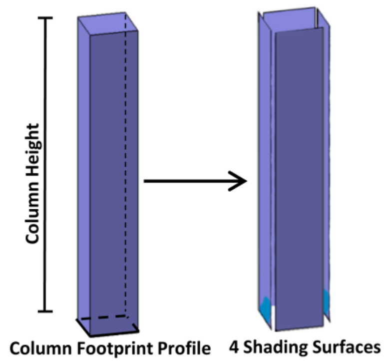

Fig. 7 The ThermalSim Plugin converts each column object in the IFC into four shading surfaces as defined by the column footprint profile and the column height.

Columns named Column.X in the IFC file are renamed as shading surfaces Shading.X.1, Shading.X.2, Shading.X.3, and Shading.X.4. Each of the child shading surfaces inherits the properties of the parent column.

2.2.3. Splitting of Window Objects with Lightshelves

The Plugin splits windows with lightshelves into an upper and a lower window, as required by EnergyPlus. This functionality prevents the designer from having to define windows in the BIM tool in an unconventional manner. If the window to be split is called Window.X, then the lower window will be renamed Window.X.1 and the upper Window.X.2. The resulting coordinate ordering is shown in Fig. 8. In the p-sets for the shading objects, the user will have defined the lightshelf HostSubSurface# as Window.X. In the output file, the window assignment is changed to the upper window number for both outer and inner lightshelves. For the window p-sets, the lower window is assigned the same p-set values as those assigned by the user in the IFC file for Window.X. For the upper window, all shading properties are assigned "NA", since EnergyPlus does not allow the upper window to have shading. All other properties for the upper window are the same as the lower window.

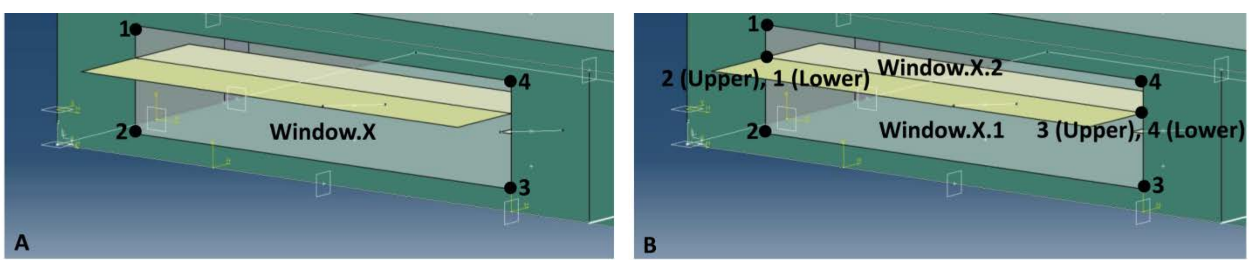

Fig. 8: Coordinates for the window split are at the intersection of the lightshelf shading object and the window fill.

2.2.4. Geometric Translation of Shading Surfaces for Non-Planar Walls

EnergyPlus requires that window shading objects are coincident with the host window planes. Therefore, the IFC2ThermalSim Plugin corrects shading device coordinates when the original BIM model constructions have thicknesses (i.e. there are gaps between the resulting construction space boundaries and the shading objects). Fig. 9 illustrates that the Plugin finds the vertex point of the shading object with the minimal distance to edges of the opening element, calculates the translation vector of the vertex point to the opening element geometry, and moves the shading geometry along the translation vector.

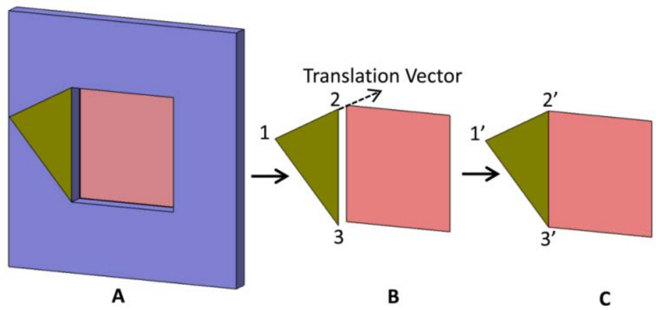

Fig. 9 The IFC2ThermalSim Plugin translates shading surfaces to be coincident with the host window when the BIM model contains constructions with thickness.

2.2.5. Post-Processing of Object P-Sets

Before outputting the p-set values, the Plugin validates them against predefined rules to determine if a default setting must be applied or if the property from the IFC must be passed through. These predefined rules prevent invalid or missing properties assigned by the designer in the BIM model. For example, if the surface type of a window or door is "InteriorWindow" or "InteriorGlassDoor", the Plugin prevents any shading devices from being assigned to it since EnergyPlus will not allow it. In this case, the property "ShadingType" will be given a value of "NA" in the output file, regardless if the designer assigned one. If a given object property is allowable but missing, a value of "UN" is written to the output file. A log file is generated along with the primary Plugin output file to alert the user to invalid or missing information.

2.3. ThermalSim Plugin

2.3.1. Common Input File for EnergyPlus and Radiance

The final step for the IFC2ThermalSim Plugin is to generate an output text file (ProjectName.out). This file is imported directly into the ThermalSim Plugin, the EnergyPlus Wrapper, and the Radiance Wrapper, ensuring that all three components use the same data.

2.3.2. Common GUI for EnergyPlus and Radiance

The ThermalSim Plugin (Fig. 10) serves as the GUI for both the EnergyPlus and Radiance Wrappers to ensure consistent input of variables between the two analyses and eliminate redundant assignment of inputs. Upon opening the Plugin, the user may select to be in EnergyPlus mode only (EPMode), Radiance mode only (RADMode), or both (EPRADMode). If the user selects EPMode, all the variables specific to the Radiance Wrapper are deactivated, and vice versa.

During the optimization initialization process, the designer imports the IFC2ThermalSim Plugin output text file, and selects the desired simulation input parameter values for opaque constructions, opening constructions, shading constructions, spaces, schedules, and economics (see Tabs in Fig. 10). The user may define each input variable through a set of enumerations stored in Excel lookup tables accessible in the Plugin directory. The inputs from the Plugin are stored in a database that is then accessed by the EnergyPlus and Radiance Wrappers.

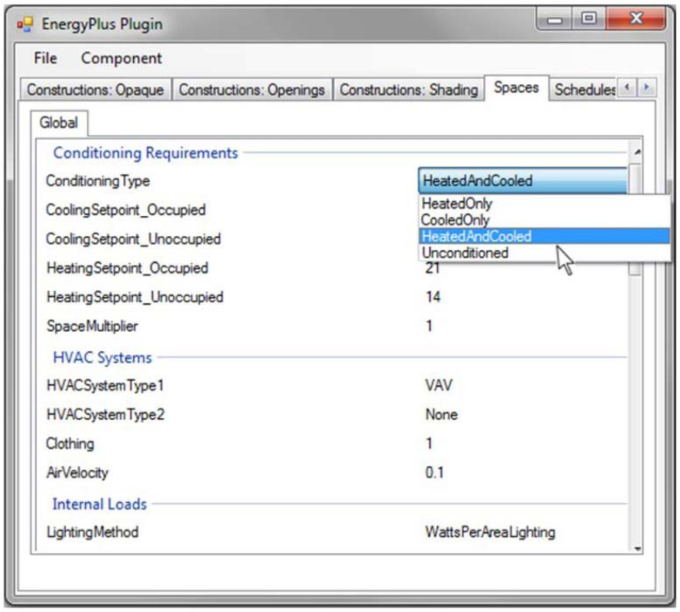

Fig. 10 The ThermalSim Plugin GUI allows the user to assign input parameters for the EnergyPlus and Radiance Wrappers. Users can modify enumeration libraries that determine the options available.

The GUI contains logic to prevent unnecessary or invalid assignment of input variables. For example, if the user specifies that the “ConditioningType” of a given space is “CooledOnly”, then the occupied and unoccupied heating setpoint variables are deactivated. Appendices C and D list supported input variables for the EnergyPlus and Radiance Wrappers.

2.4. EnergyPlus Wrapper

The EnergyPlus Wrapper, which is coded in Java, uses both the inputs from the ThermalSim Plugin GUI and the IFC2ThermalSim Plugin output text file to generate an input file for EnergyPlus (ProjectName.idf). The Wrapper then calls EnergyPlus and runs an annual energy simulation. The user may select to use a lighting schedule generated by the Radiance Wrapper. Despite the research focus on PTD, the authors did implement minimal support for HVAC systems using the available HVAC Template Objects in EnergyPlus. Appendix C shows a detailed process map of the EnergyPlus Wrapper.

2.4.1. Generation of IDF using Template Files

The Wrapper executes a process that generates the EnergyPlus input file using a series of .idf template files: SimulationParameters, Zones, DELightDaylighting, DetailedDaylighting, HeatTransferSurfaces, ShadingSurfaces, ShadingControls, MaterialsAndConstructions, ScheduleType, CompactSchedules, Infiltration, InternalLoads, HVACThermostat, HVACSystems, UtilityCosts, ConstructionCosts, and ReportVariables. Logic has been implemented to determine when to use certain templates and how to populate them.

2.4.2. Post-Processing of EnergyPlus Outputs

The primary outputs are taken from the ProjectNameTable.csv and ProjectName.csv output files. The Wrapper parses these files and post-processes some of the outputs to modify units or convert hourly data into annual values.

2.5. Radiance Wrapper

The Radiance Wrapper, which is coded in Python, uses both the inputs from the ThermalSim Plugin GUI and the IFC2ThermalSim Plugin output text file to generate a range of input files for Radiance. The Radiance Wrapper runs annual, climate-based daylighting simulations to generate several different dynamic daylighting metrics (Reinhart et al. 2006, Mardaljevic 2008, Mardaljevic et al. 2009, Walkenhorst et al. 2002). The Wrapper contains several processes to improve efficiency and accuracy including: selecting which spaces in the BIM model are to be simulated in Radiance; automatically generating daylighting sensors grids for the spaces to be simulated; generating Radiance geometry from EnergyPlus geometry; scaling the results of a partial daylighting simulation to the entire building; and generating an EnergyPlus lighting schedule for use in the EnergyPlus Wrapper. Appendix D shows a detailed process map of the Radiance Wrapper.

2.5.1. Methods for Simulated Space Selection

The Wrapper gives users several choices for how to define which spaces in the BIM model are to be modeled in Radiance. These options include simulating spaces in the Digital Project model that contain daylight sensors, exterior windows, or a user-identified space property (Daylighting=Y/N). This range of options is intended to provide the user with flexibility and reduce simulation time requirements.

2.5.2. Automatic Daylighting Sensor Grid Generation

To expedite pre-processing, the Radiance Wrapper has the ability to auto-generate daylighting sensor grid arrays based on the space geometry in the BIM model. Ideally, this array of points is spaced uniformly throughout the entire space. Generating an array of points for a rectilinear space can be done with a simple grid of points. However, if the space happens to be angled relative to the projects main axes or the space is any number of other non-rectilinear shapes, automatically generating a grid becomes a much more challenging task. The Radiance Wrapper automatic analysis point generation solution first creates a rectangle around the x and y extents of the space footprint, distributes a grid evenly within this rectangle, then individually checks each point using a custom point in polygon method (Huang and Shih 1997) to test if the point is within or outside of the space. The algorithm then iterates this process as necessary, reducing the grid spacing each step, until a specified “area per analysis point” density requirement is met.

2.5.3. Conversion of EnergyPlus Geometry to Radiance Geometry

The use of a common analytical model for both energy and daylighting simulation poses some challenging modeling issues when it comes to defining geometry. Zonal energy models need planar wall, window, and door geometry, relationships (e.g. adjacent wall/window/door, if internal), and thermal properties. Hence, a typical whole-building energy model will use infinitely thin planes to define all exterior and interior wall, floor, ceiling, window, and door surfaces. For a daylight model, the actual 3-D geometry is important as the thickness of the walls can have a significant impact on the daylight delivered to the space. Additionally, coordinate ordering requirements are frequently different between two applications (as the case with EnergyPlus and Radiance).

To address these challenges, the authors developed a methodology for using EnergyPlus geometry directly to generate Radiance geometry. First, the user assigns a thickness to all the planar surfaces defined for the energy model. For exterior walls, the Radiance Wrapper adds thickness to the inside, such that the defined plane is the exterior plane of the wall. For interior walls, it adds thickness away from the space and hence begins to reduce the area of the adjacent space. A special Radiance material type called "anti-matter" is defined for every window and door opening to "punch" a hole in the wall. The anti-matter material in Radiance removes designated surfaces within its volume. The anti-matter volume extends just beyond the interior and exterior plane of the wall to avoid any co-planar issues. Next, a glass plane (opaque for non-glazed doors) is placed using the geometry from the IFC2ThermalSim Plugin output text file making it flush with the exterior (or interior) plane. Interior window blinds, drapes, and shading systems are placed 0.05m inside of glazing plane, and exterior window shading elements are placed 0.05m outside of the glass plane.

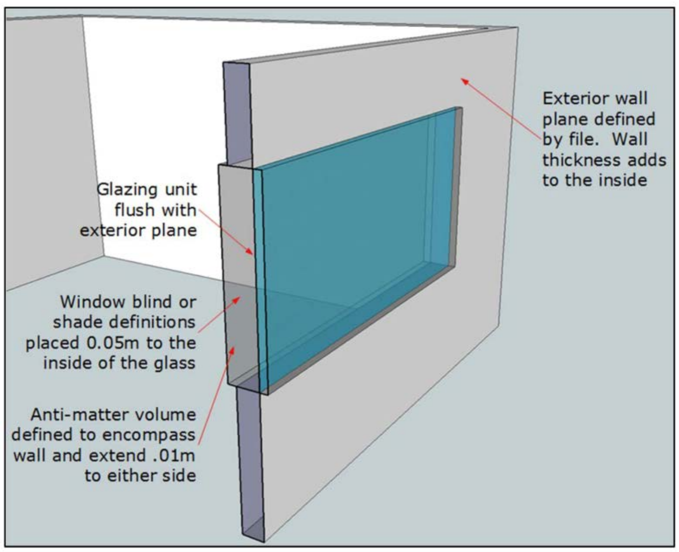

Fig. 11 The Radiance Wrapper uses the concept of "anti-matter" in Radiance to enable the generation of Radiance geometry from EnergyPlus geometry. This method is fast and ensures consistent geometry between the analytical models for the two thermal analyses.

This method is currently limited to 4-node, rectangular shaped windows, primarily due to compatibility issues with the interior window blind and shade elements. The approach enables EnergyPlus surfaces to be used directly, avoiding the complex and time-consuming task of breaking up wall polygons to surround windows.

2.5.4. Calculation of Annual Whole-Building Daylighting Performance Metrics

Calculating annual whole-building performance metrics for a building design is important to be able to compare and integrate the results consistently with the results from an annual energy simulation. The Wrapper partially accomplishes this by integrating parts of the SPOT (AEC 2008) and DAYSIM (Reinhart 2011) engines, and the development of new engine called Metrics_Calcs.exe. DAYSIM calculates annual daylight availability and is comprised of a number of separate software tools that build off and integrate with Radiance and the Daylight Coefficient Method (Bourgeois et al. 2008, Bourgeois and Reinhart 2006) for performing annual daylighting simulation. Several SPOT functions and Metrics_Calcs.exe were integrated to read in the annual illuminance file from DAYSIM and lighting and occupant schedule information from the ThermalSim Plugin to calculate several annual daylight metrics for each space selected:

- *Daylight Autonomy (DA)* (Rogers 2006): a measure of the number of hours that a given target illuminance, often 215-430 lux, is exceeded by daylight throughout the year. DA is useful for determining the daylight "potential" of a space with on/off daylight responsive electric lighting control.
- *Daylight Saturation (DS)* (Reinhart et al. 2006): Similar to DA, but accounts for hours where target illuminance is partially met. DS helps determine the daylight "potential" of a space with continuous dimming daylight responsive electric lighting control.
- *Maximum Daylight Autonomy (DAmax)* (Reinhart et al. 2006)*:* a measure of excessive daylight in a space, which can be a good indicator of glare, and assumes that a maximum acceptable illuminance is a multiplier of the spaces target illuminance, typically 10x.
- *Useful Daylight Illuminance (UDI)* (Nabil and Mardaljevic 2006): a measure of the amount of useful daylight illuminance throughout the year, with useful defined as daylight illuminance between 100 and 2000 lux.
- *Daylight Glare Potential (DGP)* (Kleindeinst and Andersen 2009, Wienold 2009): a daylight glare metric that calculates the potential for glare in terms of a percentage of occupants that would find the condition glary, given a view direction.
- *Daylight Factor (DF)* (Reinhart and Herkel 1999, Mardaljevic et al. 2009): an historic metric used to estimate the quantity of daylight in a space. It is a static metric based on a single cloudy sky condition.

These results are saved for each analysis point and as an average for the entire space. Metric_Calcs.exe then calculates the building-wide average for all simulated spaces the authors have called Total Simulated Average (TSA). Additionally, the Wrapper can average the results over all interior spaces to produce the metric Total Building Average (TBA). These metrics are an area-weighted average of the space metric values. Spatially averaging the annual daylight performance information allows the performance to be presented as a single value. However, it should be noted that doing so eliminates important and sometimes critical information about the spatial uniformity of daylight in the space. For this reason, the Radiance Wrapper saves point-by-point performance data along with the space and building-wide averages with the intent of implementing other building-wide uniformity and saturation metrics as they are developed.

2.5.5. Scaling of Annual Daylighting Performance Metrics

When the designer chooses to simulate a subset of building spaces to reduce simulation time requirements using the methods described in Section 2.5.1, the Radiance Wrapper checks for non-simulated spaces with exterior windows or glass doors and assigns the average for the given metric of all the other simulated spaces with the same dominant window orientation (N, S, E, and W). The authors have called the resulting metric Total Daylit Average (TDA). This aggregate metric is still subject to the spatial uniformity issues described in Section 2.5.4.

2.5.6. Generation of EnergyPlus Lighting Schedule from Radiance Output

To translate the daylight energy saving benefits to a whole building energy simulation, the Radiance Wrapper generates an EnergyPlus lighting schedule. The Wrapper focuses on the absolute daylight "potential" for the daylit space and simulates a simple linear continuous dimming control of the electric lighting in the daylit zones. In this way, lighting energy is predicted as simply the inverse of the Daylight Saturation value. For example, if there is a target of 400 lux and daylight is providing 300 lux, then there is a Daylight Saturation of 75% and a need for 25% of the electric lighting energy, resulting in a lighting power multiplier (LPM) of 0.25. This fraction is multiplied against the user defined electric lighting schedule(s) so as to accurately simulate daylighting saving potential on top of existing occupancy sensor, work schedule, and behavioral savings. The output text file describes the LPM of each daylit space for every hour of the year. This file is then referenced by the EnergyPlus input file when generated by the EnergyPlus Wrapper.

3. Implementation Test Case and Industry Case Studies

The authors tested ThermalOpt on a simple test case and two industry case studies that both have aggressive sustainability goals. This section discusses each of the three validation efforts.

3.1. Implementation Test Case

The goals of the implementation test case were to (1) test the technical implementation of ThermalOpt with a simple test case to validate Plugin/Wrapper functionality; (2) run a parametric trade study to test the robustness and stability of the automation process; and (3) to demonstrate the value of a running large trade study on a set of clearly defined design objectives by comparing ThermalOpt with the conventional process in Fig. 1 in terms of the number of design altenernative evaluted and the most efficient building alternative identified within a given time period. The authors chose a DoE using ThermalOpt rather than an optimization in order to allow for the simulation and visualization of performance trends over the entire spectrum of the design space. The test building was a 12,450 m^2, three-story, L-shaped office building with windows, blinds, and overhangs for all perimeter spaces. The window-to-wall ratio for each orientation was 70%, with windows centered on their respective walls (by floor) with the same aspect ratio. The perimeter depth was 12.0 m, and floor-to-floor height 4.0 m.

The design problem chosen was to evaluate the effectiveness of optimizing the overhang depth for each facade orientation (north, south, east, and west) independently to capture the effect of varying solar loads and potential tradeoffs between increased daylighting (and subsequent reduction in artificial lighting) vs. increased solar loads and HVAC consumption. The study did not consider construction costs of overhangs to focus the assessment on thermal performance only. The performance objective for the case study was to minimize annual energy costs ($/yr). The study investigated the overhang depth variable with a range of 0.5 - 4.0 m in 0.5m increments, and imposed a minimum DS constraint of 0.77 for all perimeter spaces. The selected location was Phoenix, AZ for the purpose of determining weather conditions and utility rates, and the HVAC system chosen was a variable air volume (VAV) system with perimeter reheat served by an electric chiller, a natural gas boiler, and a cooling tower. The remaining simulation parameters are listed in Appendix E. The size of the design space for varying overhang depth by orientation is 8^4 = 4,096 alternatives.

The trade study using the conventional process was executed first. For the conventional process, the authors chose to analyze as many iterations as possible within the projected time frame of the MDO trade study. To estimate the MDO trade study time, 2 iterations using ThermalOpt were run (Fig. 12). Fig. 12a shows the Digital Project model and Fig. 12b shows the use of Solibri Model Checker to check the integrity of the IFC model exported by Digital Project. The output of the IFC2ThermalSim Plugin was imported into the Radiance and EnergyPlus Wrappers, and the resulting models are shown in Fig. 12c and Fig. 12d, respectively. The EnergyPlus model was checked in Google SketchUp (Google 2011) using the OpenStudio Plugin (Ellis et al. 2008). The Radiance model was validated using a Radiance geometry viewer. In both instances, the 2LSBs, window blinds, shading objects, and daylighting sensor grids were all processed correctly, and both simulations ran without error. A single iteration after the initial MDO setup took approximately 24 minutes to complete with the following breakdown of simulation times: DP Plugin = 2.5%, IFC2ThermalSim Plugin = 2.5%, Radiance Wrapper = 70%, EnergyPlus Wrapper = 20%, and ModelCenter = 5%. The total simulation time was estimated to take 17.3 hours when executed in parallel over a 128-node computer cluster, with a post-processing time of 2 hours. The cluster hardware consists of 'master' server and 16 'slave' blade servers, each containing 2 x Quad Core Xeon 2.83 GHz processors with 16 GB RAM. Only the slave blade servers were used for simulation. The operating system for the cluster is Microsoft Windows HPC Server 2008 (Flager et al. 2009a).

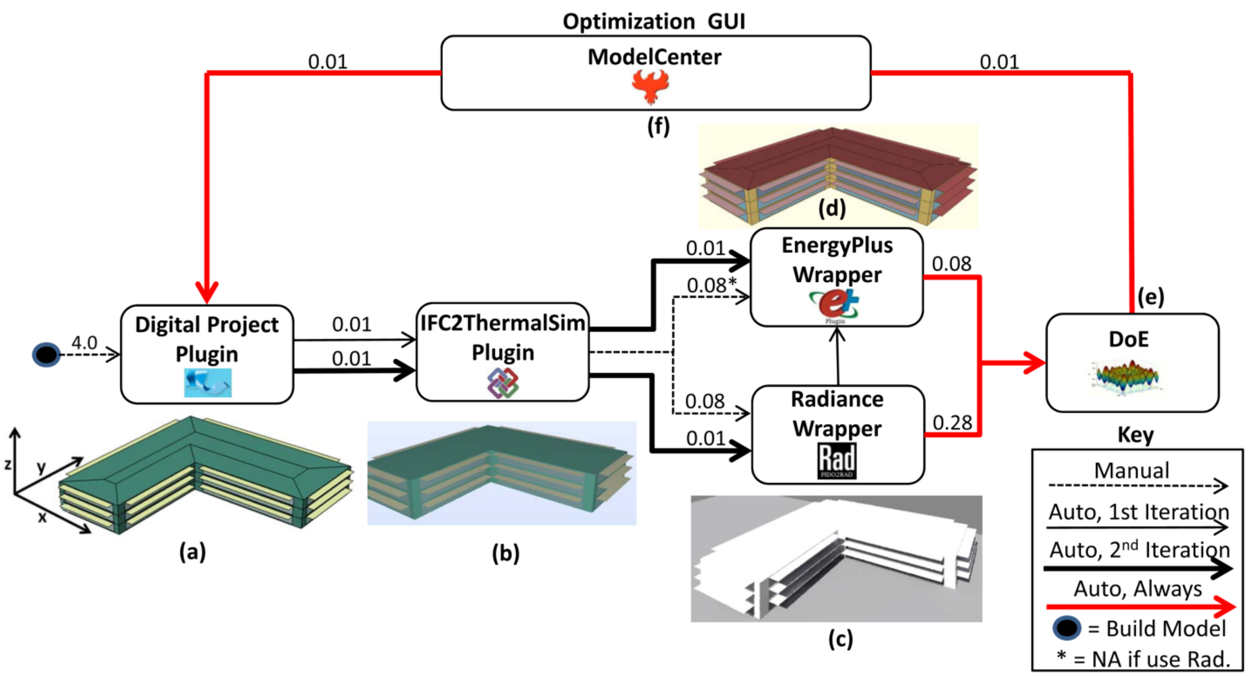

Fig. 12 This diagram shows the test case at each step of the MDO process, as well as the corresponding time. The y-axis represents true north.

In the time required to run the automated trade study, only 6 iterations could be completed using the conventional process because of the lack of automation and distributed computing capabilities. The analysis resulted in predicted optimal overhang depths of 1.5 m on the north facade, 3.5 m on the south facade, 1.5 m on the east facade, 3.5 m on the west facade, and an annual energy cost of $146,050 given the daylighting constraint. The DoE using ThermalOpt took 20.5 hours to complete, with the additional 1.2 hours from the initial estimate due to post-processing requirements. The analysis resulted in predicted optimal overhang depths of 1.0 m on the north facade, 2.0 m on the south facade, 2.5 m on the east and west facades, and an annual energy cost of $134,067 given the daylighting constraint. Table 2 summarizes the results of the conventional and ThermalOpt trade studies. The conventional process was unable to determine the optimal overhang depths as determined by ThermalOpt in the MDO environment, and ThermalOpt was able to evaluate a factor of 680 more design options than the conventional process given similar analysis time. Additionally, the annual energy cost results for the 6 conventional iterations varied from the ThermalOpt results for the same parameter settings by an average of 6%. This disparity may be attributed to the different simulation algorithms used by the various tools as well as the data integration issues described in Section 1.3.

Table 2 Run times, optimal overhang depths, and annual energy cost for the conventional process vs. ThermalOpt.

Design Process	Total Time (hrs)	# Design Iterations	Overhang Depth (North)	Overhang Depth (South)	Overhang Depth (East)	Overhang Depth (West)	Annual Energy Cost
Conventional	19.3	6	1.5 m	3.5 m	1.5 m	3.5 m	$146,050
ThermalOpt	20.5	4096	1.0 m	2.0 m	2.5 m	2.5 m	$136,067

An example of some of the visualizations that can be generated by tools in the MDO environment for the trade study using ThermalOpt are shown in Fig. 13, which describes the impact of modifying overhang depth independently for each orientation on annual electric cooling intensity, DS, annual peak electric demand, and annual energy costs.

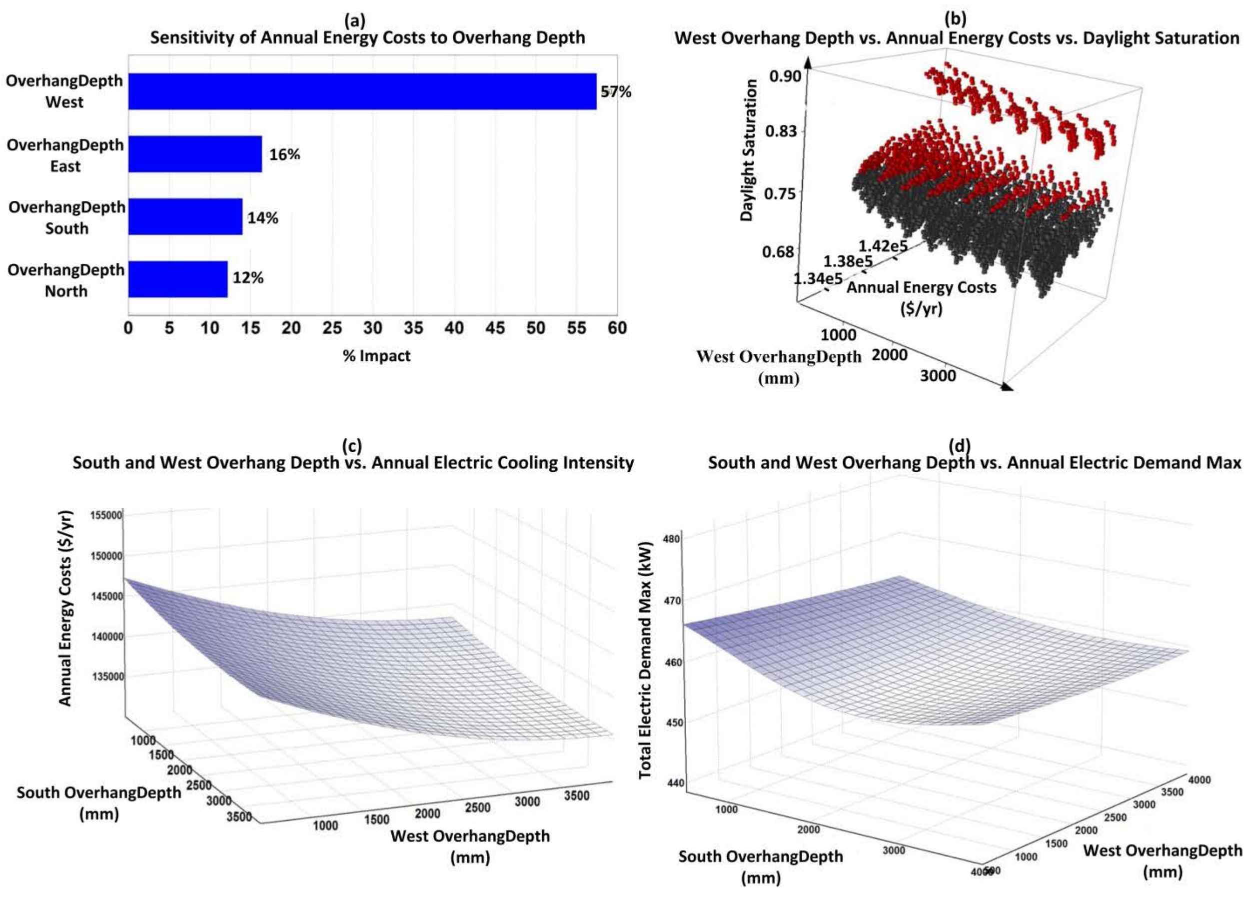

Fig. 13 The impacts of modifying overhang depth independently for each facade orientation on daylighting saturation, annual energy costs, and annual electric cooling intensity.

The results of this test case demonstrate the drastic reduction in analysis time and greater number of design alternatives that can be evaluated using ThermalOpt's fully-automated process for preparation, configuration, execution, and post-processing of analyses, particularly when used in an optimization environment. The test case also reveals the powerful trade study visualizations possible when using an automated design process in an MDO environment.

3.2. Industry Case Studies

The goal of the two industry case studies for this first phase of research was to evaluate the robustness and scalability of ThermalOpt on large, complex, real-world projects to better gauge the potential impact on practice. The emphasis was on the technical capabilities of the individual Plugins/Wrappers focusing on accuracy and consistency of data transfer, and on simulation time requirements. Accuracy of simulation results and on establishing effective MDO methodologies will be addressed in future research.

3.2.1. Industry Case Study #1: Federal Office Building

The first industry case study is a large GSA office building in Washington D.C (Fig. 14). The 7-floor, 500,000 ft2 building is undergoing a major renovation to improve its energy and daylighting performance. The renovation includes a new 105,000 ft2 south-facing glass atrium. The project is targeting LEED Silver certification. Some of the measures that will be implemented are (1) replacing the historic punched windows; (2) adding internal shading devices; (3) installing low-e vertical atrium glass filled with argon; (4) installing photovoltaic glass on the horizontal skylights; (5) adding horizontal external shading devices to the atrium wall; (6) installing daylight controls; and (7) increase wall and roof insulation.

Fig. 14 The GSA headquarters renovation is seeking a LEED Silver Certification. (Image courtesy of GSA)

The first author constructed a Digital Project model of the planned renovation using project drawings and a Revit model provided by the design team, with only minor modifications to the geometry model to meet several of the modeling requirements listed in Section 2.2.1. The IFC file was successfully exported, and is shown in Fig. 16b. Once run through the IFC2ThermalSim Plugin, EnergyPlus Wrapper, and Radiance Wrapper, all the geometry was successfully generated for the analytical thermal models, and are shown in Fig. 16c and Fig. 16d. The EnergyPlus Wrapper was able to configure the analysis for all of the proposed retrofits, and took an average of 4 hours to run using an ideal air load system. The Radiance Wrapper was able to model the internal shading devices, photovoltaic atrium glass (for daylighting impact), horizontal external shading devices, and daylighting controls. The time required to model the implemented systems on a duo-core processor was 4.0 hours in EnergyPlus and 22.0 hours in Radiance. The long simulation time for Radiance was due to every perimeter space being simulated. However, once the option was utilized to specify a sampling of spaces to be simulated and the results scaled to the entire building, simulation time was reduced to 6.0 hours, with similar overall building daylighting performance results.

3.2.2. Industry Case Study #2: Federal Border Station

The second industry case study is a GSA border station in New Mexico (Fig. 15). The 24,000 ft^2 new construction project is being designed to be the first NZE building for GSA and is seeking LEED Platinum Certification. The design incorporates a wide range of passive thermal design strategies, many of them targeted at taking advantage of the large diurnal temperature swings at the site. Passive design strategies include (1) solar chimneys to induce stack ventilation through a tempered underground thermal storage reservoir; (2) solar air preheaters for the solar chimneys; (3) nighttime purge; (4) thermal mass inside the insulation on roof, floor, and wall surfaces; (5) ground-source heat pumps; (6) a sawtooth roof with diffusing shades, baffles, and photovoltaic panels; and (7) various daylighting strategies.

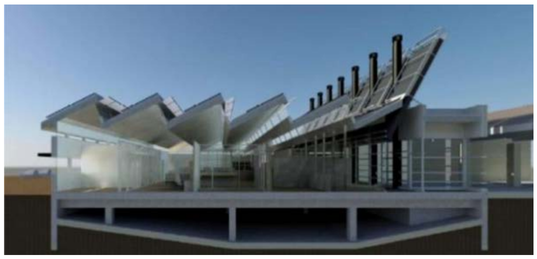

Fig. 15 A new GSA border station will be the first federal NZE building. (Image courtesy of Richter Architects)

The first author constructed a Digital Project model using project drawings and a Revit model provided by the design team. The model required more geometric simplifications than for the GSA office building, including modeling solar chimneys as rectangular columns, solar air pre-heaters as simple shading devices, and sawtooth roof extrusions as individual spaces with bounding floor surfaces. The material applied to the floor surfaces was assigned a construction “InfraredTransparent”, which enables EnergyPlus to model the solar and visible radiation as long-wave radiation. The Radiance Wrapper assigns a visible transmittance of 1.0 for this construction. With these simplifications, the IFC file was successfully exported, and is shown in Fig. 16b. Once run through the IFC2ThermalSim Plugin, EnergyPlus Wrapper, and Radiance Wrapper, all the geometry was successfully generated for the analytical thermal models, and are shown in Fig. 16c and Fig. 16d.

The EnergyPlus Wrapper was able to configure the analysis for all of the proposed systems except for the cross and stack ventilation systems. Due to limitations of EnergyPlus, these systems may only be simulated using complex airflow networks that do not lend themselves well to a fully-automated process. Solar chimneys were modeled the simplified EnergyPlus model. The Radiance Wrapper was able to model the internal shading devices and daylighting controls. The time required to model the implemented systems on a duo-core processor was 0.7 hours in EnergyPlus and 1.5 hours in Radiance.

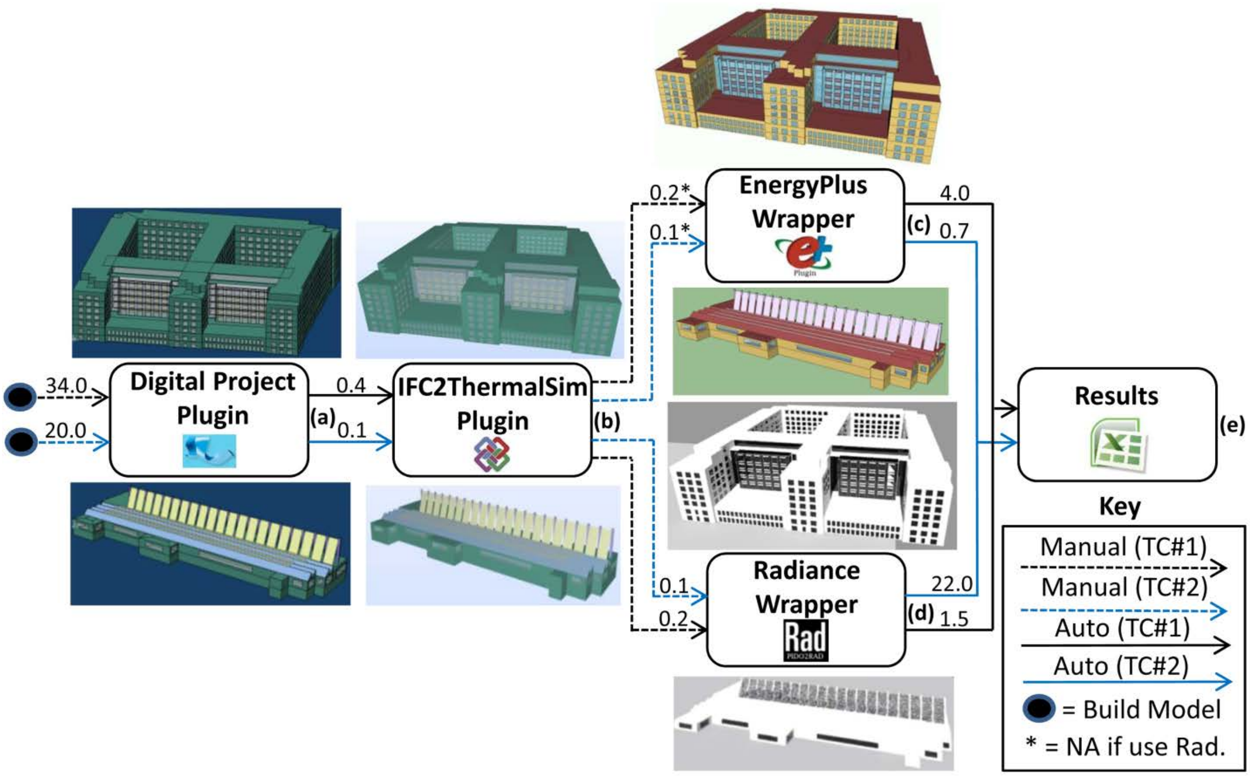

Fig. 16 Both the GSA office building and border station were successfully modeled in Digital Project and the geometry with associated construction/space properties correctly processed through the IFC2ThermalSim Plugin, EnergyPlus Wrapper, and Radiance Wrapper.

4. DISCUSSION AND CONCLUSIONS

This paper presents ThermalOpt - a methodology for automated BIM-based multidisciplinary thermal simulation that attempts to mitigate several technical barriers to BIM-based multidisciplinary thermal simulation found in practice today. The authors' test case and industry case studies demonstrate that ThermalOpt is capable of significantly reducing the time to pre-process, configure, execute, and post-process this design task while improving its consistency over conventional methods. ThermalOpt may be used in an MDO environment to leverage the value in such frameworks from running advanced trade studies and generating useful visualizations for understanding performance trends of a design space. The results of the two industry case studies demonstrate that ThermalOpt is scalable to large, complex, and high-performance buildings. While this methodology does allow for significantly improved design capabilities over current practice, the long simulation time requirements in both EnergyPlus and Radiance for large buildings do limit the application of MDO to evaluate large trade studies in a reasonable amount of time using current simulation engine capabilities and conventional computing methods. Caution must be used in formulating reasonably sized design spaces when using MDO environments to mitigate this issue until advancements in these areas of research reduce simulation time requirements.

Future research will implement the remaining PTD strategies in Appendix A and more advanced HVAC systems to enhance the thermal analysis capabilities of ThermalOpt. The authors are also investigating methods to reduce daylighting simulation times for large models using artificial intelligence (AI), in particular knowledge-based systems (KBS) (Pham and Pham 1999), and distributed computing frameworks. Existing and developing modeling frameworks for combined heat, air, and moisture analysis could also be integrated into this MDO environment (van Schijndel 2009, Woloszyn and Rode 2008, Boukhris et al. 2009).

Finally, throughout the course of this research, the authors have found that the cost-effectiveness and accuracy of an MDO process is highly dependent on designers' ability to flexibly formulate the optimization problem for specific challenges. Designers need to rapidly modify how object parameters are assigned to groupings of objects in the BIM model. This component of flexible problem formulation, which the authors call a *dynamic exchange requirement structure*, is not specifically addressed in MDO literature as a requirement, or defined in available methods. Future research will attempt to fill this gap by developing a problem formulation methodology for automated BIM-based multidisciplinary thermal simulation that enables a dynamic exchange requirement structure for flexible problem formulation (Welle and Haymaker 2011).

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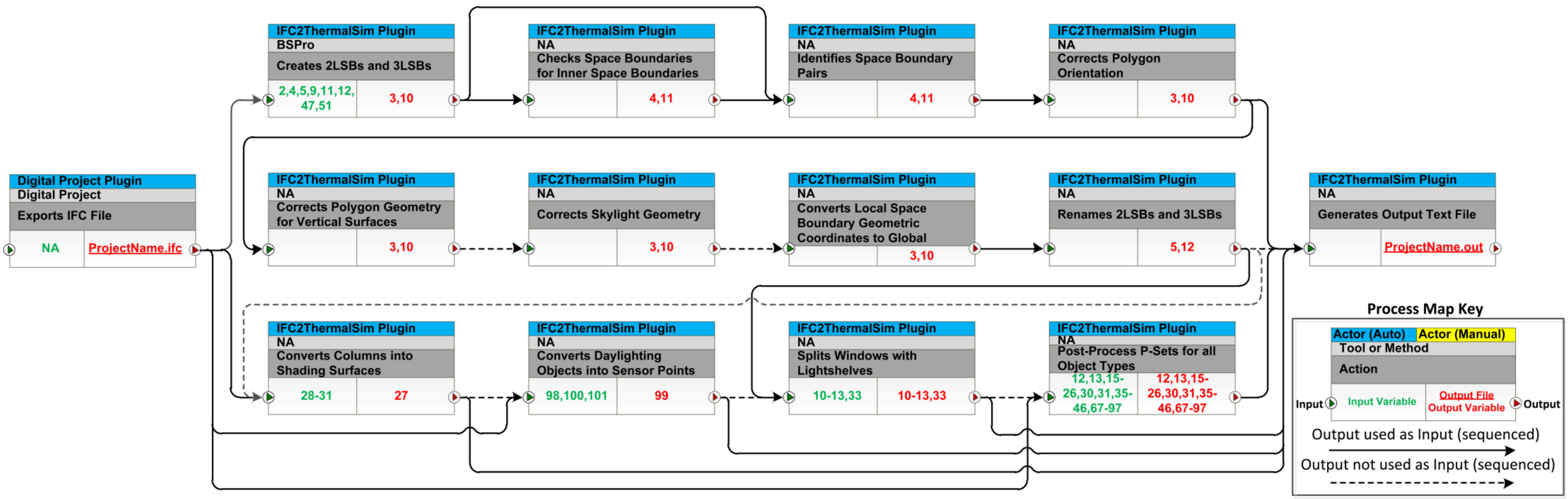
Appendix A
Passive Thermal Design Strategies Supported by ThermalOpt

PTD Strategies	ThermalOpt	PTDStrategies	ThermalOpt	PTD Strategies	ThermalOpt
LoadReduction	-	**PassiveHeating**	-	*EvaporativeCooling*	-
EnvelopeConfiguration	Yes	*DirectGain*	-	*DirectEvaporativeCooling*	-
Overhangs	Yes	InteriorMass	Yes	EvaporativeTower	No
Fins	Yes	*IndirectGain*	-	SwampCooler	No
WindowShading	Yes	TrombeWall	Yes	*IndirectEvaporativeCooling*	-
WindowShadingControls	Yes	WaterWall	No	RoofPondShade	No
ThermalMass	Yes	RoofPond (O/C)	Yes	RoofPondFloatingInsulation	No
GreenRoof	Yes	RoofRadiationTrap	No	SprayRoofDaytime	No
AirBarrier	Yes	SunSpace	Yes	*EarthCoupling*	-
RadiantBarrier	Yes	*IsolatedGain*	-	*DirectEarthCoupling*	-
NighttimeSetback	Yes	NaturalConvectiveLoop	No	EarthSheltering	No
DaytimeSetforward	Yes	**PassiveCooling**	-	*IndirectEarthCoupling*	-
SuperInsulation	Yes	*VentilationCooling*	-	EarthTube	No
EfficientWindows	Yes	StackVentilation	No	*RadiantCooling*	-
DaylightingControls	Yes	CrossVentilation	No	*DirectRadiantCooling*	-
Lightshelves	Yes	OperableWindows	No	ConcreteRoof	Yes
LightTube	No	SolarChimney	Yes	RoofPond (O/C)	Yes
LightWell	No	DoubelSkinFacade	Yes	MovableInsulation	Yes
EnergyGeneration	-	Economizer	Yes	*IndirectRadiantCooling*	-
PV	Yes	NightFlushCooling	No	RoofRadiator	No
BIPV	Yes	RoofVentilator	No	*DessicantDehumidification*	No

Appendix B
IFC2ThermalSim Plugin Process Map



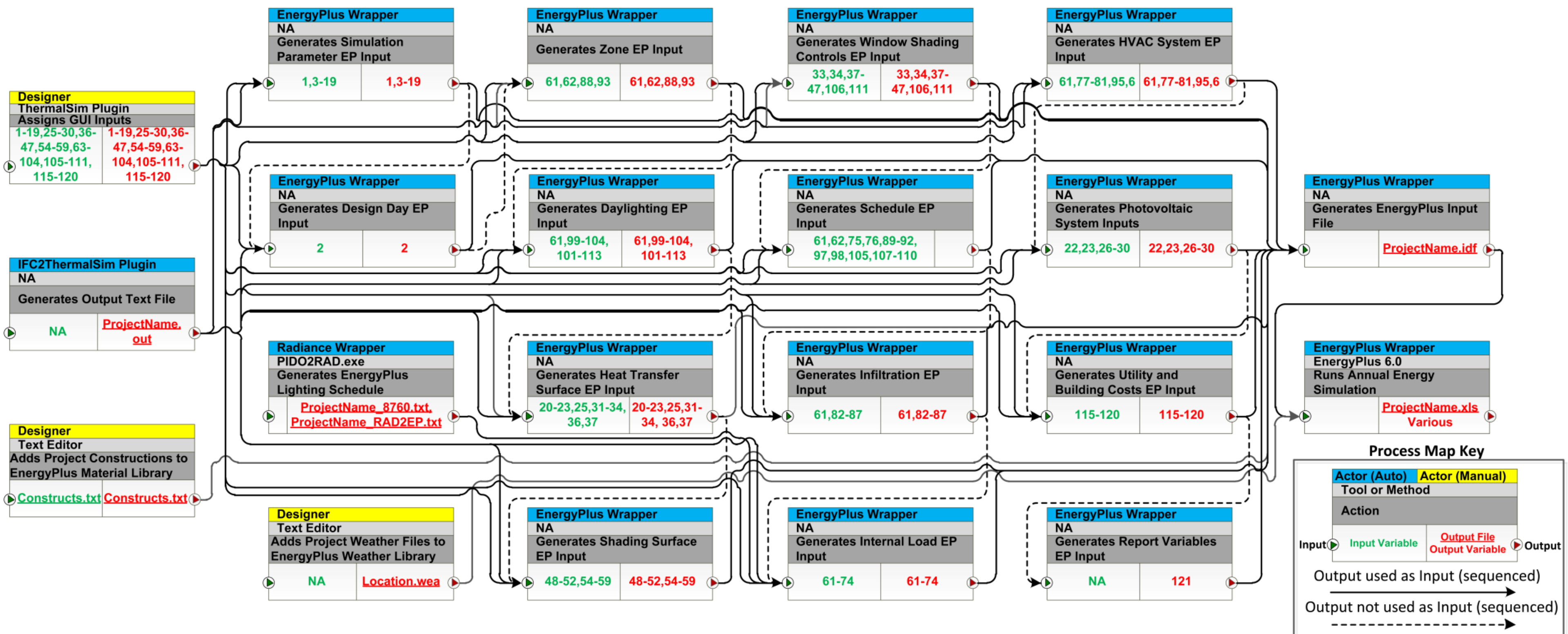
Variable Key

General		OpeningConstructions (cont'd)		ShadingConstructions (cont'd)		ShadingConstructions (cont'd)		Spaces (cont'd)		Spaces (cont'd)		Spaces (cont'd)	
1	ProjectName	15	ConstructionType	30	Surface#	46	BladeAngle	61	OccupancyMethod	77	AirChangesPerHourInfiltration	93	LightingControlType
OpaqueConstructions		16	Shading	31	SurfaceType	***Spaces***		62	PeoplePerZone	78	Conditioning_Requirements	94	PowerFractionMin
2	1LSBGeometry	17	ShadingType	32	HostSurface#	47	ObjectRelationships	63	PeoplePerArea	79	ConditioningType	95	LightFractionMin
3	2LSB/3LSBGeometry	18	ShadingConstructionType	33	HostSubSurface#	48	SpacePerimeter	64	AreaPerPerson	80	CoolingSetpoint_Occupied	96	ControlStep#
4	ObjectRelationships	19	ShadingMaterial	34	ReferenceDirection	49	SpaceHeight	65	SensibleHeat	81	CoolingSetpoint_Unoccupied	97	GlareIndexMax
5	Surface#	20	ShadingControlType	35	ConstructionType	50	SpaceVolume	66	LatentHeat	82	HeatingSetpoint_Occupied	***DaylightingSensors***	
6	SurfaceType	21	ShadingSchedule	36	DiffuseSolarReflectanceUnglazed	51	Space#	67	VentilationMethod	83	HeatingSetpoint_Unoccupied	98	SensorFillGeometry
7	ReferenceDirection	22	ShadingSetpoint1	37	DiffuseVisibleReflectanceUnglazed	52	SpaceType	68	FlowPerZoneVentilation	84	SpaceMultiplier	99	SensorPointGeometry
8	ConstructionType	23	ShadingSetpoint2	38	Glazed	53	LightingMethod	69	FlowPerAreaVentilation	85	HVAC_Systems	100	Sensor#
OpeningConstructions		24	GlareControl	39	FractionGlazed	54	LightingtLevel	70	FlowPerPersonVentilation	86	HVACSystemType1	101	Space#
9	1LSBGeometry	25	SlatAngleControl	40	GlazingContructionType	55	WattsPerAreaLighting	71	AirChangesPerHourVentilation	87	HVACSystemType2		
10	2LSB/3LSBGeometry	26	SlatAngle	41	Louvered	56	WattsPerPersonLighting	72	InfiltrationMethod	88	Clothing		
11	ObjectRelationships	***ShadingConstructions***		42	FractionLouvered	57	EquipmentMethod	73	FlowPerZoneInfiltration	89	AirVelocity		
12	Surface#	27	ShadingGeometry	43	LouverSpacing	58	EquipmentLevel	74	FlowPerAreaInfiltration	90	Daylighting		
13	SurfaceType	28	Footprint Geometry	44	LouverWidth	59	WattsPerAreaEquipment	75	FlowPerExteriorAreaInfiltration	91	DaylightingMethod		
14	ReferenceDirection	29	Extrusion Height	45	BladeReflectance	60	WattsPerPersonEquipment	76	FlowPerExteriorWallAreaInfiltration	92	IlluminanceSetpoint		

Process Map Assumptions (Appendix A, Appendix B, and Appendix C)

1. "NA" implies detail shown in previous process map or no input available.
2. Blank Input Variable boxes signify that all inputs are used.
3. Input Variable box numbers specify subsets of inputs that are used.
4. Output Variable box numbers specify outputs generated for future use.
5. Output Files listed on arrows specify subsets of Output Files are used.
6. Output Variables matching Input Variables signify a modified Input Variable.

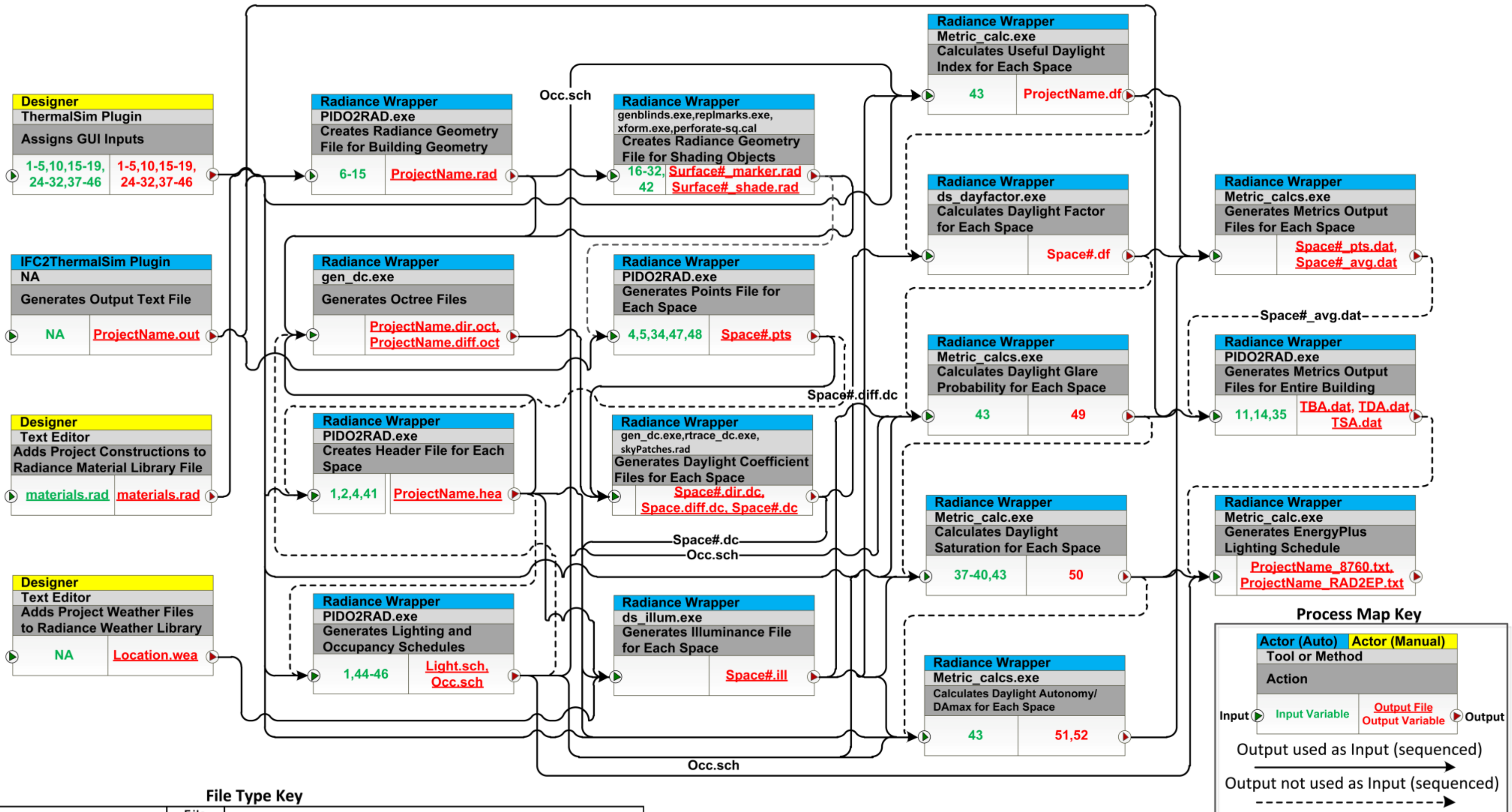
Appendix C
EnergyPlus Wrapper Process Map



Variable Key

	General		OpaqueConstructions		OpeningConstructions (cont'd)		ShadingConstructions (cont'd)		Spaces (cont'd)		Spaces (cont'd)		Economics
1	ProjectName	20	2LSB/3LSBGeometry	39	ShadingConstructionType	58	FractionGlazed	77	VentilationMethod	97	Clothing	115	InterestRate
2	Location	21	ObjectRelationships	40	ShadingMaterial	59	GlazingContructionType	78	FlowPerZoneVentilation	98	AirVelocity	116	ConstructionCosts
3	Year	22	Surface#	41	ShadingControlType		**Spaces**	79	FlowPerAreaVentilation	99	IlluminanceSetpoint	117	ShadingCosts
	SimulationParameters	23	SurfaceType	42	ShadingSchedule	60	ObjectRelationships	80	FlowPerPersonVentilation	100	LightingControlType	118	LightingCosts
4	Timestep	24	ReferenceDirection	43	ShadingSetpoint1	61	Space#	81	AirChangesPerHourVentilation	101	PowerFractionMin	119	HVACCosts
5	InsideConvectionAlgorithm	25	ConstructionType	44	ShadingSetpoint2	62	SpaceType	82	InfiltrationMethod	102	LightFractionMin	120	UtilityCosts
6	OutsideConvectionAlgorithm	26	PV	45	GlareControl	63	LightingMethod	83	FlowPerZoneInfiltration	103	ControlStep#		**Outputs**
7	HeatBalanceAlgorithm	27	PVWatts	46	SlatAngleControl	64	LightingtLevel	84	FlowPerAreaInfiltration	104	GlareIndexMax	121	Output Variables
8	ZoneCapacitanceMultiplier	28	PVType	47	SlatAngle	65	WattsPerAreaLighting	85	FlowPerExteriorAreaInfiltration		**Schedules**		
9	ShadowCalculation	29	PVFraction		**ShadingConstructions**	66	WattsPerPersonLighting	86	FlowPerExteriorWallAreaInfiltration	105	OperatingSchedule		
10	TerrainType	30	PVEfficiency	48	ShadingGeometry	67	EquipmentMethod	87	AirChangesPerHourInfiltration	106	ShadingSchedule		
11	LoadConvergenceTolerance		**OpeningConstructions**	49	Surface#	68	EquipmentLevel	88	ConditioningType	107	LightingSchedule		
12	TempConvergenceTolerance	31	2LSB/3LSBGeometry	50	SurfaceType	69	WattsPerAreaEquipment	89	CoolingSetpoint_Occupied	108	EquipmentSchedule		
13	SolarDistribution	32	ObjectRelationships	51	HostSurface#	70	WattsPerPersonEquipment	90	CoolingSetpoint_Unoccupied	109	OccupancySchedule		
14	NumWarmupDays	33	Surface#	52	HostSubSurface#	71	OccupancyMethod	91	HeatingSetpoint_Occupied	110	HVACSchedule		
15	ZoneSizing	34	SurfaceType	53	ReferenceDirection	72	PeoplePerZone	92	HeatingSetpoint_Unoccupied	111	SlatAngleSchedule		
16	SystemSizing	35	ReferenceDirection	54	ConstructionType	73	PeoplePerArea	93	SpaceMultiplier		**DaylightingSensors**		
17	PlantSizing	36	ConstructionType	55	DiffuseSolarReflectanceUnglazed	74	AreaPerPerson	94	HVAC_Systems	112	SensorPointGeometry		
18	SizingPeriodSim	37	Shading	56	DiffuseVisibleReflectanceUnglazed	75	SensibleHeat	95	HVACSystemType1	113	Sensor#		
19	WeatherFileSim	38	ShadingType	57	Glazed	76	LatentHeat	96	HVACSystemType2	114	Space#		

Appendix D
Radiance Wrapper Process Map



File Type Key

File Type	Description	File Type	Description
.ifc	Industry Foundation Classes (ifc) 2x3 file	.dr.dc	Direct daylight coefficient file
.out	Custom text file generated by IFC Plugin	.diff.dc	Diffuse daylight coefficient file
.rad	Radiance geometry file	.dc	Merged daylight coefficient file using .dr.dc and .diff.dc.
.pts	Daylighting sensor points file	.ill	Space illuminance file
.hea	Header file for DAYSIM	.df	Text file containing Daylight Factors (DF) for all space sensor points
.sch	Text file with 8760 schedule files	.pts.dat	Text file containing Daylight Autonomy (DA), Daylight Saturation (DS), Daylight Autonomy Max (DAmax), Useful Daylight Index (UDI), Daylight Glare Probability (DGP), and Daylight Factor (DF) for all space sensor points, averaged throughout the year
.wea	EnergyPlus weather file	.avg.dat	Text file containing Daylight Autonomy (DA), Daylight Saturation (DS), Daylight Autonomy Max (DAmax), Useful Daylight Index (UDI), Daylight Glare Probability (DGP), and Daylight Factor (DF) for all spaces, averaged across all space sensor points.
.cal	Calcuation file for Radiance.Instructs Radiance on ray instructions.	TBA.dat	Text file with annual daylighting metrics weighted over all building area
.dr.oct	Direct daylight coefficient file	TDA.dat	Text file with annual daylighting metrics weighted over all daylit area
.diff.oct	Diffuse daylight coefficient file	TSA.dat	Text file with annual daylighting metrics weighted over all simulated area
.oct	Radiance octree file		

Variable Key

	General		Opening Constructions (cont'd)		Shading Constructions (cont'd)		Spaces (cont'd)
1	ProjectName	13	SurfaceType	27	GlazingContructionType	41	Daylighting
2	Location	14	ReferenceDirection	28	Louvered	42	DaylightingMethod
3	Year	15	ConstructionType	29	LouverSpacing	43	IlluminanceSetpoint
	Simulation Parameters	16	Shading	30	LouverWidth		***Schedules***
4	DaylightingSpaceMethod	17	ShadingType	31	BladeReflectance	44	OperatingSchedule
5	DaylightingSensorMethod	18	ShadingMaterial	32	BladeAngle	45	LightingSchedule
	Opaque Constructions	19	SlatAngle		***Spaces***	46	HVACSchedule
6	2LSB/3LSBGeometry		***Shading Constructions***	33	Space#		***Daylighting Sensors***
7	Surface#	20	ShadingGeometry	34	SpaceFootprintGeometry	47	SensorPointGeometry
8	SurfaceType	21	Surface#	35	SpaceArea	48	Sensor#
9	ReferenceDirection	22	SurfaceType	36	SpaceType	49	DGP
10	ConstructionType	23	ReferenceDirection	37	LightingMethod	50	DS
	Opening Constructions	24	DiffuseVisibleReflectanceUnglazed	38	LightingtLevel	51	DA
11	2LSB/3LSBGeometry	25	Glazed	39	WattsPerAreaLighting	52	Damax
12	Surface#	26	FractionGlazed	40	WattsPerPersonLighting		

Appendix E
Simulation Parameters for Test Case Trade Study

Operating Hours	7:00 am-7:00 pm Monday-Friday, All Year
Occupied/Unoccupied Cooling Setpoint (°C)	22/29
Occupied/Unoccupied Heating Setpoint (°C)	21/14
Lighting and Equipment Power Density (W/m2)	12.2/16.7
Occupant Density (people/m2)	0.002
Occupied/Unoccupied Lighting Fractions	1.0/0.05
Occupied/Unoccupied Equipment Fractions	0.8/0.05
Occupied/Unoccupied Occupant Fractions	0.8/0.01
Wall Construction Type	2x6 steel frame, R-19 (U-value=.466, R=.3)
Roof Construction Type	100mm heavyweight concrete, metal deck, R-30 (U-value=.178, R=.3)
Base Slab Construction Type	100mm heavyweight concrete, no insulation (U-value=2.3, R=.3)
Window Construction Type	Double-pane, low-e, and air-filled (U-value=2.285, SC=.80, SHGC=.697, Tsol=.633, Tvis=.771)
Illuminance Setpoint (lux)	400
Daylighting Sensor Grid Spacing and Height (m)	1.5/0.8
Key: U-value=Conductance, R=Reflectance, SC=Shading Coefficient, SHGC=Solar Heat Gain Coefficient, Tsol= Solar Transmittance, Tvis=Visible Transmittance	