Energy-Oriented Design Tools for Collaboration in the Cloud

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Abstract

Emerging from the challenge to reduce energy consumption in buildings is the need for energy simulation to be used more effectively to support integrated decision making in early design. As a critical response to a Green Star case study, we present DEEPA, a parametric modeling framework that enables architects and engineers to work at the same semantic level to generate shared models for energy simulation. A cloud-based toolkit provides web and data services for parametric design software that automate the process of simulating and tracking design alternatives, by linking building geometry more directly to analysis inputs. Data, semantics, models and simulation results can be shared on the fly. This allows the complex relationships between architecture, building services and energy consumption to be explored in an integrated manner, and decisions to be made collaboratively.

1. INTRODUCTION

It is well recognized that to mitigate climate change, global energy consumption must be reduced dramatically. Buildings are currently the focus of many initiatives concerned with achieving energy reduction targets, since they consume a significant portion of delivered energy and are responsible for the most avoidable carbon emissions [1]. Recent research in the US exposes the building sector as the single largest emitter of greenhouse gases, responsible for almost half of all CO_2 produced [2]. Operational energy consumption accounts for approximately 90% of building emissions; estimated to contribute greater than 40% of all energy-related carbon emissions in the US and 33% globally [2,3]. Much of this operational energy can be attributed to the building services that maintain indoor comfort, making them the obvious target for energy reduction strategies.

Passive design measures must be employed to minimize reliance on these building services. This necessitates improved methods for designing, analyzing, and optimizing buildings, which support collaborative exploration of the relationships between architecture, comfort and operational energy. Integrated design systems that engage simulation as a decision-support tool are therefore needed, to enable the performance impacts of design choices to be quantified in a manner that accounts for building complexity realistically and reliably. This is particularly important in early design as the decisions made at this time determine around 80% of the environmental impacts and operational costs of a building [4].

Presently, however, no tools exist to meet the performance analysis needs of both architects and engineers in early design, let alone streamline the interactions between disciplines. Interdependent limitations in process and software inhibit the integration required to understand building performance and establish performance-oriented design practices. Energy simulation is typically employed to resolve building services and verify performance, and, as a result, most simulation software supports services optimization tasks that arise late in the design process. Rather than providing relative comparisons of design alternatives, as is needed early on, these tools focus primarily on deriving precise and absolute data about building performance after the design is finalized. Targeted at engineers, the majority of simulation applications have limited capacity to interface design knowledge across disciplines.

In response to this problem, we propose a novel system for streamlining the connection between architectural design and energy analysis, by linking building geometry more closely with analysis inputs, using parametric modeling to facilitate an interactive and iterative simulation process. The research that we present in this paper has been carried out as part of an Australian Federal Government funded project concerning the integration of building services constraints in early architectural design. This project is a collaborative effort involving Queensland University of Technology and RMIT

University, along with Project Services, a multidisciplinary building design and project management division of the Queensland Government Department of Public Works. Researchers from the two universities, who have backgrounds in architecture and computer science, collaborate with practitioners from Project Services in the disciplines of architecture, services engineering and IT. Two objectives guide this collaboration. The first is to provide designers with responsive performance feedback during the design process, to improve decision support and facilitate better-performing design outcomes. The second is to develop a framework that embeds performance constraints in the architectural design process, in a manner that supports the transdisciplinary exchange of knowledge. Inherent to this is the need for an integration environment that recognizes the uniqueness of individual building design projects and project teams, and supports flexibility in the configuration of both the design process and the technology that enables it. Recent advances in distributed 'cloud' computing facilitate the modularity needed in digital tools and processes to support this flexibility.

In the following section we present a case study that employed a simulation-based design strategy to assist with Green Star[1] certification. This case study is used to highlight problems with information exchange mechanisms currently engaged in contemporary practice, and inform the development of new strategies for supporting collaborative design and simulation processes.

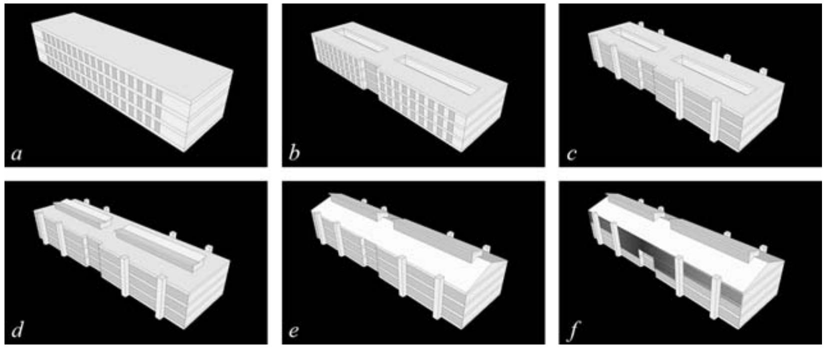
2. INTEGRATION CHALLENGES IN PRACTICE

Project Services has recently demonstrated the practical benefits of engaging energy simulation early in the design process. Their Joint Contact Centre (JCC) project, a 5100m^2 office building located in Brisbane for 24-hour call support of non-emergency police matters, has been awarded the highest Green Star rating ever given to an office building in Australia, achieving 92 points out of a possible 105. This outcome was accomplished largely through operational energy reductions arising from early performance investigations of design alternatives.

Coupled with this energy-oriented design strategy was an integrated Building Information Modeling (BIM) approach to the documentation and management of the project. Autodesk's Revit suite was used for the building modeling and, due to its established link with this design software, IES Virtual Environment (VE) was employed for the simulation. Forty-five design scenarios were modeled and analyzed; the six most significant of these can be seen in Figure 1. Tradeoffs between spatial organization, and HVAC, lighting and structural systems were explored, to obtain an optimal building solution with respect to satisfying program requirements and minimizing energy usage.

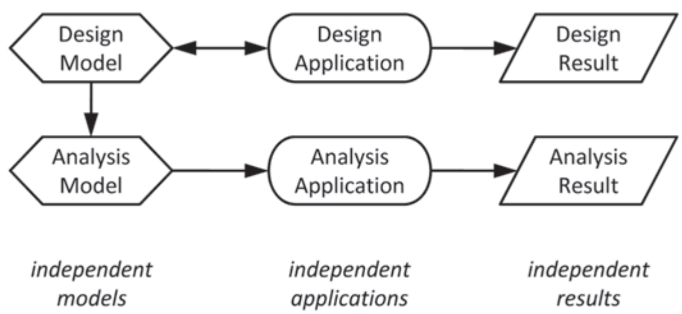
[1] Green Star is an environmental rating system that evaluates the environmental design and construction of buildings in Australia (http://www.gbca.org.au/green-star/green-star-overview/).

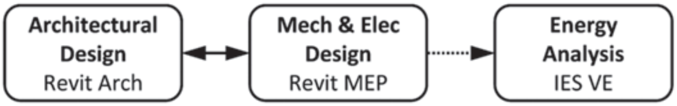
► Figure 1: Progression of the JCC design. a: floor to ceiling height of 4.5 meters. b: floor to ceiling height of 3.5metres with central unenclosed atria. c: addition of cooling towers. d: enclosed central atria. e: roof pitch of 23°. f: addition of window shading.



While this process demonstrated the effectiveness of simulation as a decision-support tool, a number of factors restricted the degree of integration achieved. These factors related primarily to the exchange of information between domains, and highlighted limitations typical of BIM-based integration strategies. Following conventional BIM practice, a *data model interoperation* approach was adopted for information exchange. In this approach, applications share data through a static instance, or series of instances, of the product model [5]. This is accomplished either through model exchange, via a neutral file format that serves as a generic common representation between applications (such as IFC or gbXML), or model sharing, where data is supplied to and extracted from a central model repository as required [6]. Figure 2 shows how this scenario results in design and analysis models being developed separately. In the JCC project, a model exchange strategy was employed, with gbXML files exported from Revit to IES-VE. Accordingly, performance evaluation was observed to be two steps removed from the architectural design process, as illustrated in Figure 3. This separation prevented interaction between domains, and gave rise to data redundancies and inconsistencies. Furthermore, since exchanges were unidirectional, from design to analysis, performance feedback could not be returned to the design environment to inform architectural decision making directly.

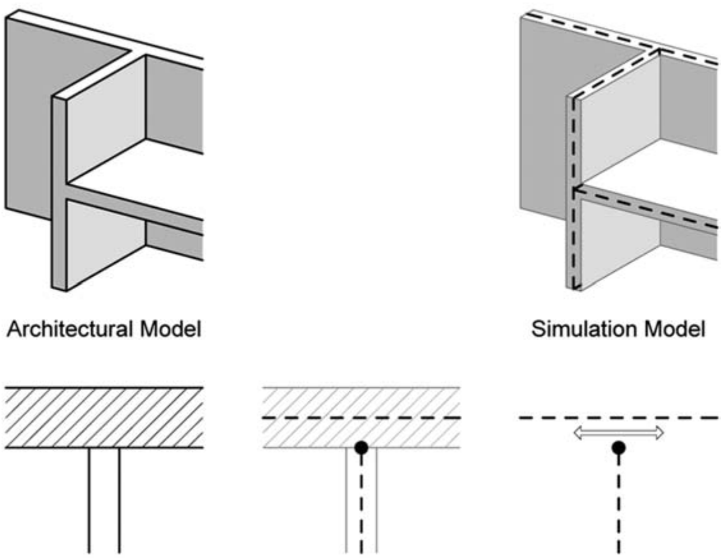
► Figure 2: Data model interoperation: in model exchange, the design model is a stand-alone file; in model sharing, it is a central data repository.





◀ Figure 3: Performance evaluation process for the JCC project.

Information exchanges were also subject to translation issues arising from different representation paradigms [7]. Transformations between design and analysis representations were found to be unreliable and to result in model inaccuracies. Figure 4 shows an example of how a 'gap' was generated at a number of wall intersections when the centerline surface geometry required for the simulation model was extracted from the solid geometry of the BIM. A simple change in wall construction prevented the centerlines from connecting in the BIM, and caused two physically separate spaces either side of the abutting wall to be treated as a single space in the simulation model. This produced significant errors in the simulation results. In addition to these transformation issues, the detailed BIM data structure proved too complex for early design, containing information superfluous in a simulation environment, while simultaneously lacking certain data required for carrying out performance assessment.



◀ Figure 4: Example of a transformation error moving between representation paradigms.

Beyond problems of information representation and exchange, there were also issues with software. While Revit has some capacity for parameter-driven modeling, it lacks an underlying associative structure that hierarchically links the geometry of each component to that of another which came before it. Without high-level parametric dependencies between objects, updates could not be propagated through the design automatically, and manual rebuilding of the model was needed for each option tested. Limitations were also experienced with the simulation software. The VE-Toolkits, software in the IES suite targeted for use in early design, could not be used as their underlying simulation defaults did not reflect the Australian context and were not editable. VE-Pro, the more comprehensive version of the software, intended for use in the later design stages, had to be used instead. It required detailed information to describe the simulation, often not reusable between alternatives. Analyses were therefore time consuming and labor intensive to carry out. Furthermore, the complex and numerical nature of the interface made translation of models and results a non-trivial task that constrained the designers' ability to understand and decide between alternatives.

It was also found that members of the project team had limited knowledge of the requirements of other disciplines, particularly concerning model inputs and outputs. The digital tools and processes employed did little to support the communication of this information or structure the interaction between design tasks and performance analysis. Without a common framework for investigation, the relationships between design and performance could not be explored collaboratively. This exposed the need for more integrated digital processes and tools that promote communication and enable seamless and dynamic interaction across domains.

3. LEARNING FROM THE AEROSPACE INDUSTRY

In the aerospace industry, digital processes for integrating design and analysis are engaged to a greater degree and more effectively. Karl Sabbagh, in his book "21st Century Jet: The Making of the Boeing 777", describes the inception of computerized aircraft design, and development of the processes that enabled aircraft components to be designed, assembled and simulated virtually [8]. Contrasting earlier design methods, which relied on physical mock-ups and permitted only limited opportunities to assess the compatibility of components, these new processes allowed aircraft designs to be tested and refined iteratively to optimize performance. Formerly disjointed design teams were unified by the newfound ability to visualize the aircraft holistically and identify dependencies between components that previously would not have been detected until construction. This led to interactions between people that would otherwise not have had reason to collaborate, and the formation of cohesive multidisciplinary design teams. The knowledge gained as a result of this process was immense, as were the savings in time and cost.

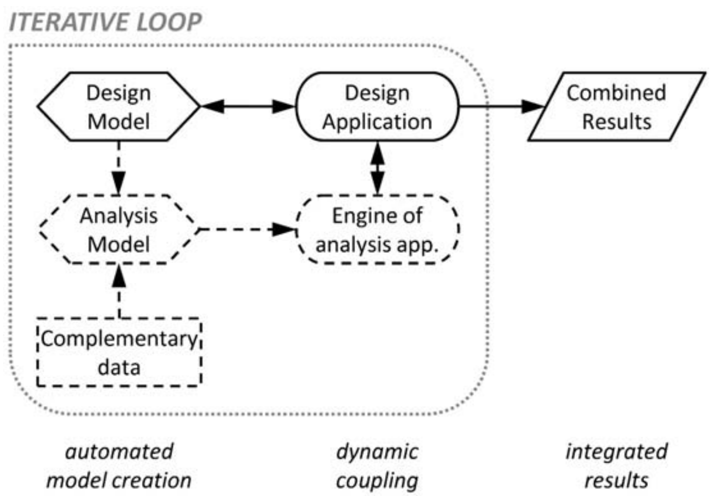
These processes have since been formalized into a methodology known as Multidisciplinary Design Optimization (MDO). The defining characteristic of MDO is that the contributions of all mutually-influential disciplines are taken into account simultaneously rather than sequentially [9]. Integrated environments for synthesis allow various digital tools to be used concurrently for design and analysis, with parametric definition of geometry playing an integral role in facilitating the iteration required to search for a system-level optimum [10]. These flexible process platforms employ wrapper and parser technologies to enable direct communication between applications and ensure the congruence of data between task-specific sub-models [11]. This coupling of design and analysis applications to automate the simulation process realizes higher productivity and improved performance outcomes [12].

While MDO methodology was originally developed for use within large conglomerate organizations typical of the aerospace industry, there is no reason why it cannot be employed within the more heterogeneous organizational structures found in the construction industry. The inherently modular nature of MDO processes, along with recent advances in distributed computing, enables adaptation of this methodology to suit the diversity of building design projects and project teams. Although the building product is not subject to comparable standardizations of form, assembly and materials seen in aircraft, recent research from Stanford has demonstrated the application of MDO to building design to result in similar benefits for design process and outcomes [13]. Expanding on this research is DesignLink, a computational framework for MDO developed by Arup [14]. This domain-independent platform uses customized plug-ins to couple parametric modeling and performance analysis applications for trade-off evaluations of constraints [15]. At present however, there is a predominantly structural flavor to the analysis software linked to the platform, and a focus on the translation of geometry between domains.

In this paper, we seek to build on existing research by examining how MDO principles can assist building performance optimization with respect to operational energy consumption. We exercise a limited implementation of MDO that investigates this specific aspect of building performance and its relationship to architectural design, to demonstrate how integration might be achieved between domains where geometry is not necessarily a common foundation. The energy-oriented design system that we propose incorporates three key MDO features: a process coupling framework; deconstructed representations; and parametric geometry definition. Each of these is discussed in the following subsections.

3.1. Process coupling framework.

A design environment that enables dynamic feedback between domains is essential to performance-oriented design. The use of a *data and process model cooperation* framework for exchanging information facilitates this feedback. Programs are effectively coupled by providing the faculty to link to other applications at run time [5]. Rather than mapping to a generic file format, such as with conventional IFC-based strategies for interaction, translation between software is direct. This removes the potential for translation errors that arise when mapping to formats not native to the applications being linked. As illustrated in Figure 5, one program controls the evaluation process and invokes the other application as required, automatically generating simulation models and performing analyses [6]. This approach is often supported between related simulation fields; in this research, we propose an extension of its typical application to provide integration with the design domain.



► Figure 5: Data and process model cooperation.

3.2. Deconstructed representations.

To avoid issues of data redundancy between domains, the building description is distributed across a series of sub-models that correspond to each coupled program and satisfy their individual information requirements. This decomposition contrasts the centralization that is becoming increasingly entrenched in building integration practice. It differs from the BuildingSMART concept of Model View Definitions, which describes different user perspectives of the IFC representation, in that it proposes domain-specific models rather than domain-specific views of the same model [16]. Since each sub-model is generated from a specific transformation procedure, it contains only information required for a defined task, in a defined format. Redundancies arising from the complexity of a comprehensive data standard like IFC are therefore avoided.

3.3. Parametric definition.

Representations are defined using high-level parametric dependencies. By structuring components through associative relationships, models can be manipulated to generate new options without manual rebuilding of the design, enabling large numbers of alternatives to be created in short spaces of time [17]. To ensure a common direction for investigation, a unified conceptual framework that identifies key parameters influencing performance must be established. We have identified seven factors critical for investigating energy performance in early design:

1. Thermal Zones (used as the geometric construct rather than rooms);
2. Glazing and Skylights;
3. External Shading;
4. Construction Types;
5. Internal Gains for Occupancy, Equipment and Lighting;
6. HVAC Systems; and
7. Weather and Environment.

These parameters must be examined in combination to gain a complete understanding of building energy performance.

4. REVIEW OF ENERGY SIMULATION TOOLS

Despite the proliferation of energy simulation programs in recent decades, there are few tools that provide integrated decision support in early architectural design. Reasons for this are well established in literature, and have been reported by the authors in an earlier research paper [18]. The problem can be summarized as a lack of connection to the needs of the designer, brought about by highly complex, non-visual and unintuitive working environments that cater primarily to engineers. Over the years, this issue has engendered a number of studies into the identification of 'designer-friendly' and 'design-integrated' criteria for simulation tool development and categorization, most notably from Augenbroe [19,20], Morbitzer [21,22] and Attia [23,24].

These two classifications are often treated as being mutually exclusive because the term 'designer-friendly' is typically used in a narrow sense to describe simplified simulation tools that lack the resolution required for engineering tasks, therefore precluding the capacity to be 'design-integrated'. From a more objective outlook, the question that stands to be asked is: Could a simulation tool be *both* 'design-integrated' and 'designer-friendly'?

In this research, 'designer-friendly' is taken not to mean simplified simulation tools, but rather, features that allow simulation tools to be used in simplified ways; typically related to interface usability and information management. This distinction ensures that the simulation needs of the architect can be met without compromising the integrity of the analysis or the needs of the engineer. While 'designer-friendly' functionality is important for the development of the system as a whole, it does not factor in the selection of a simulation tool, as the program coupling approach engages only the calculation engine of the application.

'Design-integrated' requirements, on the other hand, are critical for tool selection. These criteria outline features required to ensure reliable simulation procedures and outcomes; as well as functionality essential for the development of process networks that support the delegation of tasks to applicable system modules, and the coordination of results. Three critical integration criteria have been identified:

1. The ability to simulate the latent heat associated with high humidity climates, like those found in Australia, and the HVAC systems used to accommodate these environmental conditions;
2. The use of validated methods of calculation;
3. The capacity for software extension and customization via an Application Programming Interface (API) or scripting interface that makes the application accessible remotely.

Another consideration in the selection process is the approach that the tool adopts for information exchange. While most applications are either stand-alone or interoperable, with no or limited intrinsic ability for design integration respectively, several tools do implement a process coupling strategy. Any tool adopting this approach, as well as satisfying all three critical criteria, could benefit the development of an integration platform greatly. The degree of reusability in the system would, however, depend on the modeling paradigm of the coupled design software, i.e. whether it has the capacity for high-level parametric associations. Therefore, in addition to the three critical criteria, there are also two further desirables:

4. A coupling approach to information exchange;
5. A direct link to a parametric design environment (applicable for coupled tools only).

The results of the review against the five criteria are shown in Table 1. It should be noted that tools whose integration with CAD data is limited to the import and/or export of DWG/DXF files containing simplified geometry are considered stand-alone in this context. Also, with the coupled tools, the criteria concerning customization relates only to the coupling link, not to the underlying simulation engine.

► Table 1: Fulfilment of selection criteria by energy simulation tools.

SIMULATION TOOL	AUSTRALIAN CONTEXT	VALIDATED CALCULATION	SOFTWARE EXTENSION	INTEGRATION APPROACH	PARAMETRIC DESIGN
DeST	?[1]	✓	?[1]	Stand-alone	N/A
DOE-2.1E	✓	✓	✓		
Energy-10	×	✓	×		
EnergyPlus	✓	✓	✓		
eQUEST	×	✓[2]	✓		
ESP-r	×	✓	✓		
DesignBuilder	✓	✓[3]	×	Interoperable	N/A
Ecotect	×	×	✓		
GBS*	×	×	×		
Hevacomp	✓	✓[3]	×		
IES VE-Pro	✓	✓	×		
Tas	✓	×	✓		
Trace 700	✓	✓	×		
EcoDesigner	×	✓[4]	×	Coupled	×
IES VE-Toolkits	✓	✓	×		×
OpenStudio	✓	✓[3]	×		×
Project Vasari	×	×[5]	?		partial

** GBS — Green Building Studio*
[1] Program is only available in Chinese
[2] Application is interface to DOE-2.2
[3] Application is interface / plug-in to EnergyPlus
[4] Application uses the ASHRAE-compliant VIPweb analysis tool
[5] Application uses the Ecotect and GBS simulation calculations

As can be seen in the results, DOE-2.1E and EnergyPlus (E+) are the only applications that satisfy all three critical criteria. While DOE-2.1E is preconfigured for high-resolution assessment, E+ is a modular program that does not assume a level of simulation resolution [25]. E+ is therefore better suited to early design and has been selected for the system. Despite lacking inherent integration capabilities, significant research exists to demonstrate that extensibility is readily achievable.

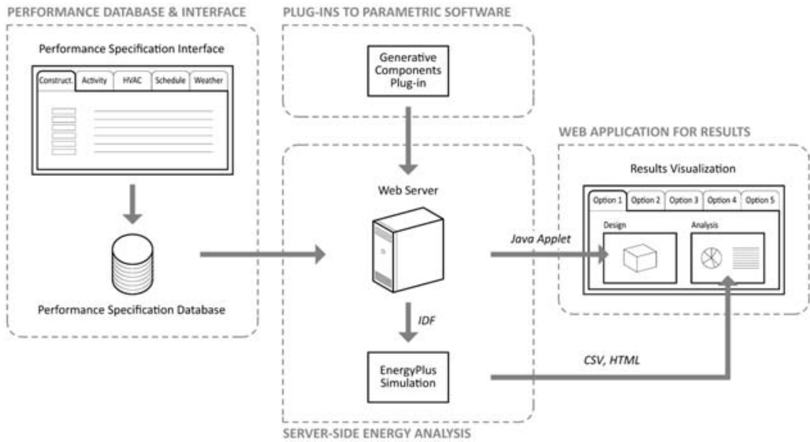
While none of the coupled programs satisfied all critical requirements, they do reveal a promising trend towards more integrated simulation environments. Their success in achieving this integration is, however, limited. OpenStudio allows E+ building geometry to be created and analyzed directly from within SketchUp; however, it is unable to handle all critical simulation inputs, and necessitates additional expertise in using E+. EcoDesigner integrates the VIPweb engine directly into ArchiCAD's program core, but is configured to act as a design aid rather than a simulation tool. The VE-Toolkits are accessible via plug-ins for both SketchUp and Revit, however, similar to VE-Pro, customization and extension is not possible. At first glance, Project Vasari appears more promising. It integrates analysis into a Revit-based design environment modified to provide 'push/pull' modeling capabilities and basic parameter-driven manipulation, and provides exceptional results visualization. However, it precludes any potential for integration with engineering domains by employing unverified Ecotect and GBS simulation procedures considered unreliable by engineers. It is also unclear whether this tool has the capacity for customization, as it has only been released as a technology preview.

In the following section, we present the structure for a design system that actively addresses the downfalls observed in existing simulation applications by engaging the key principles of MDO methodology.

5. PROPOSED DESIGN SYSTEM

DEEPA (Dynamic Energy-Efficient Parametric Architecture) is a cloud-based design system that couples parametric modeling and energy simulation software to create a decision-support tool for early design. Guided by the context of Project Services, DEEPA addresses the need for more integrated digital design processes and tools, as identified in the Green Star case study, by streamlining the generation of building geometry and analysis inputs. It responds to the multidisciplinary design environment found in Australian public practice, where projects are highly diverse and project teams are often dispersed across different Project Services branch offices and external consultancies, by supporting flexibility in the configuration of both the system technology and the design process that it enables.

The structure of the DEEPA system (which is currently under development) is illustrated in Figure 6. This openly customizable environment establishes a dynamic and cooperative design process by linking applications through a cloud-based integration platform. Here, a database automatically assigns building geometry the behavioral attributes required for energy simulation. This allows analytical models to be generated from design representations without the need for expert interpretation and translation, so that the modeling environment can invoke the simulation process directly. Evaluation occurs in close to real time, with results being pushed to a web application that displays design options and performance outcomes side-by-side.



► Figure 6: Structure of the DEEPA system.

The DEEPA system is designed using the service-oriented paradigm of cloud computing and hosted in the cloud. Cloud computing refers to the delivery of computing as a service, rather than a product, through the integration of software and resources over the Internet. Developers of cloud applications deliver their software through remote data centers and network infrastructure provided by third parties. These computing resources are purchased as fully-outsourced services on a utility basis, much like the purchase of electricity. The ability to re-provision resources to meet demand as required allows dynamic scalability of the system. Cloud services are accessed by users over the Internet, via client applications utilizing web technology (such as web browsers), eliminating the need to install software on local user machines and simplifying maintenance and support. Client applications can be consumers of multiple services, and by combining data and functionality from different sources can generate new 'mashup' services.

In DEEPA, the data, semantics, models and simulation results required for and produced by the energy simulation process exist as cloud services. Clients can be either the consumers or suppliers of data and/or functionality to these services. In our prototype, we have developed a plug-in for GenerativeComponents that consumes data required for energy simulation, such as thermal properties for different constructions, and publishes model data for simulation procedures. We are also prototyping a web interface that consumes simulation data produced by E+ to generate a visual mashup of energy analysis results. Other developers might use the DEEPA services to develop plug-ins for different modeling and simulation software or extend the web interface to include visualization of performance results other than operational energy consumption. Regardless of how the services are engaged, DEEPA allows these resources to be shared and developed by users as required.

The system consists of four key components, discussed in the following subsections.

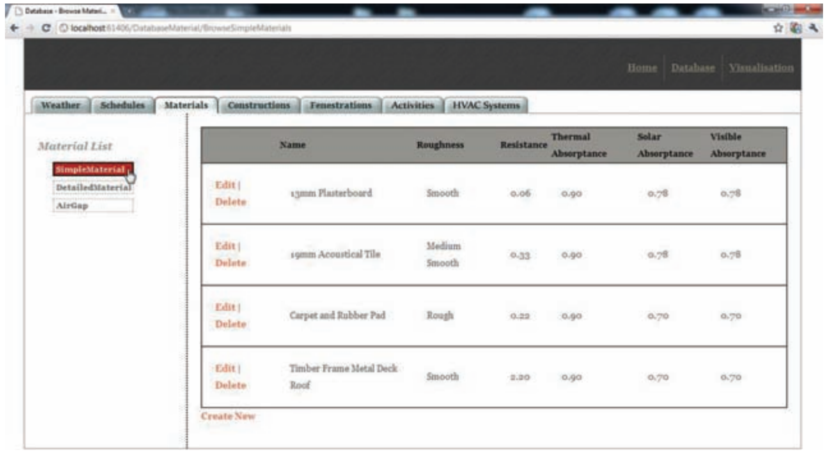
5.1. Performance specification database

The performance specification database is essential for ensuring that building geometry acquires the behavioral attributes required for simulation, without complicating input requirements for the user. It separates the numerical simulation data from the design model, allowing designers to focus on the manipulation of form. The user populates and edits the database through a graphical interface that has data organized into tab separators, as seen in Figure 7, for each of the following:

- *Weather*: to define the weather data to be used in the simulation calculations.
- *Schedules*: to define the hours of occupancy and systems operation.
- *Material Types*: to define the thermal properties of different types of materials.
- *Construction Types*: to define the combination and position of materials within the building.
- *Fenestration Types*: to define the properties of various window systems and glazing materials.
- *Activities*: to define the internal gains for occupancy, lighting and equipment, as well as ventilation rates, for each activity being housed.
- *HVAC Systems*: to define the climate control systems being used in the building.

One of the primary downfalls of existing analysis applications targeted for use in early design is that default simulation data is largely hidden from the user and usually only suits the climate and context in which the program was developed. This creates unnecessary inaccuracy in the simulation description and results. The performance specification database allows this problem to be avoided by providing users with the freedom to define their own attribute data. It also facilitates data reuse between projects.

▶ Figure 7: Web-based interface to database.

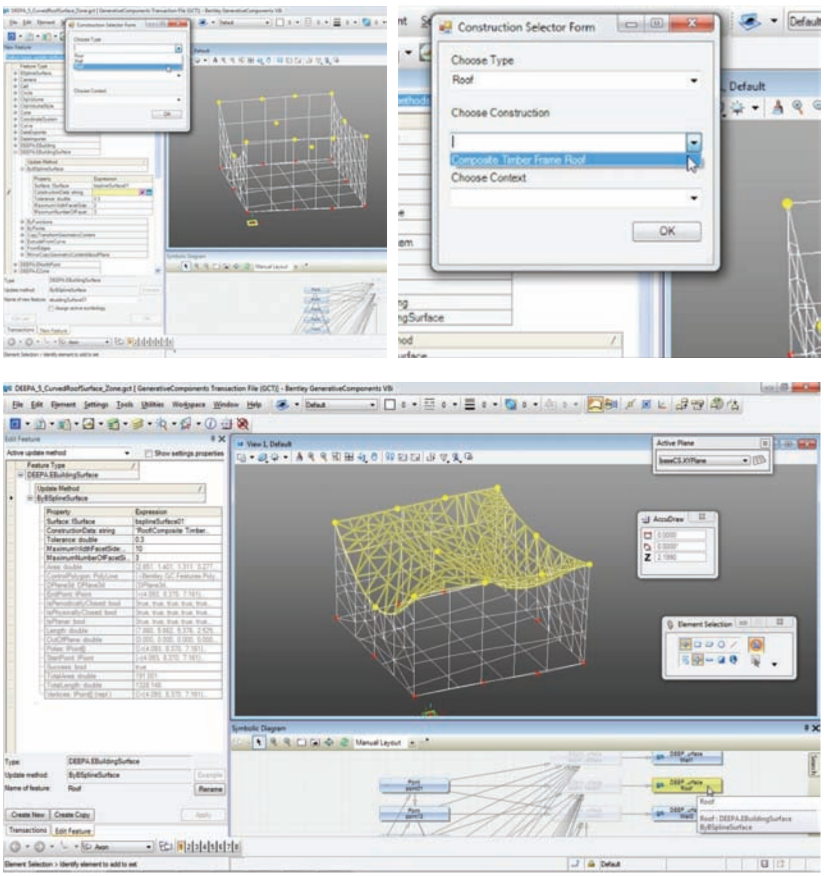


The Database Management System is implemented using SQL Server 2008, running in a sandbox and hosted on a web server operating Windows 7. The web-based interface for populating the database uses ASP.NET MVC 2 technology. WCF Data Service technology is implemented to allow data to be accessed by client applications. As a cloud service, the database allows concurrent access by multiple users who can either be populating the database or consuming its data to generate simulation models. The protocol of the data service is an XML web service which allows direct communication on port 80, the only port open in a firewalled network such as that found at Project Services.

5.2. Custom plug-in for parametric design software

Two of the high-level parametric design applications currently used in practice and research that have a low entry cost point, and are therefore accessible to the full range of small scale design practices, are GenerativeComponents (GC) and Grasshopper (a parametric plug-in to Rhinoceros). Given that GC has a well-tested extensibility, a long-standing ability for compiling new features and a built-in capacity for integration with BIM, this modeling application has been selected for the development of the DEEPA.

Additional features are embedded inside GC to ensure that design models can correctly generate corresponding analytical representations and that the simulation process can be invoked. Energy analysis requires the building to be described as a series of zones defined by closed sets of planar surfaces, to which behavioral properties must be attributed. Since high-level parametric design tools are geometry-based rather than structured around building components, they do not recognize the simulation constructs of 'zone' and 'surface'. New representations have therefore been created. A 'surface' is based on the geometry of a polygon, with the addition of an inbuilt 'construction' property to allocate conductance values. A 'zone' adopts a solid geometry to represent its internal space, and requires the additional properties of 'activity' and 'HVAC system' to determine internal gains and services loads respectively. Within GC, these properties are simply tags assigned to the geometry, as seen in Figure 8, to avoid overcomplicating input requirements for the user. Once the plug-in invokes the energy simulation procedure, however, the database is queried for the relevant attribute data for each tag, along with additional information concerning weather and building scheduling. This information, along with the geometric data from the model (which undergoes an orientation transformation to ensure correct ordering of surface vertices), is then forwarded to E+ for analysis.



◀ Figure 8: Custom plug-in for GC

The current prototype includes several custom features to facilitate rapid creation of simulation-compliant geometry. As well as generating simple planar surfaces, these features are designed to accommodate quite complex geometry through surface-faceting techniques that create a collection of planar surfaces to approximate bspline geometry, as seen in Figure 8. If this geometry were to be input manually into an E+ file, each facet would need to be defined individually, with its respective geometry, surface type, construction, and building context. Instead this feature enables automated creation of thermal surface definitions by associating each child planar facet with the properties of the parent bspline feature.

Aside from providing custom features that enable the creation of simulation-compliant geometry, the plug-in acts as a middleware between the performance specification database and GC. The inputs in the Construction Selector Form, seen in Figure 8, are populated in real-time using client-side access to the WCF Data Service published on the web server.

5.3. Server-side energy simulation

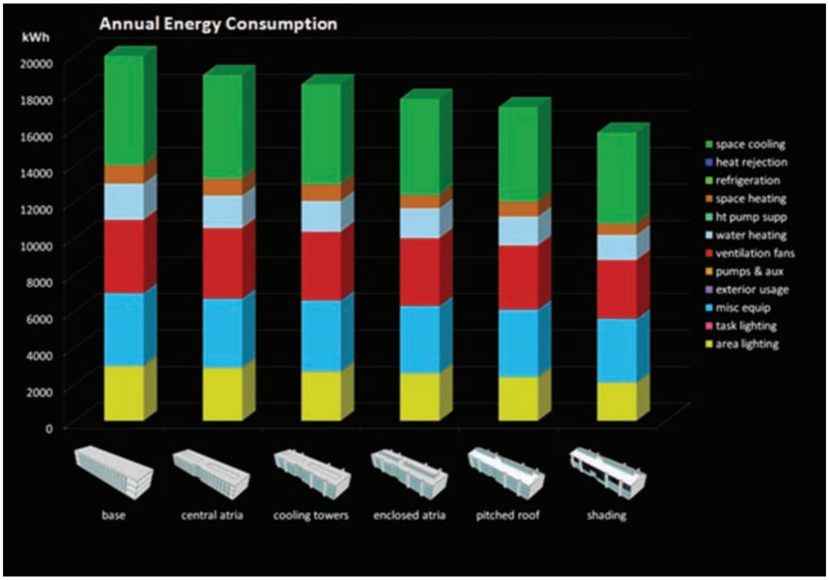
E+ performs analysis on a text-based representation of the building data known as an Input Data File (IDF), created when the simulation procedure is invoked. As the simulation is invoked from inside GC, the IDF is constructed on the fly with geometric data from the GC model and attribute data from the performance specification database. Simulation results and user information are stored in the database for each simulation run, along with the geometry from the parametric model at that point in time. This ensures that a snapshot of the design is captured for every simulation that is performed, to facilitate the tracking of design options, their respective performance results and the users that created them.

5.4. Web application for results visualization

As well as displaying the results of the energy analysis, this web application is also embedded with a Java applet that displays the stored geometry, so that design options and performance outcomes can be viewed side-by-side by multiple users. In this manner decisions can be made collaboratively. At the time of writing this article, the current DEEPA prototype generates simulation results as CSV files and webpage reports. Future works include the development of a web interface that facilitates visualization of the results in a more intuitive way, a mock-up of which can be seen in Figure 9. We also intend to return simplified simulation results to GC to provide the designer with direct access to performance outcomes within the design environment.

6. KEY BENEFITS

The DEEPA system provides a process-oriented design integration environment that enables collaborative assessment of building energy performance in early design. It offers a reliable means by which to compare the performance of early design alternatives so that more informed decisions can be made. The modular structure and use of distributed technologies facilitate a rapid, flexible and efficient simulation process, as



◀ Figure 9: Comparative visualization of energy simulation results

well as allowing system resources to be accessed, developed and shared by users as necessary.

Four key benefits are expected from the DEEPA system:

- **Collaboration:** Members of the design team are able to work in parallel to generate the building description and evaluate design alternatives. By structuring the interactions between design and analysis tasks, process and information dependencies will be more readily apparent, and a more holistic understanding of building energy performance will be possible. With design and analysis outcomes being published to a common web application, different team members will be able to review options simultaneously and make decisions collaboratively.
- **Iteration:** By integrating energy simulation into a parametric modeling environment, design options can be produced and assessed rapidly, allowing more alternatives to be considered.
- **Scalability:** The system accommodates various usage scenarios, from a single user working on a local computer to multiple users accessing the database, server and results, and can swap between modes of operation at any stage.
- **Customization:** Within the DEEPA environment, users are able to define their own attribute data in the performance specification database to reflect the unique requirements of individual projects and project teams. In addition to this, all aspects of the DEEPA system and services are customizable and can be extended as required by users to include further capabilities and features.

We are currently looking into open-sourcing DEEPA so that it can be publicly available. This presents challenges related to data integrity, security and versioning that require further investigation. However, it also presents a very significant opportunity – the potential for the development of DEEPA to be furthered not only by ourselves, but by a community of users. This modular and distributed digital framework has the capacity to act as a platform where users can create and manage unique design workflows to suit their needs, and contribute their developments back to the platform to provide a wide range of design and analysis functionality. It would also facilitate a level of flexibility that is lacking in current integration environments built around principles of centralization and standardization, and better suit the needs of multidisciplinary design teams.

7. CONCLUSION

In this paper we have presented a prototype energy-oriented design system that uses cloud computing in combination with MDO methodology from the aerospace industry to overcome limitations in process and technology currently experienced in building design integration. In the long run, it is envisaged that this system will be extended to link to more conventional BIM-based modeling systems for development and documentation in the later design stages; and to include other simulation domains, such as daylighting and airflow. But more importantly, it is anticipated that the introduction of flexible and concurrent design and analysis environments like DEEPA will strengthen design communication networks. This will support the development of more integrated design practices that facilitate a shared understanding and knowledge between disciplines that is of as great a benefit to the design process as the performance evaluation capabilities that the system provides.

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