A SCALABLE LIGHTING SIMULATION TOOL FOR INTEGRATED BUILDING DESIGN

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ABSTRACT

Integrated building design processes involve multiple disciplines and synthesize building designs in an adaptive-iterative manner. To achieve a high quality design, considerations from the various domains occur concurrently and are used collectively to ensure holistic design decisions. However, differing semantics in the disparate disciplines, non-interoperable tools and datasets, as well as the difficulty in accessing tacit expert knowledge across domains pose significant challenges to the integration of cross-domain collaborations. This paper documents our experience in conducting lighting simulation in actual building projects and our development of a scalable lighting simulation tool that demonstrates effective support for integrated design processes.

INTRODUCTION

The use of detailed simulations in architecture design has typically been associated with high costs in terms of time, manpower, training and computational resources (Bazjanac, 2001, Wong et al, 1999, Lam et al., 2004). With the mentioned information and interoperability issues in integrated design, the substantial resource requirements associated with simulations pose significant challenges to their pervasive use. By capitalizing on concepts of Shared Object Models (SOM) and plain-text markup languages (XML), this paper presents how much of the effort in conducting simulations can be automated and typical errors avoided. By using typical scenarios of concurrent energy and lighting considerations in a building project, this paper demonstrates how the preparation of input models for lighting simulations that traditionally take hours or even days can now be completed within seconds.

While simulations are excellent at evaluating the performance of building designs, the varying levels of detail (LOD) and ambiguity as a design develops limit the usefulness of traditional simulation tools and metrics from providing operative information for design decisions. As an example, the progressive availability of various building parameters results in the use of different simulation techniques and consequently not useful to performance tracking and review. This paper shows, by analogy of typical lighting design development that entails energy concerns, how the new design support tool scales effectively and provides operative information for decision making throughout the design process.

Through recounting our experience in conducting lighting simulation in actual building projects, obstacles to using lighting simulation tools are identified. A list of pertinent features is then suggested that may alleviate the low usage in practice. This list is checked against findings in contemporary research and used to guide the development of a new scalable lighting simulation tool. The same use-cases are used to demonstrate the effectiveness of the new tool.

LIGHTING SIMULATION IN INTEGRATED CONCURRENT DESIGN

The Center for Building Performance and Diagnostics, in conjuntion with United Technologies Research Center, developed integrated solutions for a quick service restaurant. To achieve a high performance holistic design solution, the multidisciplinary team collaborated in an integrated concurrent design process. The benefits and challenges of integrated design have been well discussed and documented (NIBS, Lindsey, 2003, Deru, 2004). Concurrent design attempts to reduce the turn-around time and improve the efficiency of such multidisciplinary effort by conducting the various domain tasks in parallel.

From an initial set of design documents including digital 2D CAD drawings and specifications, a series of performance mandates in the various domians were formed. The quantification of desired lighting perfomance led to the identification of appropriate benchmarks and metrics that can be used to evaluate, meaure and compare the appropriateness of various

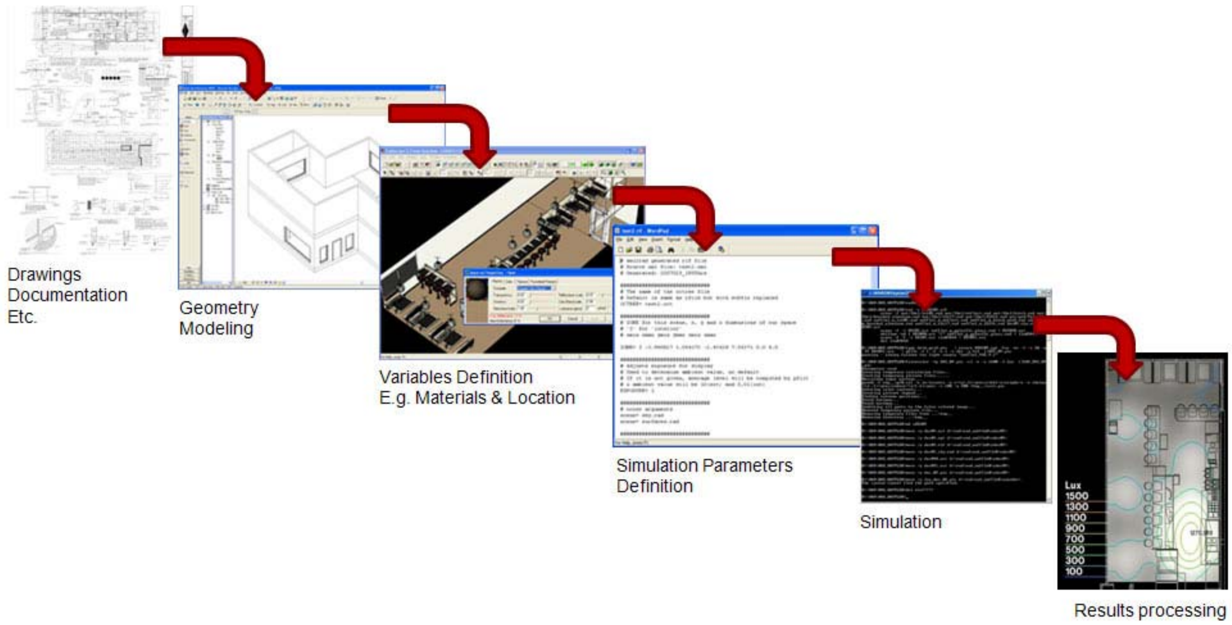

Figure 1 Multiple tools and duplicate entry of data

design strategies. By decomposing the benchmarks and metrics into fundamental radiance and irradiance levels, lighting simulation tools can be used to compute the latter efficiently. However, such results would then require further analysis and processing to become *operative* information; information that is relevant to and allows design decisions to be made. This remains largely a manual and repetitive task. It is noted that this process of problem formulation and analysis of simulation output requires much user expertise and tacit knowledge.

Even when the objectives for lighting simulation are well-defined, there remains much manual work that requires user expertise. The design information, essentially a building model, has to be remodeled with appropriate semantics for lighting simulation. Additional assumptions, such as geometric abstraction and material properties, have to be made. Often, part of this information is related to or duplicated by concurrent work in other domains. The sharing and checking of such information is done manually, error-prone and time consuming. Following the completion of the remodeling, much expertise is required to conduct the simulation and process the results. The entire process is thus time consuming, involves multiple tools and the problem of redundant data-entry and information exchange is further compounded by the non-interoperability of these tools (Figure 1).

Additional impediments to the efficient use of simulation tools in concurrent deign arise from the progressive nature of design development. First, the varying levels of detail (LOD) a design solution possesses as it develops and evolves limit the consistent use of lighting simulation tools and metrics through the stages of design. Since different facets of information are only available or refined at different stages of design, this entails the inevitable use of different performance metrics and corresponding tools at the various stages depending on what information is available. This hinders effective performance comparisons and progress tracking central to implementing integrated processes.

Second, some parameters in each domain task may be dependent on other domains or that information necessary for the tasks may not yet be available at that stage of design. Assumptions made in each domain may be conflicting with related assumptions in other domains, but the level of detail of the design may not yet be high enough for effective conflict resolutions, leading to consequences downstream.

From our experience, lighting simulation tools have shown to be potentially useful in supporting integrated concurrent design, though currently falling short by being too time-consuming and requiring significant expertise and resources to use. The varying LODs a design undergoes throughout the design process also pose significant challenges to effective simulation tool usage. The pertinent points within these two issues are summarized as follows:

Too time consuming

- Semantic differences – redundant effort in remodeling
- Interoperability – difficulty in information exchange between tools
- Operative information – repetitive and difficulty in processing results

Varying LOD

- Consistent metrics – difficulty in implementing consistent technical method
- Information availability – missing information and difficulty in error-checking

In this exercise, we used three tools: EnergyPlus and Desktop Radiance from Lawrence Berkeley National Labs, and Lightscape Visualization System from Autodesk. Identical tasks were performed on all three tools. To model the effects of daylighting, EnergyPlus uses an enhanced split-flux which is based on a series of averaged values that approximate the effects of geometry and material properties in contributing to interior illumination. Desktop Radiance employs backward ray-tracing where virtual paths from each pixel of the final image are traced backwards into the scene following the behavior of reflections and refractions geometrically. In Lightscape, the radiosity model follows the principles of radiative heat transfer theory and solves an equation where each surface in the scene emit, receives and transfers light energy with all the other surfaces, but with equilibrium within the scene.

While the above mentioned findings (too time consuming and difficulty in handling LOD) were consistent for all tools, the different technical approaches, implementations and interfaces however, were noted to present varying opportunities and constraints in conducting lighting simulations within the integrated concurrent design context. A summary of the comparison between the three tools is presented in Table 1.

Table 1 Comparison of three tools

	EnergyPlus	**Desktop Radiance**	**Lightscape**
GUI	Limited, 3rd Party	Yes	Yes
CAD Import	No	Yes	Yes
Additional Modeling	Yes	Yes	Yes
Technical Method	Enhanced Split-flux	Global Illumination	Global Illumination
Simulation Time	3 min to simulate 1 year (8760 time-steps)	60 min to simulate 1 scene (1 time-step)	60 min to simulate 1 scene (1 time-step)
Graphical Post-process	No	Limited[1]	Yes
Results Output	Yes	Yes	No
Model Output	Open-source code and input/ output formats	Open-source code and input/ output formats	Proprietary code and input/ output formats
Batch Processing	Yes	Yes	Limited[2]

[1]Simulations produce either illuminance or luminance values, not both. Static analysis renders only of false color and iso-contour plots. No numerical value grids, averages nor interactive sampling.

[2]Proprietary formats inhibit batch processing input files for the similar scenes but different times or locations. Similar output format restricts batch processing results for analyzes.

LITERATURE REVIEW

Using modeling tools (Bazjanac, 2001) was found to be a difficult, time-consuming and error prone process. The effort to prepare for simulation and analysis of results was noted to be mostly manual and tedious, and accounted for almost all the effort and time spent; computational effort and time was insignificant by comparison. Geometry acquisition was particularly noted to be difficult, accounting for up to 80% of the effort in input preparation. While the findings were based on energy modeling, the similar nature of tasks and functionalities of tools available for lighting allow the findings to be applicable to the lighting domain.

Correspondingly, research (Augenbroe 1991, 2001) and industry surveys (Wong et al, 1999, Lam et al., 2004) have revealed a low usage of modeling tools in industry. The reasons for such included:

- Large amounts of data inputs were difficult and time consuming to prepare
- Outputs difficult to interpret and apply in design decision making, requires expert knowledge to translate to design information
- Difficult to ascertain level of accuracy

Contemporary lighting simulation tools (Ubbelohde, 1998, Kopylov, 1998, Roy, 2000, Bryan, 2002, Estes, 2004) were found to have the following shortcomings:

Difficult to use

- Hard to learn, frustrating to learn many tools
- Geometric input tedious and error prone

- Required inputs difficult to obtain
- Modeling limitations
- No feedback on accuracy
- Output difficult to interpret

Does not support integrated, concurrent design processes

- Difficult to transfer data between domains
- Does not validate assumptions
- Difficult to conduct parametric analysis
- Difficult to transfer findings between domains

For physically accurate tools, only Radiance, Lightscape Visualization System (since then acquired and discontinued by Autodesk, Inc), and Inspirer from Integra Inc. (not distributed in United States) were mentioned. All the tools require significant effort in remodeling building geometry. “Simplistic” tools such as Lumen Micro from Lighting Technologies Inc. often achieve user-friendliness at the expense of accuracy, often to the extent of being unsuitable for use in architecture design. At the other extreme, the highly accurate Radiance tool was difficult to use, requiring much training and time to use well.

A recent survey (McGraw-Hill, 2007) shows that 28% of building firms in the United States use Building Information Models (BIM) and estimates this figure to grow to 49% by 2009. The main motivation cited by the respondents to adopt BIM is the ability to reduce costs by spending less time reentering data manually and other repetitive tasks, and improving communication among stakeholders. The survey also notes an average of 49 hours spent per project on building codes checking and a significant industry interest in automated code checking technology.

A NEW LIGHTING SIMULATION TOOL

Based on the findings from the use of lighting simulation tools and literature review, a new lighting simulation tool is developed with the objective of reducing the time and effort required to use lighting simultaion tools in integrated concurrent design. This is achieved by making the tool 1) interoperable with other tools so that it can exchange and reuse information modeled in other tools regardless of semantics, 2) scable such that valid assumptions are used and that consistent metrics can be used notwithstanding the availability of information in various LOD, 3) provide funtionalities to process simultion results into operative information automatically, and 4) easy to learn and use throughout all stages of design.

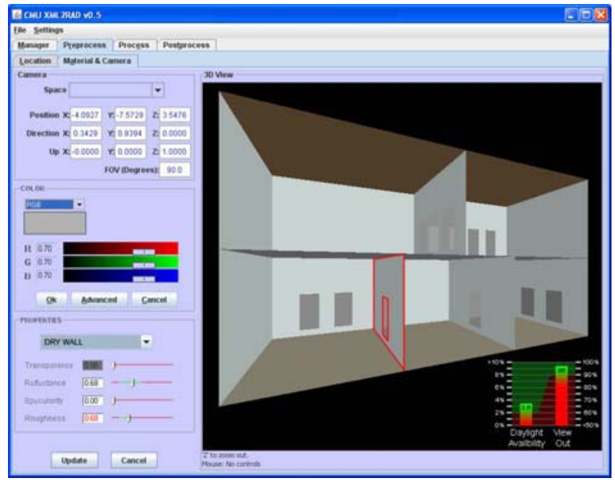

Figure 2 A new lighting simulation tool

Interoperability

Efficient information exchange and reuse is achieved by capitalizing on developments in Shared Object Models (SOM) and plain-text markup languages (XML). A model schema that is comprehensive enough to include all necessary information and semantically compatible with the diverse domain views, yet lightweight enough for efficient query and use, is developed by extending the gbXML schema (GBS, 2002) to include lighting information. This XML-based schema is used to construct a holistic BIM that is implemented across the design team as a SOM. The SOM can then be can be parsed into several lightweight domain specific Domain Object Models (DOM) by the different tools.

The new tool implements a semantic translator that parses the SOM automatically to form a DOM suitable for use by lighting simulation. There is now a seamless sharing and reuse of building information between the design tool (Revit), the energy tool (EnergyPlus via GreenBuildingStudio), and the new lighting tool (Figure 3). By eliminating the need for manual remodeling, error- and consistency checking, the single largest obstacle and time/effort-cost of using lighting simulation as mentioned in the earlier discussions is avoided.

Following the principles and benefits of utilizing a SOM, similar project-wide, application-independent datasets of construction types, materials, location and sky information are developed. The same extended XML-based schema is used to organize this information to ensure portability and ease of parsing.

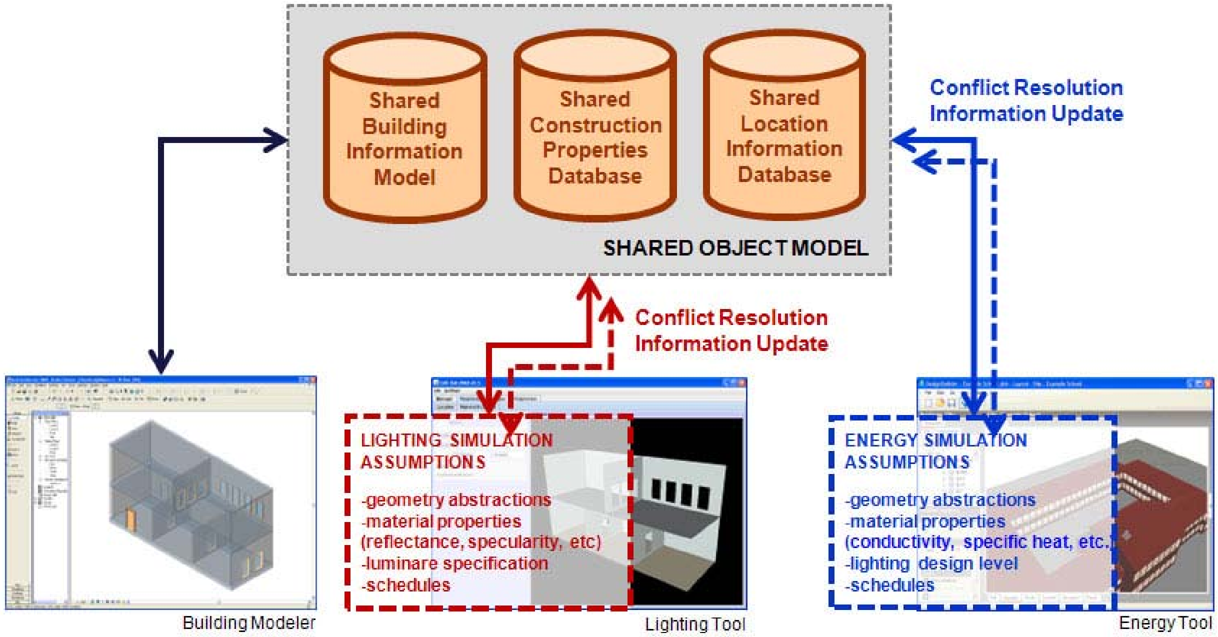

Figure 3 Error and consistency checking across domains via SOM

Together with the SOM, these data sets are shared across the project team. The use of common datasets across the design team can then ensure consistency in assumptions made in each domain. Specific user definition of variables and parameters can also be validated against these datasets automatically without the need for user intervention.

Scalability

To overcome the problem of incomplete or missing information due to the LOD of design, the idea of using appropriate placeholders is used to ensure a well-formed model at all times. This allows the use of a consistent benchmarks and metrics throught the design process. By completeing the SOM with information from the implemented external datasets, consistency between the various DOMs is ensured. This enhances concurreny since dependency between tasks is reduced, and the potential downstream problem of impossible specifications and products is avoided.

Given the fact that the building industry typically employs a relatively limited variety of standard practices, the preparation of this shared data set is relatively straightforward. A rule-based algorithm is used to populate the SOM by querying the shared datasets according to available information and the context of such information. In cases where the required information is absent from the dataset, a nearest-neighbor search allows the selection of appropriate values. The entire process is automatic and instantaneous; there is no need for user intervention to review the SOM or search for appropriate and consistent assumptions, the time and effort to prepare a well-formed lighting model is greatly reduced.

The problem of LOD, where information in the DOM is missing due to the stage of design, is essentially reframed as that of level of confidence (LOC), where the BIM is used keeping in mind that certain assumptions have been made. Scalability is achieved since a consistent methodology is used regardless of the level of information availability and precision. The use of LOC may also be more consistent with professional practice considerations such as due diligence and consistent with the progressive nature of design.

Operative Information

Besides the fundamental radiance and irradiance values, the new tool identifies common useful lighting codes and benchmarks to better provide operative information for design decisions. The additional benefit of using codes and benchmarks is that they eventually have to be evaluated during design submissions. Currently, codes and benchmarks are seldom used as performance metrics during design development because their calculation is often time consuming, both in terms of computation as well as documentation. The LEED rating system is a popular benchmark for high performance green buildings and includes two credits for lighting performance: daylight availability (EQ 8.1) and external view availability (EQ 8.2) in building spaces.

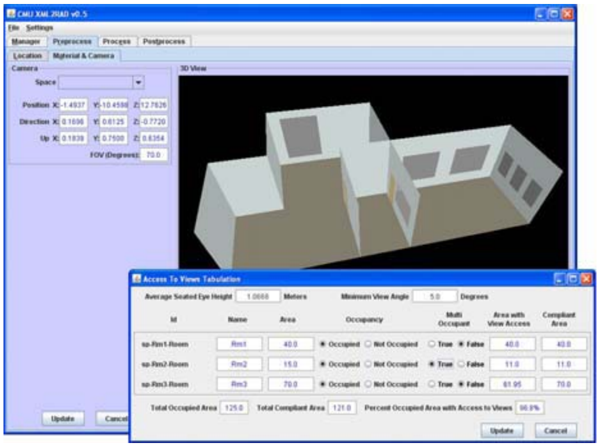

Figure 4 Automatic calculation of LEED EQ 8.2

To provide operative information in a timely fashion, the new tool formulates the two LEED credit procedures as computable problems, and optimize them for fast automatic evaluation. The typical LOD problem where nescessary information is only available in the later stages of design development is avoided by the LOC approach discussed earlier. The new tool calculates both credits in a matter of seconds and this information is available throughout all desgin stages (Figure 4).

The new tool also supports parametric studies and provides post-processing features including false-color, luminance and contrast ratio visualizations, various tone mapping functions, as well as results comparisons to provide metrics and analyses supporting typical lighting design decisions.

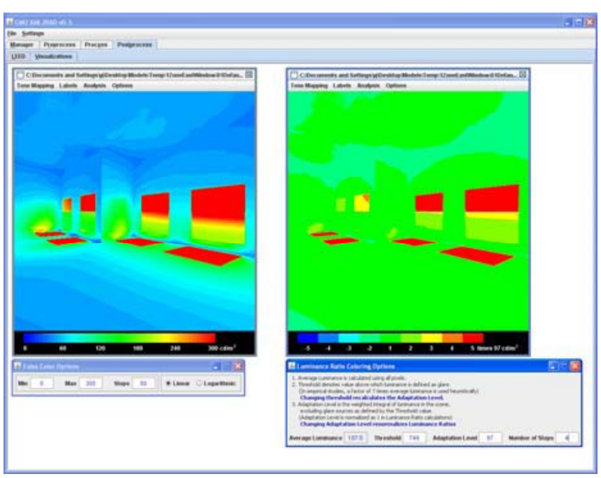

Figure 5 False-color (left) and luminance ratio (right) analyses. Corresponding feature options GUI below each image

User Interface

The design (Figure 2) of the graphical user interface (GUI) reinforces the workflow of simulations and the display of parameters is flexible to reflect the changing LOD along different stages of design. In keeping with the notion of LOC, the GUI employs color coding to cognitively distinguish between user specified values and those that are populated automatically by querying the datasets. Similarly, the recommended ranges of values for various parameters are presented in the same manner.

To facilitate faster cognition of the context of various attributes, the new tool uses an interactive 3D model viewer to let users inspect and edit the information. The tabulation of the LEED benchmarks are also dynamically linked to this viewer; changes made to the model results in an instantaneous update of the LEED evaluations. The tabulation format of these benchmarks is also consistent with submission requirements. This contributes to the reduction of common time consuming manual activities.

To improve the ease of use of the tool, help menus and documentation within the GUI makes explicit some of the tacit knowledge in conducting simulation. Together with the mentioned recommended value ranges and color-coding, the inspection of parameters and use of appropriate values is made easier; there is no need for additional research or depend on user expertise. Another objective of the documentation is to avoid the inappropriate use of metrics by highlighting the underlying methodologies in a succinct manner (Figure 6).

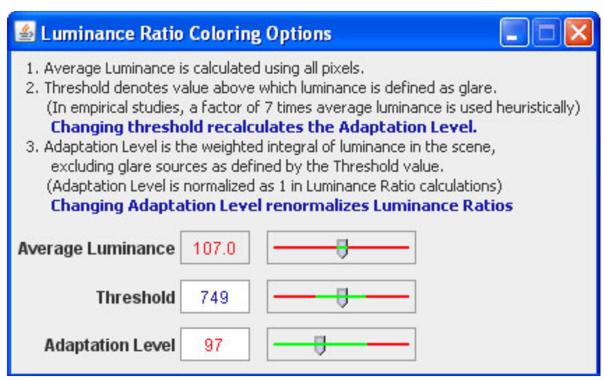

Figure 6 Luminance Ratio GUI

DEMONSTRATIVE USE

Two use-cases demonstrate the use of the new tool and the drastic reduction in time and effort required to use lighting simultaion tools in integrated concurrent design. In the first case, a lighting simulation is performed on a preliminary sketch design to assess the suitability of particular design strategies. In traditional practice, a lighting model would first have to be built from the design model, and missing attributes in the model researched and populated. Depending on the simulation tool to be used, appropriate input files will then have to be prepared from the lighting model. After successful simulation, the results will then be analyzed to provide information in suitable performance metric. The entire process would typically take hours if not days, even when excluding simulation computation time. The user is also expected to be highly trained with much domain expertise and knowledge.

When using the new tool (Figure 7), the building model that serves as the project SOM is exported from the design CAD tool in a XML-based format. This is parsed by the new tool automatically to build a lighting DOM. The necessary geometry processing and population of missing information based on the externalized data and contextual rule sets are performed instantaneously and without any user intervention. The user can inspect and edit all parameters if desired. In the case where LEED performance benchmarks are used, the results are available within seconds. In the case that a detailed simulation is desired, all necessary input files are prepared automatically. Once simulation computation finishes, the tool provides a host of analysis and visualization features to aid the generation of operative information from the simulation output. The entire process, excluding simulation computing time, takes only seconds, and is almost completely automatic. In comparison, there is no need for special training or expertise requirement when the new tool is used.

Figure 7 Existing design model from external CAD software (left). Automatic processing and population of missing values instantaneously and without user intervention (middle). Simulation results and analysis (right).

In the second use-case, lighting simulation is performed on developing design; simulation is used to guide decisions on optimal strategies. Multiple domian considerations are undertaken concurrently following the tenets of integrated design. In this case, the user is forming a better understanding of the design problem and exisiting (partial) solution. By making minor changes in the model, the user might test his theories inductively and perhaps arrive at new ideas for improving performance. In this case, updates in the performance metrics should be fast, ideally in real-time. In traditional practice, the time-constraint is a major obstacle given the multiple manual tasks described in the first use-case. Since contemporary lighting simulation tools do not explictly support parametric studies, the entire process has to be duplicated for each design iteration. The time consuming process of analyzing lighting performance also impedes the workflow of comparative design investigations.

When using the new tool, the lighting model is prepared effortlessly as demonstrated in the first use-case. In the case that the SOM is repeatedly changed, the same workflow in the previous use-case applies. For parametric studies on lighting related parameters on the same SOM such as time and material properties, the new lighting tool includes a parametric files generator that automatically generates a sequence of simulation input files and a single batch file to execute the sequence of simulation runs.

The provision of fast LEED rating calculations (Figure 4) supports comparative studies by providing performance metrics dynamically and continuously. As an example, both LEED calculations and tabulations are updated within seconds when changes, such as material properties, are made to the model. Such metrics are available regardless of the stage of design and LOD of the SOM. Post-processing features such as comparison of simulation outputs are also available in the new tool to facilitate and reduce the time and effort in parametric studies.

CONCLUSION

The implementation of a project-wide SOM and data sets allows the new tool to achieve unprecedented interoperability for lighting tools. By automating previously manual modeling and conflict resolution tasks, the new tool drastically reduces the time and effort required to prepare lighting simulations.

The concept of LOC and innovation in formulating the LEED benchmarks as computable within seconds make consistent performance metrics available throughout all design stages. The list of post-processing features is similarly geared towards providing operative information that enables design decisions within time-frames suitable for design processes.

While the Radiance rendering engine is currently used for radiance and irradiace calculations, the benefits from the LEED benchmark algorithms suggest advantages in developing a new simulation engine.

The new engine should model lighting physics more comprehensively and allow performance metrics to be calculated more effectively; the metrics should be computed in time frames complementary to design processes and presented dynamically like what has been done for the LEED benchmarks.

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