AN INVESTIGATION INTO A VISUAL FRAMEWORK AND WORKFLOW INTEGRATING BUILDING INFORMATION MODELING AND ENERGY SIMULATION SOFTWARE IN THE EARLY DESIGN STAGE

A Thesis in Architecture by
Rohan Haksar

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The thesis of Rohan R. Haksar was reviewed and approved* by the following:

Ute Poerschke
Associate Professor of Architecture
Thesis Advisor

Loukas Kalisperis
Professor of Architecture

George Otto
Affiliate Professor of Architecture

Alexandra Staub
Chair, Graduate Program and Associate Professor of Architecture

*Signatures are on file in the Graduate School.
ABSTRACT

Current technological advancements coupled with the energy crisis and climate change are influencing architectural design thus necessitating changes in the design process. New tools like Building Information Modeling (BIM) allow architects to generate a single comprehensive building model which can share data with all participants of the design team. Energy simulation software (ESS) allow architects to analyze the energy efficiency of the design from the initial design stage, thus better informing design decisions.

Architects are already using Building Information Modeling (BIM) and Energy Simulation Software (ESS). However, energy simulations are not incorporated at the early design stage (EDS) for site analysis and schematic design and are carried out at the end, thus making minimal design changes possible. This reduces the efficiency and overall quality of the design since the lack of initial energy analysis does not encourage sustainable strategies to be incorporated from the beginning. In order to have a truly sustainable design it is essential that architects are able to carry out energy analysis from the very beginning of the design process, maximizing site potential, incorporating energy conscious strategies and optimizing energy conscious design early on. The simulation results also provide the architect with the ability to make quantitatively informed design decisions for energy efficiency.

Integrating BIM and ESS allows simulation data to be read with reference to the building model, thus making the energy analysis more comprehensible for designers and thus allowing design decisions based on it. When combined, these tools can help optimize energy efficiency and ensure the designer is able to make informed design decisions at the early design stage resulting in a more contextual, climate responsive and energy efficient design.

Thus, the research aims to investigate how an integrated BIM – ESS framework can be created and used in the early design stage. The research design uses methods such as archival research, literature review and test
designs to answer this question.

Eventually the research aims at creating a framework of visualizations and the process to integrate BIM and Energy Software thus, enriching the design process by allowing architects to make informed design decisions at the EDS. These investigations will suggest what data is relevant, what assumptions can be made and how this data can be combined at the early design stage. The main goal is to define the framework of a visual interface and the relevant process integrating BIM and energy software for easily comprehensible analysis.
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CHAPTER 1 : INTRODUCTION

1.1 RESEARCH CONTEXT

1.1.1 BACKGROUND

Architecture has always been an expression of people's desires but it has also always been grounded in people's needs and necessities. Both aspects have driven and will continue to drive architecture forward. In today's ecologically ravaged world, architects need to address energy efficient building and there is a desire for an integrated way to deliver these buildings.

The architectural industry has seen numerous technological advancements over the last 25 years with respect to Computer Aided Design (CAD). The advent of CAD saw a shift to computer representations from hand drafted drawings. As more and more technologies appeared, various agencies became involved in the building process. Back and forth communication between these agencies became vital for the building project. Such necessities led to building information modeling or 'BIM'. This approach provided a three dimensional representation along side the two dimensional CAD drawings. In an ideal scenario, which has not been achieved yet, it provides for a single repository for all the project data thus allowing all the agencies to communicate with it. “BIM is the creation and use of coordinated, consistent, computable information about a building project in design - parametric information used for design decision making, production of high-quality construction documents, prediction of building performance, cost estimating and construction planning “(Krygiel 2008, p.27).

Another rapidly advancing digital tool is Energy Simulation Software (ESS) which help analyze the energy efficiency of a building through a variety of simulations from thermal analysis to daylighting to ventilations gains. The field of ESS has also witnessed major advancements since 1996 when the U.S. Department of Energy compiled its first list of 50 such software. Today the list stands at almost 400, (http://apps1.eere.energy.gov/buildings/tools_directory) and many of these have started providing visual representations of the
simulations rather than text based results provided by earlier ESS.

BIM and ESS are tools which can help the design process achieve energy efficiency. BIM allows the creation of building models with information accessible to all participants in the design. ESS enables architects to analyze and test the energy efficiency behavior of the building through various simulations. Thus, each contributes to increasing the efficiency of the design and when combined allow the designer to make more informed energy conscious design decisions. The integration of these tools is, simply put, the direct exchange of data among different software applications. “Such exchange requires a common data model that is shared (or at least “understood”) by the exchanging applications” (Bazjanac and Crawley 1999).

Although BIM and ESS have been available for the past 15 years, architects have been reluctant to use them as part of the initial phases of the design process. This is mainly due to the fact that such tools are predominantly detailed in their calculations and do not support intuitive decision making necessary in the early design stage (EDS). Another problem is the lack of easily comprehending the results from the energy simulations, which are more text based rather than visual.

Despite the perceived importance, there is still no definitive workflow or framework for the integration of BIM and ESS in the EDS. Tools such as plug-ins and flexible file formats allow data from the building model to be used for energy analysis however the results are still not always visually comprehensible. In order to visually combine the relevant information, there are different formats available such as graphs, tables as well as two and three-dimensional views. However the amount of information available through these different mediums also varies. It is essential to choose a relevant medium, which not only combines data in a visually comprehensible manner but also conveys the required amount of data to the designer. ‘Visualization of simulation results through a number of graphs may well reduce the richness of the ‘integrated’ simulation.’ (Mourshed et al., 2003).

One of the shortcomings is the lack of integration and use of simulations in
the EDS. Architect Sid Thoo in his article, “Interoperability and sustainable design”, rightly mentions that we must identify how and when to integrate simulations in the design process (Thoo, 2008 p. 5). Most architects and engineers run the simulations at a later phase of the design process allowing little room for modifications. If energy simulations are carried out at the EDS, the need to incorporate aspects of sustainability and energy efficiency early on can be better addressed. “Our Energy Modeling Team is also engaged later in design to perform more detailed simulations, but it is the early involvement that is important to set the strategies for the building”, noted Mark Dietrick, AIA, chief information officer at the architecture and engineering firm Burt Hill (Malin 2007, p. 9). This proves that design firms and other involved agencies appreciate simulations at the EDS which can positively influence sustainable design. Visually integrating these results with the building information model can help the entire design team including engineers and architects make informed design decisions early on which contribute towards the overall sustainability and energy efficiency of the design.

This is related to another issue and that is the amount of data present in the building model and how much of it is needed for the simulation. Designers do not use ESS at the EDS because of all the data required for energy analysis may not be available early on. Thus, it becomes important to identify what data is required for the energy analysis and what data can be excluded. As Drury Crawley, AIA, Technology Development Manager at the U.S. Department of Energy, rightly said, “For example including every closet in the model of a large building increases computer processing time without significantly affecting results” (Malin 2007, p. 7). In addition to identifying relevant data, certain assumptions can be also made for data that is not available at the EDS. As Mario Guttman, AIA, vice president and CAD director at the architectural firm, HOK said, “It’s not as simple as pushing a button and getting an energy number. Analysis requires a lot of simplifying assumptions, and understanding what is really important and what isn’t” (Malin 2007, p.7). Thus by identifying relevant data and making certain
assumptions it is possible to carry out energy simulations at the EDS.

This research proposes to better integrate BIM and ESS at the EDS. This requires a better understanding of the issues under investigation such as steps of EDS which require analysis, identifying relevant data and assumptions as well as methods to visually integrate this BIM-ESS data.

This integration is a key element of a broader trend in design towards integration of design disciplines and knowledge-based decision making. The common perception of sustainable design is that it uses eco-friendly materials, active techniques like photovoltaic and passive strategies such as rainwater harvesting. “However, a fundamental tenet of true sustainable design is the integration of all the building systems within themselves as well as with the external economic and environmental realities of the project.” (Krygiel 2008, p. 211). As architects we must try to integrate available digital tools to better influence and inform the design process. This integration between technologies can be bridged by creating a workflow linking them.

The aim of the research is to support the integration and incorporation of BIM and ESS into the beginning of the design process and have easily interpretable visual results from the simulations. This is done by a set of visualizations and processes combining relevant data and eventually allowing informed design decisions for energy efficiency, resulting in a more sustainable design.

1.1.2 THESIS STATEMENT

This thesis is an investigation into a visual framework and workflow integrating building information modeling (BIM) and energy simulation software (ESS) in the early design stage (EDS).

From this problem statement arise the following questions:
1. What is the current situation of BIM and ESS integration?
Exploring the current situation by means of archival research will provide a better understanding of the topic. It will establish what has already been done in the field and what needs to be done. This will better define the research question within the appropriate context.

2. What are the problems currently affecting the integration of BIM and ESS?
Gaining knowledge of problems affecting the integration of BIM and ESS and finding relevant solutions is instrumental to the integration of BIM and ESS data. A test design will be used to identify existing problems with integration in the EDS and how to present the integrated results in a visual and easily comprehensible manner.

3. What design data is relevant at the early design stage?
It is essential to identify data relevant for integration and what data assumptions can be made at this stage. This also helps reduce simulation run time and cut out redundancy.

4. How can an integrated framework better visually combine BIM and ESS?
The framework aims to create a series of visualizations appropriate for the early design stage, combining results from ESS and BIM. This integration allows a better visual understanding of simulation results and allows data to be interpreted in a certain context. The framework also contains a documentation of the process followed to integrate BIM and ESS.

5. How can discrete disjointed energy data be combined to help energy design decisions?
Not only does the framework make an attempt to visually combine BIM and ESS data, it also aims to combine different energy data to show how they affect each
other. Rather than studying energy data like the solar radiation only with respect to the design, it must also be read in conjunction with other relevant data such as shadows which impact the solar radiation. Thus, it is important to note that different energy parameters not only affect the design but also affect each other and thus ultimately affect the design. By studying different energy data together, there combined impact on the design can be studied and help in making design decisions.

1.2 METHODS OF INQUIRY

The research proposed to visually integrate BIM and ESS in the EDS and used archival research and test designs as the main methods of inquiry for this purpose. These methods were used to help establish the existing state of integration, identify steps and data relevant for integration as well as evaluate the usefulness of the integrated visualizations.

The first step was to establish the current state of BIM-ESS integration and the problems associated with it. This meant expanding the literature review to identify problems faced by designers with respect to the current level of integration, using simulations at the EDS, interpreting the results and data abstraction.

Having established the present situation of BIM – ESS integration with respect to the EDS, a test design was used to study the initial design process and identify relevant data. This data, from BIM and ESS, would then be integrated into visualizations to form the proposed framework. The process followed to generate these visualizations would also be documented and clearly defined for future use by external designers.

The visualizations along with the clearly defined process for integrating BIM – ESS would comprise a proposed framework which would then be used by an external designer in a second test design to evaluate the framework. By using the framework, the designer was able to evaluate its usefulness and the feedback would help further refine the framework. The design process would also
be observed to gauge the usefulness of the proposed framework and further refine it.

Thus, the research used the above methods to establish the current level of integration, identify data relevant for integration at the early design stage, create a proposed framework and refine the framework based on external feedback.

1.2.1 ARCHIVAL RESEARCH : TO ESTABLISH CURRENT SITUATION OF BIM – ESS INTEGRATION.

In order to successfully integrate BIM – ESS data, it was important to establish the existing level of integration. This would allow the research to identify what it could build on as well as identify existing problems in current levels of integration. Though these tools have been around for some time, their use within the architectural community only began in the last 10 years. As a result, there were very few books available. Thus, the research concentrated on articles and conference papers to study what has been done regarding BIM – ESS and the current level of this integration.

1.2.2 TEST DESIGN I : TO LEARN RELEVANT SOFTWARE, CHOOSE RELEVANT DATA AND CREATE FRAMEWORK.

The research required using BIM and ESS tools to generate the data for integration and visualization. It was not within the scope of the research to evaluate all available BIM-ESS tools. Thus, as the researcher was familiar with Autodesk Revit it was selected as the BIM tool. Autodesk Ecotect has an existing integration with Revit, via the gbXML file format and thus it was chosen as the ESS tool. As the researcher hadn't used Ecotect earlier, the test design was helpful in learning to it.

The research needed to identify steps of the EDS as well as relevant data
at these stages which needed to be visually integrated. To achieve this, a test design of a single family energy efficient home (Figure 1.1) in State College, PA was used. Through the design process, the research was able to identify steps of early design like site analysis and orientation analysis where simulations could be run and the data visually integrated with the BIM model. Finally, after identifying these steps the design helped select relevant information from the ESS like wind roses and plans from the building model which could be visually integrated.

Thus, the Test Design I was used by the research to learn the selected software, select steps of the EDS and relevant data at these steps for visual integration. This helped create the initially proposed framework and workflow.

![FIGURE 1.1: Test Design I: Perspective view of energy efficient house.](image)

1.2.3 TEST DESIGN II : EXTERNAL EVALUATION OF FRAMEWORK FOR FURTHER REFINEMENT.

Using a single test design to identify steps and data from the EDS would not help create a comprehensive framework with a wide range of applicability. In order to identify more steps of the EDS as well as evaluate the usefulness of the already identified steps, a second test design was used. This design would involve a project with a different program and site, done by a designer external to
the research.

The test design II was used by the research to refine the framework in three main ways. First, by observing how the external designer used the framework and was able to take design decisions based on the visualizations, the research would be able to refine it. An evaluation of the framework and workflow by the external designer would also allow the research to further refine it. Finally, using a different design would help the research identify additional steps of the EDS for the framework.
CHAPTER 2 : LITERATURE REVIEW

2.1 NEED FOR LITERATURE REVIEW

This chapter summarized the current knowledge with respect to integrating BIM – ESS in the EDS. This would provide the research a context as well as precedents to develop the framework within. Given the current emphasis on sustainable design, architects are looking for a way to make informed energy design decisions. Companies providing CAD tools have realized this and are attempting to integrate building and energy data to allow this informed decision making. With so many approaches being taken simultaneously, the research needed a way to consolidate the information available, learn what has been done and use this knowledge to develop and propose a framework. In order to learn more about the current level of BIM – ESS integration, the research conducted an archival research of relevant literature. BIM and ESS are relatively new tools in the field of sustainable design and as a result, there is not a lot of literature regarding the integration of these tools. Apart from the few books available, the research concentrated on journals and conference papers sourced from indexes such as the CuminCAD.

2.2 EXISTING BIM – ESS INTEGRATION

The architectural and engineering community have realized the need to integrate energy analysis with the building design thus, providing the opportunity to make informed decisions early on in the sustainable design process. Various approaches have been taken to integrate BIM and ESS at the EDS not only by CAD software companies like Autodesk and Bentley, but also architectural firms and individuals in the architectural community. The archival research reviewed relevant literature, different approaches to BIM-ESS integration and how the research could build on them. The following overview is ordered by BIM applications to which ESS applications are related.
2.2.1 EXISTING BIM – ESS INTEGRATION : SOFTWARE BASED

Autodesk Revit can be used in combination with an ESS in two different versions: Autodesk Revit Architecture and Revit MEP. Initially Autodesk Revit Building, now Revit Architecture, was linked directly to the ESS, Green Building Studio (Autodesk Revit Whitepaper 2005, p.8). This linkage was done on-line via the creation of a geometrically correct thermal model of the design while applying local building code assumptions and creating a DOE-2 input. It then runs the simulation and gives results in the user's browser window. The DOE-2 input file can also be used to run simulations on other energy simulation programs like eQuest and EnergyPlus. This data transfer is evident in a case study of the design of the Queens Psychiatric Center Community Services, New York by Architectural Resources in 1991 (Autodesk Revit Whitepaper, 2005. p.8). The designers created the model in Revit Building and then generated the DOE-2 input file which allowed them to run base case studies. This was done for various configurations of zones and features. This was then used to modify building R-values and edit the HVAC system. The single model allowed them to run simulations without recreating the geometry thus saving them valuable time.

Fig 2.1 Queens Psychiatric Center Community Services, New York : Solar Study in Revit

Autodesk Revit MEP has collaborated with IES, another energy
simulation software and uses its engine to calculate illuminance levels as well as heating and cooling loads. This compatibility with IES has been extended to Revit Architecture in terms of a plug-in which allows the gbXML model to be created and used for energy analysis within Revit Architecture. The analysis can be run within Revit Architecture and allows the user to detail the different zones within Revit. The plug in allows the user to detail the building components before running the analysis. When data regarding the building components is not available, standardized assumptions are made by the plug-in. The analysis however is not visual and compares the design energy efficiency to that of a standardized similar building type.

Fig 2.2 IES energy analysis done using plug-in for Revit

However Revit isn't the only BIM software available to designers. Green Building Studio, which is already integrated with Revit, has developed a plug-in for use with ArchiCAD. The plug-in helps define HVAC zones and validate the BIM model to increase the chances that the energy simulation will provide useful results. In this case a gbXML format file is generated which is used for analysis on Green Building Studio's server. The software also makes DOE-2 input files available for engineers. Energy simulations require a lot of information which may not necessarily be in the BIM file. The software uses certain assumptions to fill these gaps. These help the software be used at the early design stage and not only at the final stage. The president of the company which created Green
Building Studio sums it up saying, “The whole point of this tool is early-stage modeling” (Malin 2007, p.7). ArchiCAD has also established some level of compatibility with another ESS, Autodesk Ecotect. Ecotect's intuitive graphical user interface has made it quite popular amongst architects. ArchiCAD's gbXML plug-in for Green Building Studio has been modified to translate data into Ecotect allowing mapping of zones and tracking of components like walls and windows. Ecotect itself has developed connections to open source energy simulation softwares like EnergyPlus and Radiance which offer simulations beyond the scope of Ecotect.
Bentley System’s have their own suite of energy simulation products like Engineering Analysis and Building Services & Simulation to add a degree of sustainability to their BIM software, Bentley Architecture. (Cleveland 2008, p. 19). Bentley Architecture is based on the versatile Industry Foundation Classes (IFC) framework. It was developed by the International Alliance for Integration in 1995 to promote bi-directional transfer of data between software applications. The IFC framework consists of the IFC file which unlike other file formats is neutral, open source and not controlled by any single entity. This flexible data structure allows users to store required data and take it to another software. Though the IFC framework is widely popular, Bentley has been unable to use the IFC file to integrate its BIM application with ESS. This is evident in current attempts by Bentley to use the gbXML format to promote integration between its BIM and Simulation tools.

Having compared the mentioned softwares it is evident that the file formats play an essential role while using BIM models for energy analysis in an ESS. The formats for data transfer range from the traditional .dwg to the newly proposed ecoXML. GbXML is the most common file format for energy simulations. It was developed by Green Building Studio and is based on extensible markup language (XML). It has a text based syntax and is similar to HTML. It is used to detail spaces like rooms in a Revit model which are read as building volumes in the ESS and can be used to compute different analysis like thermal comfort. Thus, gbXML eliminates the need to manually recreate the model or use a text input file. The drawback however is that it is intended specifically for storing space and energy related data and cannot store comprehensive data such as construction details for the entire building model.

The text based IDF file is a time consuming process employed by EnergyPlus. Despite giving amongst the most accurate energy simulations, the text based file format offers little or no versatility with respect to integration with BIM tools and visualization of analysis.
The IFC file, as already stated, is the most versatile offering almost full interoperability. IFC is also non-proprietary and open source like gbXML. However the fundamental difference is that it allows total bi-directional interoperability between the IFC model and any IFC-compliant BIM model. The IFC model represents not just building components like doors and windows but also abstract concepts like schedules.

Fig 2.5. IFC format file

Autodesk's acquisition of Ecotect and Green Building Studio in 2008, along with their agreement with Bentley to work together for interoperability will further enhance the existing integration. Yet there are still some underlying problems which need to be resolved. Having considered the current situation with regards to interoperability, there are still certain vital gaps in knowledge.
### TABLE 2.1 Literature Review Summary

<table>
<thead>
<tr>
<th>Energy Simulation Software</th>
<th>Bldg. Service and Simulation</th>
<th>E Quest</th>
<th>Ecotect</th>
<th>Energy Plus</th>
<th>Engineering Analysis</th>
<th>Green Building Studio</th>
<th>IES</th>
<th>Radiance</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARCHICAD</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>REVIT</td>
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<tr>
<td>REVIT MEP</td>
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<tr>
<td>SKETCHUP</td>
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<td></td>
</tr>
</tbody>
</table>

**KEY**
- **DIRECT SOFTWARE LINK**
- **INDIRECT SOFTWARE LINK** (plug in or input file)
2.2.2 EXISTING BIM – ESS INTEGRATION : INDUSTRY BASED

Attempts at integrating BIM – ESS into the EDS are not limited to software companies alone. Architectural firms are realizing the benefits of this integration and how it can inform the design process. The architectural firm HOK has used BIM for over 300 projects but has only recently integrated it with ESS for sustainable design. In the Sheraton Ulaanbaatar Hotel, Mongolia, Autodesk Revit Architecture was the BIM tool and Autodesk Ecotect was the ESS. The Revit building model was used in Ecotect to study solar shading and a location for photovoltaics on the roof. Dickson Mak, a project architect at HOK summed up the design process by saying, “Before we used these tools, we had to make many design decisions based upon educated guesses. With the help of Revit Architecture, Ecotect, and other analysis software, such as IES, we are much more confident in our sustainable design decisions.” *(Autodesk 2008, p. 3)* However it is important to note that since there is no defined workflow for integrating BIM – ESS into the EDS, HOK was only able to use these tools midway through the design process *(Autodesk 2008, p. 4)*.

![Fig 2.6. Solar Studies for Sheraton Ulaanbaator, Mongolia by HOK](image)

Burt Hill is an architectural engineering firm also using these tools in the sustainable design process. Autodesk Revit Architecture and IES were used as the BIM and ESS tools respectively for the design of the New Literacy Center in Springfield, PA *(Autodesk 2008 p.2)*.

"We are using the information-rich digital model created with Revit Architecture in
combination with sustainability analysis tools very early in the schematic design phase to evaluate specific aspects of a green design”, said Mark Dietrick, director of research at Burt Hill (Autodesk 2008). However this analysis was limited to optimizing the windows to increase daylighting, reduce glare and achieve energy efficiency. Due to the lack of a defined framework, these tools are limited in their use and not used early on in the design process. Burt Hill has since further integrated these tools into the sustainable design process as seen in their Delaware Community College project. The design team was faced with a site and context which forced them to make decisions which were not always sustainable (Burt Hill 2008, p. 1). Thus, the team had to carry out analysis to decide what decisions could improve the building performance while meeting other project requirements. The design team used Autodesk Revit Architecture with IES to analyse the design and began with a standardized building, an example of data assumptions being made in the absence of design data. This made them realize early on that they require sun shading devices. The integration and subsequent analysis allowed them to also accommodate a south facing curtain wall, required as per the program as well as design the mechanical system. “Much of this feedback occurred during early design development and late schematic design, allowing the design team to include these features as part of early cost estimating, therefore there was less risk of any proposal to ‘value engineer’ these necessary features, or comprise their aesthetic quality due to price or complexity” (Burt Hill 2008, p. 2).
Another architectural firm, SOM is using algorithms and related programming through its Black Box program to integrate energy analysis into the design process. This has been done to study sunlight access optimization for the Avant Garde project in Moscow, Russia. However this requires multiple tools and programming expertise to link these tools. Thus this process may not be suitable for smaller firms and individual designers due to the programming and financial implications of owning and linking these tools. Dr. Andrew Marsh, the creator of Ecotect coined a term, “Performative Design” (Thoo 2008) to describe the integration of BIM – ESS at the EDS. Carl Galioto and Paul Seletsky, from SOM used this term to describe the integrated design approach taken to design the skylight at the Koch Center for Science, Math and Technology (Rousseau 2008). They also view this integration as a way to have a, “more informed, more productive dialogue with these engineers and to advance that up to a higher plain (Rousseau 2008).
Fig 2.8. Sunlight access optimization study for Avant Garde project in Moscow by SOM

SOM has also managed to use IFC as a medium between BIM and Ecotect in one of their projects. The original design was exported as a series of 3D coordinates representing the building shell. Ecotect was then used to analyze the glazed portions of the facade for solar radiation and to derive an optimum shape for minimum solar gain. The new updated 3d coordinates creating a new, improved facade were then imported back into the BIM software and used to update the model. Thus, a bi-directional inter operable work flow was achieved using the IFC format whereby Ecotect was used to analyze the facade and make necessary changes. The revised facade was imported back into the BIM tool and used to update the BIM model. Further suggestions have included combining IFC and XML to create ifcXML and Square One Research, creators of Ecotect have called for a new language, ecoXML.

2.3 Existing Energy Analysis Visualization

Having established the relevance of integrating BIM – ESS at the EDS, the research also proposes a visual method for integration. The research had identified the lack of visually comprehensible results as one of the reasons architects prefer not to use ESS in the EDS. In order to propose a method of visualization the research reviewed the existing visualization options for energy simulation results and their level of integration with the building model.
There have been major technological advancements in ESS in the past few years. Not only are there more than 300 softwares available, they are rapidly evolving to suit professionals other than just engineers. This is a result of a larger shift towards an integrated, more efficient design process. Autodesk Ecotect began as an attempt to bridge this gap between ESS and architects by providing visual results for energy analysis like daylighting and thermal comfort. ECOTECT is relatively unique amongst performance analysis tools as it offers graphical analysis, is visually appealing and is intended for use during the early conceptual stages of design. It integrates a relatively simple and intuitive 3D modeling interface with a range of analysis functions. (Marsh et al. 2001, p.1). While certain analysis can only be displayed as graphs and are not visually related to the building mode, Ecotect is able to visually relate certain simulation results to the building design.

Every design decision impacts other aspects of performance, and many of these impacts do not become apparent until after construction, when the building is actually being used. “As a result, the simultaneous analysis of many different performance parameters is absolutely essential” (Marsh 1992, p.1). Ecotect is yet to deal with this issue of layering different information like the research proposes for integrating multiple, relevant simulation results with relation to the building model.
A similar approach to providing visual simulation results is Energraph, developed at Texas A&M University. It uses 2D bar charts, 3D surface plots and animations as ways to represent the energy analysis data. As a tool for energy efficient building design, Energraph can be used both in early and late design stage. (Degelman et al. 1992, p. 11). Early on the designer can evaluate the site and at a later stage alternative designs can be tested. The software uses data assumptions based on standardized building types if data is not available at the EDS, has a graphical interface to make entering data easy and has interactive analysis updated as the model is modified. However it is not linked to a CAD or BIM design tool and the user is forced to choose from pre-defined building types to use as the building model for analysis. In addition, the visual results can not be layered to study the various energy parameters in relation to the design.
The consortium of BRE, Cardiff University, Cambridge Architectural Research, Southfacing Services Ltd and Bobby Gilbert & Associates are developing a tool, Climatelite to visually integrate energy data at the EDS. It aims at converging the visual languages in manual and computer analysis methods where precedents of traditional visualization techniques exist (Alexandra et al., 2009 p.6). This tool is currently under development and seeks to build upon the visual integration offered by a tool like Ecotect. Most existing ESS, irrespective of visualization capability, provide quantitative data. For a designer, the quantitative data holds less importance than the ability to visualize the qualitative effect of various design strategies, thus, raising the need of comparative indicators for a number of cases. (Alexandra et al., 2009 p.4). Climatelite proposes to layer various analysis results to allow the designer to study the cause-effect of all relevant factors and then take informed design decisions. However it is restricted to the site and its relation with the building whereas at the EDS, it is important to also consider the building form and its energy efficiency.
2.4 CONCLUSION

It is evident from the literature review that there is a need for integrating BIM – ESS into the EDS. Different approaches have been tried but each is limited in its use as it has been developed to solve a certain problem rather than actually integrate energy simulations at the EDS. While certain methods integrated BIM-ESS, the analysis was not graphical and when graphical analysis was available, different data could not be layered and studied in relation to one another. The proposed framework not only integrated BIM-ESS but also allowed layering of this data to create visualizations for informed decision making. This involved building on what was has already been done in this field and learning from the current shortcomings. The literature review helped learn about what softwares could be used by the research to develop the framework. In addition, it provided an insight into existing ways of using the building model for energy analysis like plug-ins and flexible file formats. By studying the different approaches taken to integrate BIM – ESS at the EDS, the research was also able to substantiate the relevance of the problem. It was also important to note that these approaches have used different BIM and ESS softwares. Similarly, though the research is constrained to work with certain software, it does not imply that these are the
only tools capable of integrating BIM – ESS. Thus, the research used the literature review to gain an understanding of the current situation of BIM – ESS integration in order to develop the proposed framework.
3.1 DESIGN PROGRAM

The research design proposed two test designs in order to develop framework, evaluate it and further refine it. The test design 1 was used to learn the relevant software, identify stages in the EDS where simulations were required and to generate the relevant BIM-ESS data. At the EDS, the design was still operating at a schematic level and thus, lot of building data such as materiality was not available to the designer. This prevents designers from using ESS as there is the pre-conceived notion that simulations need to be detailed and require a large amount of design data. The research acknowledged this problem and used the test design 1 to identify what data was required from the building model and the ESS to run the proposed simulations at the different steps of the EDS. As Drury Crawley, AIA, Technology Development Manager at the U.S. Department of Energy, rightly said, “For example including every closet in the model of a large building increases computer processing time without significantly affecting results” (Malin 2007, p. 7).

Using the test design 1 to identify this data also meant identifying what assumptions can be made regarding BIM and ESS data not available early in the design process. As Mario Guttman, AIA, vice president and CAD director at the architectural firm, HOK said, “It’s not as simple as pushing a button and getting an energy number. Analysis requires a lot of simplifying assumptions, and understanding what is really important and what isn’t,” (Malin 2007, p.7)

The design program for the test design 1 involved designing an energy efficient single family home in State College, PA (Fig 3.1, 3.3). This site was chosen as it was important to develop a contextually relevant design in addition to being energy efficient and the researcher was familiar with the town of State College. The design program was beneficial to the research because to analyze and achieve energy efficiency, energy simulations were required. As the
researcher had not used ESS before, this was an opportunity to learn ESS and use them to generate energy data for visual integration.

The client profile for the design was a single family with the parents teaching at the Pennsylvania State University. They had two children, a high school going son and a daughter who was in kindergarten. Thus, the design program required at a minimum a 2 bedroom home with a living room and kitchen. The site in State College was an empty plot on the Northern boundary of the Pennsylvania State University and the design brief required the home to respond to the local architecture (Fig. 3.4) of homes in the vicinity.

To sum up, the test design I was used to:

1. Learn the relevant BIM and ESS software to generate data for visual integration
2. Identify steps of the EDS to run energy simulations
3. Identify relevant data from BIM – ESS for the simulations as well as what assumptions can be made.
4. Develop the proposed framework by generating visualizations integrating the BIM and ESS output data.
5. Take energy design decisions based on the visualizations and evaluate their impact on overall energy efficiency of the design.
6. Document the process and workflow required for integration for use by an external designer in test design II
DESIGN PROGRAM:

Designing with Energy and Environmental Simulation tools: An Energy-Efficient Single Family House in State College

- Preliminary design was due after two weeks.
- Each week had an assignment and clearly defined goal.
- Each assignment was used to generate BIM-ESS data.
- This data was used to explore ways of creating the visualizations.
- Each week the student submitted a report about if and how the visualizations helped take design decisions.
- The design process and decisions were documented to evaluate the usefulness of the framework.

<table>
<thead>
<tr>
<th>WEEK</th>
<th>DESIGN STAGE</th>
<th>SIMULATION TOOL</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Start Design</td>
<td>Autodesk Revit</td>
</tr>
<tr>
<td></td>
<td>Design Concept</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Climate Data Collection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Macro and Micro Climate, sun data, wind data, temperature, humidity, rainfall, sky cover, site conditions, water resources, waste, vegetation.)</td>
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<tr>
<td></td>
<td><a href="http://solardat.uoregon.edu/">http://solardat.uoregon.edu/</a> <a href="http://solardat.uoregon.edu/PolarSunChartProgram.html">PolarSunChartProgram.html</a></td>
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<td></td>
<td><a href="http://www.weblakes.com/lakewrpl.html">WRPLOT:</a></td>
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</tr>
<tr>
<td>2</td>
<td>Design Concept</td>
<td>Autodesk Revit</td>
</tr>
<tr>
<td></td>
<td>General ideas concerning: sun orientation, wind orientation, site shading, massing/volume, orientation study</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Climate Consultant 3.0</td>
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</tbody>
</table>
|   | Sun studies, shading studies (including vegetation), principal functional layout and inner organization | Autodesk Revit  
|   |  
|   | Autodesk Ecotect Analysis  
| 3 |  
|   | Orientation Analysis – Internal daylighting and thermal comfort. | Autodesk Revit  
|   | Autodesk Ecotect Analysis  
| 4 |  
|   | Materiality Analysis – Internal Thermal Comfort | Autodesk Revit  
|   | Autodesk Ecotect Analysis  
| 5 |  
|   | Wind Studies – Natural ventilation pattern, site and building scale, location and size of openings. | Autodesk Revit  
|   | Autodesk Ecotect Analysis  
| 6 |  
|   | Natural Ventilation | FLUENT  
| 7 |  
|   | Daylight Factor | Autodesk Ecotect Analysis  
| 8 |  
|   | Daylighting (Facade Studies) Analysis of facade shading devices: horizontal/vertical, fixed/movable. | Autodesk Ecotect Analysis  
|   | http://susdesign.com/sunan gle/  
| 9 |  
|   | Refinement of design based on visualizations. |  
| 10 |  
|   | Evaluation of visualizations and their usefulness |  
| 11 |  
|   | Final proposed visualizations |  
| 12 |  
|   | Compilation of all design steps in a week-by-week | Present all programs  
| 13 |  
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3.2 SOFTWARE SELECTION

The research proposed visually integrating BIM – ESS at the ESD and to do so it was essential to identify the BIM and ESS software that would be used to generate the data for integration. The research however did not imply that these were the only software which could be used to generate BIM-ESS data at the EDS. To understand the software selection, it is also essential to understand what the technologies offer which can enhance energy efficient design.

3.2.1 BIM SOFTWARE SELECTION

Unlike traditional CAD tools like AutoCAD, BIM allows all agencies to collaborate and add data to a common building model. It would be greatly beneficial to the design process if relevant data from the building model could be used for energy analysis. This would indirectly increase the efficiency of the design process as the designer would not need to enter data again for the simulations. Current technological advancements have recognized the need for a more integrated sustainable design process and have developed file formats like gbXML which facilitate an easy transfer of the building model to the ESS. This ensures that not only is the building geometry successfully transferred to the ESS for simulations, but more importantly, the buildings zones and volumes are also imported into the ESS. This is significant since energy simulations like thermal comfort and daylighting, which can influence the design at an early
stage, require zone volumes for computational purposes.

There are numerous BIM software packages available and it was not feasible for the research to evaluate them all and then select an appropriate software due to time constraints. Since the researcher was already familiar with Autodesk's BIM tool, Revit Architecture, it was chosen as the BIM software for the research.

3.2.2 ESS SELECTION

Energy Simulation Software (ESS) help analyze the energy efficiency of a building through a variety of simulations from thermal analysis to daylighting to ventilation gains. The field of ESS has seen major advancements since 1996 when the Department of Energy (D.O.E) compiled its first list of 50 such software. Early versions of ESS targeted the engineering community and were text based. This was a primary reason why architects were reluctant to use them. Today however, the list of ESS on the D.O.E. website, (http://apps1.eere.energy.gov/buildings/tools_directory/) stands at more than 386 and many of these have started providing visual representations of the simulations rather than text based results provided by the earlier software. This presented a problem for the research regarding which software to choose and what basis should it be chosen on.

Autodesk Ecotect Analysis was chosen as the ESS since it was one of the few ESS meant for use by architects at the EDS. In addition, it supported the gbXML file format which allowed a smooth translation of geometry and zone volumes from the BIM tool to the ESS. It also provided a certain degree of visual results of the simulations. Ecotect was also quite comprehensive in the range of simulations it offered with the capability to carry out site climatic analysis, thermal comfort, daylighting and shading. This was also beneficial as the researcher was not familiar with any ESS and this meant only one ESS had to be learnt to carry out the simulations and generate the desired data.
3.3 DATA COLLECTION

The test design allowed various data collection which will be described as follows.

IDENTIFY STEPS OF EARLY DESIGN WHERE ENERGY SIMULATIONS CAN BE RUN

Incorporating energy simulations into the EDS required identifying the different steps of early design where simulations could be used. By doing so it allows the designer to exploit the site conditions as well as integrate passive strategies into the design early on. As the design progressed, different steps were identified such as site analysis and orientation analysis. The research documented these steps but does not imply that these are the only steps or they have to follow a specific order. The proposed steps were:

1. Site Analysis
2. Orientation Analysis
   2.1 Thermal Analysis related to building orientation
   2.2 Daylighting Analysis related to building orientation
3. Building Skin Optimization
4. Ventilation Analysis
5. Shading Analysis

WHAT SIMULATIONS CAN BE RUN AT THESE STEPS?

Once the research established that a certain step of the EDS were important for the design decision making, the next step was to identify what simulations were required to be run at this step. Depending on how far the design had been developed and what information was available certain simulations could be run. The choice of simulation could also be done based on what design decisions the designer wanted to take and what energy information was required from the design. The test design I helped identify simulations for the different steps of the EDS like thermal comfort and daylighting analysis to choose an optimum orientation for the building.
Energy simulations depend on a certain amount of information in order to carry out calculations and present the outputs. The research proposed using BIM which allowed the designer and all related agencies to add data to a single building model. Using existing file formats like gbXML, this data could be taken to the ESS. However, since the research dealt with the EDS it was important to note that a lot of data was not available at this stage. This made it important to identify what was relevant to the simulations from the data that was available. The research understood that since it was the EDS, all the required data may not be present and thus identified if any assumptions could be made or certain standard data used. An example of this would be the orientation analysis based on thermal comfort when the wall construction was not known and a generic brick wall with insulation was used for the design. In the next step of building skin thermal analysis, different wall constructions were evaluated and at this step, data was added to the building model to detail the wall.

TABLE 3.2 : Proposed steps and relevant energy simulations.

<table>
<thead>
<tr>
<th>NO</th>
<th>STEP</th>
<th>ENERGY SIMULATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SITE ANALYSIS</td>
<td></td>
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<tr>
<td>2</td>
<td>ORIENTATION ANALYSIS</td>
<td>DAYLIGHTING</td>
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<td></td>
<td></td>
<td>THERMAL COMFORT</td>
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<tr>
<td>3</td>
<td>BUILDING SKIN OPTIMIZATION</td>
<td>THERMAL COMFORT</td>
</tr>
<tr>
<td>4</td>
<td>VENTILATION ANALYSIS</td>
<td>FLUID FLOW</td>
</tr>
<tr>
<td>5</td>
<td>SHADING ANALYSIS</td>
<td>DAYLIGHTING</td>
</tr>
</tbody>
</table>

WHAT DATA FROM BIM - ESS IS RELEVANT FOR THESE SIMULATIONS AND WHAT ASSUMPTIONS CAN BE MADE?

Energy simulations depend on a certain amount of information in order to carry out calculations and present the outputs. The research proposed using BIM which allowed the designer and all related agencies to add data to a single building model. Using existing file formats like gbXML, this data could be taken to the ESS. However, since the research dealt with the EDS it was important to note that a lot of data was not available at this stage. This made it important to identify what was relevant to the simulations from the data that was available. The research understood that since it was the EDS, all the required data may not be present and thus identified if any assumptions could be made or certain standard data used. An example of this would be the orientation analysis based on thermal comfort when the wall construction was not known and a generic brick wall with insulation was used for the design. In the next step of building skin thermal analysis, different wall constructions were evaluated and at this step, data was added to the building model to detail the wall.
HOW CAN THE RESULTS FROM THE ESS BE VISUALLY INTEGRATED WITH THE BUILDING MODEL?

The research needed to generate BIM-ESS data to explore ways to visually integrate it such that design decisions could be made using the visualizations. The test design I was used to generate this BIM-ESS data. Once the data was generated the research experimented with different methods of layering and visually integrating this data. The research used these visualizations to study the energy data in relation with the building model and take energy design decisions based on the inferences. By using the visualizations to take design decisions, the research was able to internally evaluate the usefulness of the different visualizations and select one as the basis for integration at the different steps of the EDS.

WHAT DESIGN DECISIONS WERE MADE ON THE BASIS OF THESE VISUALIZATIONS AND HOW DID IT INFLUENCE THE DESIGN?

The research proposed ways of integrating BIM – ESS data to better inform the design process. The test design I was used to generate data and visualizations integrating this data. In order for the research to be useful to designers it was essential to evaluate the usefulness of the design decisions taken on basis of the visualizations and how they impact the energy efficiency of the design. The test design I was evaluated in terms of energy efficiency and the usefulness of the proposed framework was established.
CHAPTER 4 : CREATION OF FRAMEWORK

4.1 IDENTIFY STEPS OF EDS FOR VISUALIZATION.

The research proposes a framework to integrate BIM – ESS in the EDS by identifying steps of early design for energy simulation, the relevant data and how to visually integrate it so that the designer can make informed design decisions. Through a test design, relevant steps of the EDS will be identified for integration. This chapter will describe the following three relevant stages:

- Site Analysis
- Orientation Analysis
  - Thermal Analysis
  - Daylighting Analysis
- Building Skin Optimization

In order to gain maximum efficiency and incorporate sustainability into the design, it is essential to react to the prevalent site conditions. Thus, the first step of EDS for integration is the Site Analysis. Studying the site informs the designer about what factors can enhance the design and what can prove to be detrimental. Based on this data, the designer can take design decisions early on and thus design the building efficiently. However, there is an enormous amount of data which needs to be considered for site analysis and this leads to the question of what is relevant to the designer at the EDS. The first step will identify the relevant data with respect to the site analysis and propose a way to visually layer it.

Having studied the site and made design decisions like room locations based on the analysis, it is important to orient the building in an optimal manner. This would mean orienting the building to exploit natural factors like daylight and ventilation while staying within the context of the site. The context would allow the building to fit into the surroundings and be relevant. This presents a conflict, whether the building should be oriented to achieve maximum energy efficiency through ways like natural lighting and ventilation or be oriented in context to the...
surrounding buildings. It shows that designing is a complex process and climate and the surrounding environment are just two examples of a relevant context for the design. This example makes it apparent that energy simulations will never solve the complexity of making design decisions but, by concentrating on a particular aspect, they provide valuable information which helps the designer make informed design decisions.

The proposed framework recommends using various orientation options with the relevant thermal comfort and daylight analysis and comparing them to see which orientation is the most efficient, which is contextually relevant or which is optimized to meet both parameters. Thus, the research proposes Orientation Analysis as the next step for visual integration by layering thermal and daylight analysis with climatic data to choose a suitable orientation.

With the site conditions examined and the optimum orientation chosen, the designer can develop the design in terms of form and related materiality and the subsequent impact on the energy efficiency of the design. In order to be sustainable and energy efficient, the design must integrate passive strategies and building materials while staying true to the design program and context. To choose the relevant materials, the designer must be able to compare the effects of different materials on the design in terms of energy efficiency. BIM allows the designer to specify the building materials being used and this data can be layered with thermal comfort from the ESS. Visually integrating this data from BIM – ESS will help the designer make informed design decisions regarding the materials being used. Thus, the research proposes Building Skin Thermal Analysis as the next step for visual integration in the ESS. This visualization can be used to study specific zones or the entire design and make informed design decisions.

By initially analyzing the site and orientation options, passive strategies can be incorporated. Studying the building form and materials allows the designer to choose optimum materials which will enhance the energy efficiency of the design. Active technologies, which are relatively more costly and require
regular maintenance, can be placed at a later stage to supplement the existing sustainable strategies.

Using test design I, the research was able to recommend three steps of the EDS for visual integration of BIM – ESS. It is evident that these are not the only relevant steps of EDS for integration and the research takes this into account by proposing a test design II by an external designer to evaluate the proposed framework and explore other potential steps. However in order to do this, the research first proposed and developed the following framework of integrated visualizations and relevant workflows for the three steps identified using test design I, so it could be used by the external designer in test design II. In the following, these three steps will be described in depth.

4.2 SITE ANALYSIS VISUALIZATION

In the test design I, the site analysis was investigated as the first step for visual integration, since it is important for designers to study the site and see what conditions can be used to increase efficiency of the design, what needs to be avoided and what is the context they are designing within. From these factors, it is evident that there is a lot of data that needs to be analyzed, layered and understood in order to make informed design decisions. The research identifies the data relevant at this step and how it can be visually integrated in order to make informed design decisions.

4.2.1 IDENTIFY RELEVANT DATA FOR VISUAL INTEGRATION

For a thorough and informative site analysis, it is necessary to identify all the relevant data, the relationships between this data and the assumptions to be made since it is the EDS and all building information may not be available to the designer. It is also necessary to identify what data needs to be generated in the BIM tool and what needs to be generated in the ESS. The test design I was used as a means of gathering this information.

As part of the preliminary data collection for the test design I, the site plan
was obtained using Google Earth, however designers can decide how they would prefer to generate the site plan. In order to obtain climatic data, the relevant weather file in the .wea format, was obtained and used to generate weather data in Ecotect, the ESS. The climatic data included wind roses, sun path, solar radiation and shadow range. This data does not have to be generated within the mentioned tools and the designer is free to choose the ESS to generate the data. The designer may also choose to use free web based tools to generate data like sun path and wind roses. A basic preliminary integrated visualization (Figure 4.1) was created layering this information on top of the site plan.

Figure 4.1: Initial example of layering data

However, this did not account for the shadow range, sun path and solar radiation potential which play an important part in the energy performance of a building. This preliminary visualization also did not use the capabilities of the BIM tool which could extend to providing a shadow range for the surrounding environment.

The site and relevant surroundings which could impact the design in terms
of shade and wind flow were modeled in Revit Architecture, Autodesk's BIM tool. The BIM tool is preferred to conventional CAD drafting tools since once the building model is created, data can be added to it and it can be used at all stages of the design process. Using BIM also expedites the process of using the building model for energy analysis due to the flexible file formats and existing integration. The building model can be exported to the ESS, with the relevant data, as a gbXML file and used for analysis. The BIM tool's capabilities also allow it to be used in a three dimensional manner such that the plan maybe used for the visualizations but the three dimensional model is used to generate shadows. The extent to which the surrounding environment is modeled is unique to every design and thus the designer must identify and model everything that can influence the shadow range, wind analysis and solar radiation. The research recommends that at a minimum the adjacent building be modeled since they would significantly affect the energy performance of the building. In this respect, the test design was informative as it showed how modeling the adjacent landscape would affect the shade falling on the building and how this would also vary from summer to winter as the trees shed their leaves. Such details would be design specific and the designer would need to be aware of this and model accordingly.

Thus, the relevant data for site analysis visual integration was identified and compiled into Table 4.1.

<table>
<thead>
<tr>
<th>SITE ANALYSIS : RELEVANT DATA AND TOOLS</th>
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<tr>
<td><strong>BIM</strong></td>
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4.2.2 METHOD OF VISUAL INTEGRATION

While developing the framework it was essential to keep in mind that the applicability must extend beyond the scope of the test design I and should be useful to the architectural community as a whole. Thus, the method needed to be simple yet provide an informative visualization.

Since the relevant information to be layered was all in a two dimensional plan format, that became the basis of the visualization. The site plan would thus form the base on which the data could be layered allowing the climatic data to be read in conjunction with the site and surrounding buildings. There also needed to be a systemized way of layering so that there wasn't an information overload resulting in incomprehensible visualizations. This meant going back to data identified and studying how to organize and layer it. Eventually the research was able to layer the relevant data by creating a basic visualization consisting of a circular space surrounded by a concentric grid (Figure 4.2).
The purpose of the grid was to layer wind temperature and frequency. A divergent color scale was used to denote wind temperatures and the grid cells denoted the frequency. This was done as this was the only data which did not necessarily need to be layered exactly on the site plan. The innermost circle of the grid was used to layer the sun path. Within the circular space, the site plan was layered at a known scale and the relevant scale and orientation was mentioned in the visualization. The shadow range was layered on the relevant places in the site plan. Thus specific areas were identified to layer information and prevent a data overload making it visually comprehensible as shown in Figure 4.3.
Inferences:

- Warm winds from the West, South West
- Solar radiation from East to West through South
- High solar energy potential

Conclusions:

- Design must place living spaces to maximize daylight and warmth from South
- Service areas can be placed to the North to act as buffers to the cold winds
4.2.3 ENERGY DESIGN DECISIONS BASED ON VISUALIZATION.

The reason for developing the framework is to take design decisions that make the design more energy efficient. Evaluating the usefulness of the framework meant analyzing whether the proposed visualizations were helpful in taking design decisions and whether the decisions taken improved energy efficiency. Using the visualization generated for site analysis, the designer was able to identify certain climatic factors to exploit and take certain design decisions based on the visualization. By layering the wind temperature and duration and studying it with respect to the sun path, it was evident that the North – West portion of the site would be subject to cold winds and that buffer spaces would be needed. Similarly studying the wind and sun data also showed that the southern part of the site is ideal for sun spaces and warm winds to warm the house. The additional detailed modeling of the surrounding environment including vegetation allowed the shadow range to be displayed and thus identify areas of the plot that will be shaded. The trees also helped inform the design that though they would provide shade in summer, they would be barren in winter and let in the low winter sun. This is relevant since the moderate climate of State College would require the sun to enter the house in winter. By layering the relevant information and analyzing it in relation to one another, the designer was able to make design decisions which would help shape the design and make it more energy efficient.

These decisions could have been taken without layering the data and using the framework. Studying the data in insolation would have presented various options but nothing concrete. Layering the data, especially the climatic data, shows the complexity of the data at a glance and ensures the designer considers all the climatic factors. This allows it to be studied in relation to other factors thus supporting the designer in taking the most appropriate design decisions and exploit the prevalent site conditions.

The first proposed visualization for site analysis was thus not only able to identify relevant data from ESS and BIM but also layer it in a visually comprehendible manner. The integrated visualizations present the designer with
simulation results integrated with the building model. The visualizations do not tell the designer what is to be done but present information in a visually comprehensible manner. The designer, who has knowledge of ESS and BIM, is able to use the visualizations to read the information, evaluate different approaches and then take an informed design decision based on the data. Thus, the designer can better optimize the design for energy efficiency early on in the design process.

4.3 ORIENTATION ANALYSIS: Thermal and Daylight Analysis

The Site Analysis Visualization layered relevant site information and allowed the designer to exploit the potential of the site. The next step would be to evaluate the optimum orientation for the design and this would involve evaluating various parameters like local context, thermal comfort and daylighting. Layering of relevant information is helpful when considering such parameters and in order to respond to the site. At this step, the designer was not only concerned with the overall orientation of the building but also where to locate different zones and functions. This required a method of layering information to allow the designer to see the energy efficiency of the building and internal zones with respect to different orientations and locations of zones. In addition it will also help the designer evaluate how the design responds to the local climate and context. Similar to the first step, the research first identified relevant data, integrated it visually and used the integrated visualization to make design decisions.

4.3.1 IDENTIFY RELEVANT DATA FOR VISUAL INTEGRATION

In order to decide the optimum orientation of the design, the designer needed to consider the local climate, context, building form and footprint and the related energy efficiency. The research had already identified relevant climatic data for the first step of site analysis. This included the sun path, wind frequency and temperature and solar radiation. Apart from solar radiation the rest will be layered with other relevant data to evaluate an optimum orientation. For the test
design. This data was obtained through Ecotect using the .wea weather file for State College.

In terms of local context, the site image, obtained from Google Earth, with buildings and landscape in the immediate surroundings was used. This was done so that the design could be developed in context with the surroundings. Including the surroundings gave the designer an idea about the scale and orientation of the nearby buildings. By including the landscape, the designer could see the effect on the design in terms of shading and protection from winds and how this could affect the interior of the building. This would further help in deciding where to locate the different building zones.

At this step, it was essential to see how efficient the building was with respect to different orientations. The efficiency was measured in degree celsius for internal thermal comfort of occupants and daylight factor for daylighting potential. These parameters were important while evaluating orientation options as they helped increase energy efficiency without addition of active technologies. If the orientation can provide a good degree of thermal comfort for the occupants, it would lead to reduced heating and cooling loads. A good daylighting option would reduce the amount of artificial light required as well as improve indoor environmental quality. These simulations were generated using Ecotect, though they can also be generated using other ESS.

All the above identified data needed to be layered with respect to the design. For this purpose the research used the BIM model to generate the relevant floor plan with a level of detail showing the schematic location of various zones, walls, doors and windows. This was done in order to study the thermal comfort level in the different zones and the windows help understand the daylighting analysis. The surrounding environment which was earlier modeled in the BIM tool, Autodesk Revit for the site analysis was also used to generate a plan of the nearby buildings and landscape. While the BIM tool could be any of those available to the designer, it is the amount of data and level of detail required at this stage that is important.
Since the orientation was to be analyzed using the parameters of Thermal Comfort and Daylighting, it was essential to develop separate visualizations for each parameter in order to evaluate the design. This meant identifying what, out of the identified data, would be relevant for the two visualizations. This data was identified and compiled into Table 4.2.
### Orientation Analysis: Relevant Data and Tools

#### 7. Daylighting

- Site Image: Google Earth
- Site Plan: Autodesk Revit Architecture
- Site Surroundings: Autodesk Revit Architecture
- Sun Path: Autodesk Ecotect
  - [http://solardat.uoregon.edu/SunChartProgram.html](http://solardat.uoregon.edu/SunChartProgram.html)
- Wind Roses: Autodesk Ecotect, Climate Consultant
- Shadow Range: Autodesk Revit Architecture
- Solar Radiation: Autodesk Ecotect
- Daylighting Analysis: Autodesk Ecotect
- Thermal Analysis: Autodesk Ecotect
- Design Drawings: Plan
  - Autodesk Revit Architecture

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<thead>
<tr>
<th>BIM</th>
<th>ESS</th>
<th>OTHER</th>
<th>TOOL</th>
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<tbody>
<tr>
<td>Site Image</td>
<td>Site Plan</td>
<td>Autodesk Revit Architecture</td>
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<td>Site Surroundings</td>
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<td>Wind Roses</td>
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<td>Shadow Range</td>
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<td>Design Drawings</td>
<td>Design Drawings</td>
<td>Autodesk Revit Architecture</td>
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</tbody>
</table>

Table 4.2 Orientation analysis: Relevant data and tools

#### 4.3.2 Method of Visual Integration of Relevant Data

For the framework to be successful and applicable to all designers, it must have a generalized method of visually integrating the data. For this purpose, a similar circular image used as a blank base for the site analysis visualization, was used. The site image with the plot and the immediate surroundings was layered into the blank circular space in the center. This would form the basis on and around which relevant climatic and energy data would layered.

Since the orientation was to analyzed using two different parameters of Thermal Comfort and Daylighting, individual visualizations were developed for
4.3.2.1 METHOD OF INTEGRATION FOR ORIENTATION ANALYSIS – THERMAL COMFORT

This visualization used the site image in the central circle as a base on top of which the relevant information was layered. The building plan generated from the BIM model was layered onto the relevant position on top of the site image at the required scale. As mentioned earlier, this plan was detailed with data like zones and walls which would impact the thermal analysis.

Though various orientation options were to be evaluated, the climatic data would remain the same thus this was layered first as it would be a constant for all the thermal comfort visualizations. For thermal comfort it is also important to consider the effect of winds on the design. For this purpose, the circular grid was used to input wind temperature data as done in the site analysis visualization. The sun path was also layered as this would allow the designer to evaluate how the sun can be used to affect the thermal comfort. The shadow range was relevant to daylighting and thus not layered. Thus, this would be the data which would be constant throughout the Thermal Comfort Visualization.

Since various orientations were to be evaluated on the basis of the thermal comfort provided, the thermal analysis outputs would be variable and different for each orientation. The thermal comfort analysis was carried out in the ESS, Ecotect across a two dimensional grid in a plan view, along the XY axis. The results of this simulation were saved as an image file (Figure 4.4) in a .jpg format. This image was then layered, at the relevant scale on top of the building plan for the visualization. By doing so, the designer was able to see the thermal comfort levels in the different zones of the design. Similarly, simulations were run for the different orientations and the results layered to form different visualizations (Figure 4.5 & 4.6) for the various orientation options.
Figure 4.4 Thermal Analysis generated in Ecotect – First Floor

Figure 4.5 Building plan – First floor
Inferences:
- Cold winds from North, North West
- Warm winds from South, South East
- Living Spaces (Blue) below comfort level of 21°C – 26°C
- Garage (Purple) warmer than living spaces

Conclusions:
- Orientation not optimized for thermal comfort within living spaces
Figure 4.7 Proposed Orientation Analysis: Thermal Comfort Visualization Option

**Inferences:**
- Cold winds from North, North West
- Warm winds from South, South East
- Living Spaces (Purple) at comfort level of 21°C – 26°C
- Garage removed from design

**Conclusions:**
- Orientation and design optimized for thermal comfort
4.3.2.1 METHOD OF INTEGRATION FOR ORIENTATION ANALYSIS – DAYLIGHTING

Similar to the thermal comfort visualization, the site image was layered at the required scale, into the central blank space. The building plan from the BIM tool was layered on this image at the relevant scale and position with data like windows, zones and walls which would impact the daylighting.

Since various options were to be evaluated for their daylighting potential, the daylighting analysis would be the variable data while the climatic data would be a constant. Thus, the relevant climatic data was layered first. For daylighting analysis, the wind temperature and frequency was not relevant and thus not layered. The sun path allowed the designer to see the potential areas where natural lighting could be provided at different points of the year thus, it was layered on the site image. In addition, the shadow range of the surrounding environment allowed the designer to see what obstructions would be provided to the natural light. Thus this data too was layered on the site image.

The daylighting analysis for the various orientations was generated in Ecotect across a two dimensional grid in a plan view. The results, in the form of .jpg images (*Figure 4.7*) were layered on top of the building plans in the related visualization options. This allowed the designer to see the daylighting potential of the different zones across a range of orientations.
Figure 4.8 Daylight analysis generated in Ecotect – First floor

Figure 4.9 Building plan – First floor
Figure 4.10 Proposed Orientation Analysis: Daylighting Visualization Option 1

**Inferences:**
- Shadows cast towards East, not affecting available solar radiation from the South
- Favorable daylighting only around living room and greenhouse

**Conclusions:**
- Orientation not optimal for daylighting
Inferences:
- Shadows cast towards East, not affecting available solar radiation from the South
- Favorable daylighting in living room, greenhouse and kitchen

Conclusions:
- Orientation and design best optimized for daylighting
4.3.3 ENERGY DESIGN DECISIONS BASED ON VISUALIZATION.

The designer used the visualizations to evaluate an orientation relevant to the surrounding built environment and an orientation with maximum solar exposure. These orientations were evaluated along the parameters of thermal comfort and daylighting potential while also considering local climate and context. It was assumed that the orientation which fit in with the surroundings buildings was less energy efficient than the orientation which maximized solar exposure and that the visualizations would support this.

Using the thermal comfort visualization, the designer evaluated the two orientations on the basis of thermal comfort within the building. The option with maximum solar exposure (*Figure 4.5*) had the major inhabited zones at an unfavourable temperature of 0 – 5 degrees. This would require the design to provide additional heating to raise the temperature to the comfort level. In addition, the zones were not directly getting the effect of the warm winds. The site relevant orientation (*Figure 4.6*) had the major zones at a higher temperature of 5 – 10 degrees as compared to the other option. In addition, the zones on the periphery were also oriented towards the warm winds.

The daylighting analysis was used to further evaluate the two orientation options. The orientation with maximum solar exposure (*Figure 4.8*) had a daylight factor (DF) of 2 at the Greenhouse and some daylight penetration around the South and West facades. The interior of the building did not receive any daylight. The second option (*Figure 4.9*) had a DF of 1.5 through half of the greenhouse, South and West facades. Similar to the first option, there was no daylight penetration in the interior of the building. The shadows cast by both options were towards the service areas of the staircase, toilet and kitchen and thus were not a factor in deciding the optimum orientation.

Based on these visualizations, the designer chose the site relevant orientation (*Figure 4 & 5*) as the optimum orientation. This was because it offered a higher level of thermal comfort which meant a lower heating load. In addition, the major zones were oriented towards the warm winds which is also beneficial
since the region required heating for nine months of the year. Though the other orientation offered a higher DF, it was in the Greenhouse zone which is not inhabited. Both options did not offer daylight penetration into the interior of the building. Thus using the integrated visualizations, this orientation was chosen as it satisfied local context and provided a higher degree of thermal comfort as compared to other option. This was against the original assumption that the orientation with maximum solar exposure would be more energy efficient. Thus by integrating and layering data, a holistic approach can be taken and informed design decisions can be made.

4.4 BUILDING SKIN THERMAL ANALYSIS

Once the site has been analyzed and the optimum orientation achieved, the design must be further developed and detailed. At this stage it is essential to evaluate the different building skins in terms of their materiality and their impact on the energy efficiency of the design. The designer can edit and experiment with different building skin materials in the building model. The relevant materials can be seen in the plan view which is used as the base to overlay the thermal analysis data generated in the ESS. This building model can be exported to the ESS using the gbXML file format with the relevant materials. In case the materials are not recognized by the ESS, they may have to be manually added again however the building geometry will be transferred. This is another advantage of using BIM over traditional CAD drafting tools. By layering the thermal analysis data on the building plan, the designer is able to see how the thermal comfort changes with different skin materials. This allows the designer to choose materials and accordingly design the building skin for optimum thermal comfort and energy efficiency. For this visualization too, the research identified relevant data and level of detail, visually integrated the data and used the integrated visualization to take informed energy design decisions.
4.4.1 IDENTIFY RELEVANT DATA FOR VISUAL INTEGRATION

To decide the optimum material and composition of the building skin for energy efficiency, the building design with zones and skin materials must be known. This data can be entered into the building model by the designer and seen in a plan view. This view is used to layer the thermal analysis data. To provide a context, a satellite image of the site is used. In addition, climatic data like the sun path and wind temperature is also considered so that any decision taken regarding the building skin does not affect other factors like the wind temperature or orientation.

This visualization uses the same satellite image, generated using Google Earth, as used in the earlier visualizations. The building model was updated with the various material options for the building skins. The different materials and wall compositions can be seen in the building plan and this image, with the material data, is what is required for this visualization from the BIM tool.

Multiple thermal analysis were carried out in the ESS for the different building skin options and the output saved as 2D grid images. It is important to ensure that when the building model is taken to the ESS for analysis, the relevant materials are recognized by the ESS. If not, the simulation model may need to be updated manually. Since this visualization helps decide optimum materials for the building skin, it is essential that the correct materials are present in the model for thermal comfort analysis.

The above identified data is then layered and visually integrated to allow for informed design decisions as well as compiled into Table 4.3 for reference.

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<thead>
<tr>
<th>BUILDING SKIN OPTIMIZATION ANALYSIS : RELEVANT DATA AND TOOLS</th>
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<td>Building Skin Materiality</td>
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<td>Autodesk Ecotect</td>
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Table 4.3 Building skin optimization: Relevant data and tools

4.4.2 METHOD OF VISUAL INTEGRATION

In order to evaluate the different materials for the building skin, the designer must be able to see these materials in conjunction with the relevant thermal analysis. In order to do this, the scale at which the visualization was created must be bigger than the scale used for the site and orientation analysis.

The previously used circular base image was used again and the relevant data was layered on top of it. The site image was first layered in the central blank circular space. The building plan, detailed with relevant skin materials in the BIM tool, were then layered on top of the site image. Both images must be at the same enlarged scale so that the materials can be seen in the building plan.

Finally, the related thermal comfort analysis images, generated in Ecotect, are layered on the building plan at the relevant scale. This allowed the designer to see how the thermal comfort levels are distributed over the design and how they change with different materials in the building skin.

The wind temperature was entered into the circular grid surrounding the image circular image with the layered data. This data is important as the wind temperature also affected the thermal comfort of the design.
Inferences:

- All living spaces (Purple) below thermal comfort level

Conclusions:

- Design not optimized for thermal comfort
Inferences:

- Major living spaces above thermal comfort level
- Kitchen below thermal comfort

Conclusions:

- Design better optimized for thermal comfort

4.4.3 ENERGY DESIGN DECISIONS BASED ON VISUALIZATION.

The visualizations were used to visually integrate data from the BIM tool and ESS and evaluate the performance of different materials as part of the building skin. The design used a brick timber frame wall and a double brick cavity wall as the options to be evaluated. These were chosen keeping in mind the local
context in terms of aesthetics, elevations and construction. Based on the visualizations, the designer would take a design decision regarding the materiality of the building skin. The orientation for both options was the same, chosen in the earlier step by comparing the different orientation visualizations and evaluating them on the basis of thermal comfort and daylighting.

The first option (Figure 4.10) analyzed had a brick timber frame wall. The wall section was designed and detailed in Autodesk Revit, the BIM tool and a thermal analysis was carried out in Ecotect. The thermal comfort throughout the first floor was between 5°C – 10°C, well below the required comfort level of 21°C – 26°C. This would result in extra heating to match the required comfort level and thus decrease energy efficiency.

The next option (Figure 4.11) had a double brick cavity wall and showed a marked improvement over the earlier option. The major living spaces on the first floor showed an increase in thermal comfort levels and were between 10°C – 15°C. The kitchen and staircase were still between 5°C – 10°C, but they are not inhabited all the time and are relatively small. The greenhouse had temperatures between 10°C – 15°C with the periphery achieving 15°C – 20°C. This was quite favorable as the design uses the greenhouse to trap solar radiation and transmit throughout the house. Thus, using the second option of a double brick cavity wall proved more favorable and resulted in a higher level of thermal comfort and subsequently lower heating requirements.
CHAPTER 5: REFINEMENT OF FRAMEWORK

5.1 EVALUATION AND REFINEMENT OF FRAMEWORK

The test design was used by the research to generate relevant data and explore ways of visually integrating it to propose a framework. However, it is important to note that this proposed framework was developed using a single design and thus was not comprehensive. The proposed steps of early design for integrating BIM – ESS were unique to the test design and there was scope for additional steps and relevant simulations to be added. The method of visual integration was also not absolute rather it was an example of how the relevant BIM-ESS data could be visualized in an integrated manner. For the next step of this research, the expertise of the thesis committee was used as well as participatory observation of test design by an external designer to further refine the framework.

5.1.1 EVALUATION OF FRAMEWORK BY THESIS COMMITTEE

At the end of the Spring 2009 semester, the proposed framework consisting of three steps and the relevant workflows was completed. The framework was presented to the thesis committee for an external evaluation to gain feedback to further develop the framework. As the researcher was familiar with the framework and the process used to generate it, there existed a possibility of its applicability not extending outside the research. Thus, the external evaluation helped the research analyze the framework from a different perspective.

Overall, the proposed framework with the relevant steps, data and simulations was accepted however there were certain concerns over the visualizations and data overloading. These were as follows:

Data overload in base image:

While creating the original base image to layer the energy and building data, it was important to identify what basic data was required by the designer.
This included a space to layer the data as well as the ability to annotate the visualization in terms of scale and orientation. The proposed base image (Figure 5.1) had these different variables set up separately across the visualization. However on adding the BIM and ESS data, there was a data overload as relevant data was within the base image as well as around it. This made it difficult to read and relate information around the image to the data layered in the centre.

Figure 5.1 : Proposed Base Image

Solution:
The base image and the required data, scale and orientation, were further evaluated and the research identified the possibility of integrating the orientation data into the base image. The base image was developed to contain building data with energy data like the sun path and wind roses layered over it. Such
energy data is orientation specific and thus, it made sense to combine the orientation into the base image. This would ensure that base image (Figure 5.2) would contain all the relevant and related energy and building data and make it easier to read the data in relation to one another.

![Figure 5.2: Refined Base Image](image)

**Conflicting Colour Scheme:**

At the site analysis step, the research identified wind rose data and solar radiation as the relevant data to be overlaid on the site plan. Wind data allows the designer to exploit opportunities for natural ventilation while solar radiation data can be used to design shading devices and analyze photovoltaic potential. The proposed site analysis visualization (Figure 5.3) had this data layered along with the sun path and shadow range. However, there was a conflict in colour schemes as the research proposed shades of the orange colour to signify solar
radiation and a similar colour was used to indicate wind temperatures within the range of 30° – 35°C. Visually the wind and solar data looked similar especially for the summer months and thus made it hard to differentiate the data. The framework proposed layering energy data to study its effects on the design and for this it is important that the designer be able to read the data. As this primary purpose was not being served by the existing colour scheme, the committee recommended selecting appropriate and diverse colour schemes for the different data sets.

Figure 5.3 : Proposed Site Analysis Visualization for refinement

Solution:
For the framework to be used and understood by a larger audience, a universal colour scheme would have been most appropriate. The research investigated colour schemes used for weather and energy analysis for application in the framework. However none of the existing colour schemes were
applicable to the wide range of data being integrated by the framework. Most weather colour schemes did not have provisions and colours for energy data and vice-versa. However, the research was able to identify the Navy Operational Global Atmospheric Prediction System (NOGAPS) as a potential colour scheme which could be incorporated and adapted by the framework. This system had distinct colour codes for wind, thermal and solar radiation which were adapted to the specific requirements of the framework using Color-BrewerPlus Component developed by Cindy Brewer at the Penn State Geography Department. This was used as it has been carefully designed to be a diagnostic tool for evaluating the robustness of individual color schemes (Brewer, 2006). Using these tools in tandem, the research was able to resolve the colour conflict between data sets and generate a refined site analysis visualization (Figure 5.4).

![Site Analysis: Micro Climate Study – Hottest Month](image)

**Figure 5.4:** Refined Site Analysis Visualization

**Data Overload: Orientation Analysis: Daylighting**

The proposed framework combined relevant energy and building data in a
visual manner and this led to a data overload with the Orientation Analysis: Daylighting visualization. The data overload involved multiple energy and building data being layered and thus making it hard to visually comprehend the data. While creating the visualization for the Orientation Analysis: Daylighting (Figure 5.5), the research identified the sun path, wind roses, shadow range and daylighting analysis as the relevant energy data to be integrated with the building model. While the sun path and shadow range influenced daylighting and shading decisions, the wind roses did not provide any information relevant to the daylighting analysis. The wind rose data was selected as there existed the circular, concentric grid to enter the data and a similar visualization, Orientation Analysis: Thermal Analysis required the wind rose. On further evaluation, the wind rose had a tendency to confuse the designer who would look for a way to relate and connect the wind data to the daylighting analysis. This would also reduce the effectiveness and legibility of the energy data present for the daylighting analysis.

Figure 5.5 : Proposed Orientation Analysis : Daylight Analysis for refinement
**Solution:**

In order to resolve the issue, the research re-examined the Orientation Analysis: Daylighting step of the EDS and identified energy data which would affect daylighting and thus influence design decisions. This data included the sun path, shadow range and daylighting analysis. The wind roses would impact thermal comfort and airflow within the design thus, they were not considered for this step. Having identified this data, the Daylighting visualization was then refined (Figure 5.6) for the proposed framework.

![Orientation Analysis: Daylight Analysis](image)

Figure 5.6 : Refined Orientation Analysis : Daylight Analysis

### 5.2 TEST DESIGN Ⅱ: TO FURTHER EVALUATE AND REFINE PROPOSED FRAMEWORK

Another method to evaluate and refine the proposed framework was via participatory observation of the external test design Ⅱ. This method was proposed to gauge the usefulness of the framework when used by designers not familiar with the research. This exercise was important as the framework has
been developed by the researcher who was familiar with the process. For it to be applicable to designers in general, they must be able to replicate the process to create the visualizations and also comprehend them in order to make informed design decisions.

Thus, the test design II was used to gain feedback from an external perspective and refine the framework accordingly. In addition, the researcher also evaluated the process, design decisions and eventually the design which was developed using the proposed framework. The research had documented workflows to create the visualizations and framework and these were used by the external designer to replicate the framework.

The design brief for the test design II was a sustainable residential mid-rise building in Nablus, Palestine. The design was developed by studying a similar, existing building in Nablus, its energy usage and subsequently designing a sustainable mid-rise with an improved energy-efficiency. In addition, the new design would also use vernacular elements and integrate them into the new design. To establish a baseline energy efficiency for similar, existing buildings and compare the energy usage of the new design, energy simulations were required. The proposed framework helped identify the different steps and relevant simulations which could be carried out to compare energy efficiency and also take design decisions. The steps and simulations proposed in the framework were not absolute and the test design II also helped identify additional steps, simulation and data relevant for visual integration.

Thus, the test design II was used to:

1. Refine the proposed framework based on the evaluation by the external designer.
2. Evaluate the usefulness of the framework in terms of design decisions taken by the external designer.
3. Identify additional steps, simulations and relevant data for BIM – ESS visual integration at the EDS.
5.2.1 DEFINE FRAMEWORK AND PROCESS FOR EXTERNAL DESIGNER TO FOLLOW

To ensure that the external designer was able to use the framework to create the visualizations, the research documented the workflow used to create the proposed framework. The research proposed a sequence for the steps beginning with the site analysis then choosing a suitable orientation and eventually developing the building materiality. Individual workflows were created for each of the three proposed steps thus making designers able to use them individually or in the sequence as proposed. The advantage of individual workflows for each step was that they could be used separately if needed, rather than have designers go through the entire process from the site analysis up to analyzing building materiality.

The workflows were documented as text and video tutorials thus giving designers a choice regarding the path they would like to follow. The text documentation (Figure 5.7) included:

- The aim of the visualization
- BIM and ESS data required for layering in the visualization
- A step by step description with process images of how to layer the data.

Figure 5.7: Text Based Workflow
Similarly a video tutorial (Figure 5.8) was created which showed the creation of the framework by the researcher and could be followed by designers to create their own visualizations. The documentation was then provided to the external designer to create the visualizations and use them for analysis in the test design II.

![Video Tutorial of Workflow](image)

**Figure 5.8 : Video Tutorial of Workflow**

### 5.2.2 PARTICIPATORY OBSERVATION OF DESIGN

While the external designer created visualizations for energy analysis, the research simultaneously carried out a participatory observation of the design process and outcome. This method was used to evaluate how the designer was able to use the framework to create the visualizations and take energy design decisions based on it. Using this process, the research was able to evaluate how easy it was for the external designer to follow the documented visual and textual workflows. This included carrying out the relevant simulations at the proposed steps and collecting the relevant BIM – ESS data for visual integration. In addition to this, the research also observed how effective the proposed system of layering information was. Once the designer was able to create these visuals,
they were used to study the energy efficiency of buildings used as case studies. Based on these analysis and the designer’s inferences from them, design decisions were taken for the new sustainable mid-rise with an increased energy efficiency.

The design brief involved studying the energy usage of a typical mid-rise building in Nablus, Palestine and designing a prototype mid-rise with an increased energy efficiency. Both buildings, the typical mid-rise for analysis and the new design, were located on the same site. Thus, the site also had to be analyzed to examine potential energy efficient elements which could be incorporated like daylighting and natural ventilation. The designer used the site analysis, the first step of the proposed framework, to analyze the site conditions. The designer chose to follow the textual documentation of the required workflow to create the visualization. Data collection was relatively simple as the designer had a satellite image of the site to layer the energy data on. Using the recommended sources, the designer was unable to find the weather file for Nablus but decided to use the Jerusalem weather file as it was only 30 miles away relatively close and almost at the same elevation. The surrounding urban environment was modeled within the ESS and the terrain file imported into the ESS. Using this data, the designer was able to generate the energy data consisting of wind roses, shadow range and sun path to layer on the site image using the base image provided to the designer. The designer had prior experience with Adobe Photoshop, the photo-editing software used to layer the data, and thus was able to successfully use the base image provided to create the site analysis visualization (Figure 5.9).
It was important for the research to not only study the ease with which the visualization was created but to also analyze whether design decisions were taken on the basis of the information it provided. It was observed that the designer used the wind data to propose locations for the courtyards as well as a building form which would promote natural ventilation. The sun path layered with the shadow studies helped shape the form as the designer used a slender form to allow maximum daylight to penetrate the interiors. This was another example of how layering different data can inform the design process rather than analyzing data separately.

With the site analyzed and potential design strategies identified, the designer analyzed the energy efficiency of a typical Nablus mid-rise on the chosen site. This building was analyzed on the two parameters of thermal comfort and daylighting. The designer used Autodesk Revit Architecture as the BIM tool to model the mid-rise prototype and Autodesk Ecotect for the energy
analysis. The designer was familiar with Revit and did not face any difficulty in creating the building model. The BIM model was then exported into the ESS using the gbXML file format for the energy analysis. At this stage the designer encountered one of the problems associated with simulations at the EDS and that was regarding the simulation run-time. A common reason why ESS is not used at the EDS is the long simulation run-time which is normally due to excess data which is not required at the EDS and does not significantly affect the analysis like furniture. The research had identified this as one of the issues affecting simulations at the EDS and identified what data is relevant at each of the proposed steps, so that this problem can be avoided. It is also important to identify what data is not relevant so that the designer does not model it and run simulations with the data as it may increase simulation runtime. A common example is furniture which does not affect energy simulation but considerably increases the simulation runtime. As this problem still occurred it was documented and further examined. However, on further examination it was not due to unnecessary, irrelevant data but due to modeling errors where the designer created individual zones for every spaces. Zones deal with the volume of a space and similarly conditioned spaced should be grouped into a single zone. Once the designer was made aware of this by the researcher, the energy model was corrected accordingly. This occurred as the designer was not familiar with the ESS.

The energy model was then used to carry out the thermal comfort and daylighting analysis. Once this data was obtained from the ESS, the designer used the documented workflow to integrate it with the building plan to create the Site Orientation visualizations (Figure 5.10 & 5.11). The designer studied these visualizations to make design decisions for the new sustainable mid-rise building. Using the thermal comfort visualization (Figure 5.10), the designer was able to infer that the typical floor plan did not have the required level of thermal comfort especially at the periphery. Thus the new design would need to develop a floor plan which had an improved thermal comfort while staying true to the local
apartment layouts. The designer studied the daylighting visualization (Figure 5.11) and inferred that the existing floor plan was not conducive to daylighting as it was not narrow enough to let daylight into interior spaces. Based on this analysis, the designer decided to use a slender form for the new building which would promote daylighting.

Thus, the designer was not only able to create the visualizations for three proposed steps but also took design decisions such as a proposed building form and courtyard position based on the visualizations.

Figure 5.10 : Orientation Analysis : Thermal comfort visualization developed by external designer
5.2.3 EVALUATION OF FEEDBACK FROM DESIGNER

Using the documented workflows the external designer was successfully able to create visualizations to analyze case studies of similar mid-rise buildings in Nablus. Based on these analyses, energy design decisions for the design of the new sustainable mid-rise were taken. The research observed this process as well as obtained feedback from the designer regarding the usefulness of the framework. This feedback was essential to refine the framework based on recommendations made by users of the framework. The external designer was helpful in highlighting the advantages of the framework, how it influenced design decisions and also shortcomings in the framework. These shortcomings mainly regarded communicating the process to the user as the designer was able to understand the visualizations once they were created and make design decisions based on it. The feedback and the subsequent refinement of the framework
based on it is detailed as follows.

**Aim of Visualization and data combinations:**

The designer used the textual workflow to create the visualizations and found it helpful and informative in creating the visualizations. The process images along side the workflow also served as a helpful reference while layering the data to create the visualization. However, the designer did mention that it would have been helpful if there was an introductory paragraph detailing the aim of the visualization and what can be inferred by layering the different data sets. This would help designers combine certain data sets rather than all the data recommended for that step if they just needed to study certain energy parameters and their related effects.

**System of layering data:**

The proposed framework used a base image to layer the relevant BIM-ESS data and create the visualizations. This image was set up as a photoshop format file with the different, empty layers to enter the data. These layers were named as per the relevant data, such as “Sun Path” for the layer to place the sun path in. The designer found this system complex as new layers were created every time data was added in addition to the existing, empty and named layers.

**Usefulness of visualizations for design decisions:**

As mentioned earlier, the designer was able to use the visualizations to make design decisions, for example the location of courtyards and the building form. However, the site analysis step did not inform the designer much, though the designer felt this was more due to the prototype being a simple design and did not take away from the importance of the site analysis visualization. The building orientation visualizations for thermal comfort and daylighting were extremely useful and provided information which helped shape the new building.

**Additional steps required:**

The research had recommended three steps of the EDS for developing
visualizations but these were not absolute as they were developed using a single test design. While developing the test design II, the designer required different analyses to evaluate the existing prototype and these were not part of the proposed framework. These included natural ventilation and shading analysis.

5.2.4 REFINEMENT OF FRAMEWORK BASED ON FEEDBACK

**Aim of Visualization and data combinations:**

The research evaluated this suggestion made by the designer and found that it would be able helpful to provide the aim of each visualization and the information that could be obtained from the visualization. This would tell designers what each visualization could be used for. In addition, by outlining what information can be inferred from layering different data sets, designers had the option of layering just the data they need to analyze. This is beneficial if the designer does not always want to create the entire visualization and only needs to study the relation between certain energy parameters.

**System of layering data:**

The designer was informed that the system of layers was developed to ensure the designer did not leave out any data for the visualizations. Without this system it would be inconvenient to constantly refer to a list of relevant data. The layers were also supposed to be used to place information rather than create new layers for the data. The designer had encountered this problem while developing the first step of site analysis. Having understood the utility of the layering system, the designer was able to successfully use it for the next two visualizations.

**Usefulness of visualizations for design decisions:**

In the test design I, the site analysis visualization helped make design decisions regarding the layout of rooms while in the test design II, the designer
did not find it as useful as the building orientation visualizations. In order to further test the usefulness of this visualization as well as the overall framework, the research proposed it be used by other designers external to the research. This was done, as mentioned later, using architects and engineers from the AE 597D Sustainable building methods (Figure 5.12) and Arch 497A BIM studio classes. Using this method, the usefulness was further validated.

Figure 5.12 : Visualization developed for Centre for Sustainability Charrette

**Additional steps required:**

While proposing the framework, the research maintained that it was not final and there was scope to add steps based on their usefulness in the EDS. Using the test design II, additional steps like natural ventilation and shading analysis were added to the proposed framework. Using multiple designs to identify potential steps of the EDS would increase the applicability of the framework and enable a more thorough evaluation of the design early on.
5.3 FURTHER REFINEMENT OF FRAMEWORK

Using feedback from the test design II and the thesis committee, the research was able to identify areas of the research for further development. This included improving the existing visualizations and workflows as well as adding additional steps for integration. This refined framework was then further evaluated by external designers to test its usefulness.

5.3.1 IDENTIFY ADDITIONAL DATA AND STAGES FOR VISUALIZATION.

In addition to the proposed steps for integration, the test design II was able to identify two additional steps which are beneficial to the design process. These are the steps of natural ventilation and shading analysis. To develop these steps, the research used the Test design I to generate data for integration at these steps. This data was then integrated to create the visualizations and evaluate design decisions based on it. The process used to create visualizations for these steps is detailed as follows.

5.4 NATURAL VENTILATION ANALYSIS

This step was essential as the natural ventilation potential needed to be identified early on as it could influence the building form as well as the internal layout of spaces. Ventilation depends on the nature of local winds and climate, which were already analyzed in the site analysis visualization. Unique to this step was the need to study the effect of airflow not only in a two-dimensional plan view but also a sectional view. The first three proposed steps were developed integrating energy data and the plan view from the building model. However for the natural ventilation analysis, a plan and sectional view was required for integration with the energy data. Thus, in addition to identifying relevant data and visually integrating it, the research had to develop a method to incorporate a sectional analysis into the framework.
5.4.1 IDENTIFY RELEVANT DATA FOR VISUAL INTEGRATION

For this, the primary data required was the ventilation analysis which allows designers to understand the existing airflow patterns and identify ways to improve or control it as required. Attempting to generate this data resulted in a previously mentioned shortcoming, the complexity of ESS. In order to run a ventilation analysis, a computational fluid dynamic (CFD) program was required. CFD tools are mainly built for engineers and not designed for use by architects. Thus, they are not flexible in terms of modeling building geometry and the results are not visually comprehensible. The research examined the various tools which have been recommended for ventilation analysis in the design process and faced numerous obstacles which have been documented in Table 5.1.

<table>
<thead>
<tr>
<th>SOFTWARE</th>
<th>RESULT</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHOENICS</td>
<td>Unsuccessful</td>
<td>Not available for free</td>
</tr>
<tr>
<td>ECOTECT</td>
<td>Unsuccessful</td>
<td>Only computes grid and visualizes analysis done in external CFD Tool</td>
</tr>
<tr>
<td>WINAIR4</td>
<td>Unsuccessful</td>
<td>Not available commercially</td>
</tr>
<tr>
<td>FLUENT</td>
<td>Successful</td>
<td>Not available for free. Done with external help from Penn State ITS Research Group</td>
</tr>
<tr>
<td>NIST-FDS</td>
<td>Unsuccessful</td>
<td>Not available for free</td>
</tr>
<tr>
<td>ESP-R</td>
<td>Unsuccessful</td>
<td>Ecotect export possible as .cfg but unable to load Ecotect export file</td>
</tr>
</tbody>
</table>

Table 5.1 Ventilation analysis : Software review
Due to these obstacles, attempts have been to integrate and visualize CFD simulations into the design process by ESS such as Ecotect and IES. The research had already used the BIM model to create a zone-based gbXML and generate energy data for the previous steps in Ecotect and thus, used it again for the ventilation analysis. The workflow recommended by Autodesk required a three-dimensional grid to be set up within Ecotect and this along with the gbXML model was exported to an external CFD simulation tool. The CFD tools recommended by Ecotect were FLUENT, NIST, and WinAir 4. The research faced numerous problems in sourcing and using these tools. WinAir 4 was a prototype and thus not available commercially. NIST did not process the file from Ecotect and FLUENT was an extremely complex tool and not suited for modeling geometry. However, despite the lack of a suitable CFD tool, the research was able to identify FLUENT as the CFD tool and generate the data with the help of the Penn State ITS Research Group. However, as mentioned earlier, these programs are not meant for intuitive decision making and are not suitable for modeling entire buildings, and a similar problem was faced when using FLUENT. The test design was used to generate the data and despite being a relatively simple model, it proved to be too complex for FLUENT. Thus, a portion of the design, the living room, had to be identified for analysis and remodeled in FLUENT rather than the entire design. In this manner, the research was able to generate ventilation analysis which included horizontal and vertical airflow rate within the living room.

In order to optimize ventilation within a space, it was also important to study where the wind came from. Studying the wind roses can help a designer position openings which can exploit local winds and channel them through the building. The wind roses also helped the designer identify hot and cold winds and which of these winds could be used depending on local climate. Thus, in addition to the CFD results, the wind roses were also layered in this step.

The CFD data generated using FLUENT provided horizontal and vertical airflow within the space. Hence, the previously used methods of layering data on
the building plan did not suffice. In order to study the vertical airflow, which would help the designer decide the window size and layout, the data had to be layered on the relevant building section. Thus, in addition to the plan, the relevant building section was also required from the BIM model for creating the visualization.
5.4.2 METHOD OF VISUAL INTEGRATION

As mentioned above, the introduction of the sectional view required a different method of visual integration than the method used for the first three steps which only used a two-dimensional plan view. While studying the horizontal and vertical airflow, it was important to study them together in a single visualization rather than separately. This meant developing a visualization which incorporated the plan and section and established a relation between them. The relevant energy data, identified earlier, would be overlaid on these images.

The research used the existing base image to create a visualization for the horizontal ventilation across the space. Instead of a blank central space, the research proposed using a grid in this space to facilitate an easy way to enter data.

A satellite site image was placed in the central space and the building plan, from the BIM tool, was overlaid on this at the relevant position. With the plan overlaid, the research used a photo-editing software, Adobe Photoshop, to delete the portion of the room, for which the analysis was done. By doing so, the grid in the

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**Table 5.2 Ventilation analysis : Relevant data and tools**

<table>
<thead>
<tr>
<th>BIM</th>
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<th>TOOL</th>
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<tr>
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<td>Site Surroundings</td>
<td></td>
<td>Autodesk Revit Architecture</td>
<td></td>
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<tr>
<td>Wind Roses</td>
<td></td>
<td>Autodesk Ecotect, Climate Consultant</td>
<td></td>
</tr>
<tr>
<td>Ventilation Analysis</td>
<td></td>
<td>FLUENT</td>
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<tr>
<td>Design Drawings - Plan</td>
<td></td>
<td>Autodesk Revit Architecture</td>
<td></td>
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<tr>
<td>Design Drawings - Section</td>
<td></td>
<td>Autodesk Revit Architecture</td>
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86
central space appears in the analyzed space. The research then proposed using the grid to enter the relevant colours for the different airflow speeds which were obtained form the ventilation analysis done in FLUENT. Since the research already had colour scales for the wind temperature, thermal comfort and daylighting, the colour scale for the ventilation airflow rate had to be unique to avoid it being confused with these other data sets. Thus, the research examined colors relevant to ventilation as well as those not already used in the research.

Based on this and using the Color-BrewerPlus Component (Brewer, 2006), a divergent color scale ranging from green to blue was developed. This along with the grid was used to enter the ventilation data in the analyzed space. The wind temperature data was layered into the concentric grid surrounding the central space as was done for the previous visualizations of site analysis and thermal comfort. In this manner the research was able to generate the visualization for the horizontal ventilation analysis.

With the horizontal ventilation analysis done, the research required to develop a system for the vertical ventilation analysis as well as relate it to the horizontal analysis. As the horizontal analysis had a central space with a dense grid and the circular grid for the wind, the research developed a similar grid system in a vertical rather than circular manner. The central space had a dense grid where the section from the building model was layered. This grid had a less dense grid on either side to layer wind temperature. The spacing for this grid was the same as that for the concentric grid for the horizontal analysis in order to develop a constant relationship between the horizontal and vertical analysis.

Similar to the technique used earlier, a photo-editing tool was used to delete the portion of the building being analyzed, thus replacing it with the grid which was underneath. The ventilation data was then entered into this grid using the colour scale to complete the visualization for vertical ventilation analysis. The vertical grid could also be resized as shown in (Figure 5.14) depending on the scale of the section.

However, despite the wind temperature being related via the grid, the plan
and section did not have a relationship and to establish this, the research introduced a constant section line. This section line was placed at the base of the vertical analysis grid and a similar line was placed on the horizontal analysis. The section line on the horizontal analysis was rotated to signify where the section had be cut. The section line was then used as reference to rotate the horizontal analysis such that its section line was exactly aligned with the constant section line of the vertical analysis. In this way, the research was able to generate a visualization (*Figure 5.13*) for ventilation analysis incorporating and relating the horizontal and vertical analysis.
Inferences:
- Winds between 10 – 15°C strike inlet windows of living room
- Wind enters living room at 1m/s and leaves through kitchen window at 5m/s
- Internally the wind moves faster and higher as it goes across the space

Conclusions:
- Current window size and layout promotes natural ventilation in summer months
5.4.3 ENERGY DESIGN DECISIONS BASED ON VISUALIZATION.

One of the limitations of the ventilation analysis was the complexity of the ESS available for CFD simulation. Due to complexity with transferring the geometry from the BIM tool, the area for analysis was reduced to a single volume, that of the living room. Thus, the ventilation analysis visualization was used to evaluate the ventilation within the living room only. The analysis was carried out for the month of June and the wind rose generated in Ecotect were used to determine the speed and temperature of wind entering the living room windows. Using the visualization, the research was able to see how the design allowed winds from the East and South-East ranging between 10 - 15°C to enter the living room windows. Using the plan and section analysis, it was seen that the
wind starting at a rate of 1m/s picked up speed as it move across the room and left the room from the windows across the room at 5m/s. Thus, the existing window design and layout promoted ventilation through the space in the summer months, which was the only time natural ventilation would be used due to the location.

5.5 SHADING ANALYSIS
The previously mentioned steps allowed the site and building form to be developed in an energy efficient manner. The next proposed step provided a way to further optimize the design by providing suitable shading. Shading devices allow the designer to control the heat and light entering the building and manipulate it as per the requirement. Studying the shading device design with respect to the sun angles and daylighting potential can help the designer see how they respond to the sun and how they impact the interior spaces. The sun angles were required to be studied in a sectional view while the daylighting analysis, as done previously, was analyzed in a plan view. Thus, for this step too, the visualization had to use the plan and section view from the BIM tool to layer the relevant energy data.

5.5.1 IDENTIFY RELEVANT DATA FOR VISUAL INTEGRATION
The shading analysis was developed to help the designer take energy decisions to optimize the shading devices with respect to the sun angle and daylighting. Sun angles are different throughout the year and these are best studied in a sectional view to see the different positions throughout the year and how the shading device responds to this. For this purpose, a sectional view taken through the shading device was used from the BIM tool. To study how the shading impacts daylighting, the research used a plan view of the relevant space from the BIM tool. This was similar to the approach taken while developing the step for Site orientation: daylighting analysis.

To analyze the different sun angles, it is important to note the sun position at
the date and time under analysis. In addition, the angle made by the sun's ray from this position are also important as they allow the designer to see how the sun strikes the design. Using Ecotect as the ESS and choosing an appropriate date and time, the research was able to generate sectional data with the sun position and the angle of the sun ray. This data was used to layer with the building section and study the sun angles. For the daylighting analysis, the relevant space was analyzed using the gbXML file exported from the BIM tool. The analysis in the form of a two dimensional grid was the data taken from the ESS to layer on the building plan. It was also important to locate the sun position for the daylighting analysis so it could be used to establish a relationship between the section and plan as the section was already using the vertical sun position to establish the sun angle. For this, the research generated the relevant sun positions and sun path in a plan view in the ESS. Using this BIM and ESS data, the research was able to proceed to define a way to visually integrate it.

### SHADING ANALYSIS: RELEVANT DATA AND TOOLS

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<tr>
<td>Site Surroundings</td>
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</tr>
<tr>
<td>Sun Path</td>
<td>Autodesk Ecotect</td>
<td><a href="http://solardat.uoregon.edu/SunChartProgram.html">http://solardat.uoregon.edu/SunChartProgram.html</a></td>
<td></td>
</tr>
<tr>
<td>Shadow Range</td>
<td>Autodesk Revit Architecture</td>
<td></td>
<td></td>
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<tr>
<td>Shadow Range</td>
<td>Autodesk Revit Architecture</td>
<td></td>
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<tr>
<td>Daylighting Analysis</td>
<td>Autodesk Ecotect</td>
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<tr>
<td>Sun Position</td>
<td>Autodesk Ecotect</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sun Angle</td>
<td>Autodesk Ecotect</td>
<td><a href="http://susdesign.com/sunangle/">http://susdesign.com/sunangle/</a></td>
<td></td>
</tr>
<tr>
<td>Design Drawings - Plan</td>
<td>Autodesk Revit Architecture</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.5.2 METHOD OF VISUAL INTEGRATION
As the shading visualization also used sections and plans for the analysis, the research proposed using the same method as used in the ventilation analysis visualization. This meant having the section and plan on the same visualization and using the section line as a constant to establish a relationship between the two. However, the plan and section were further developed in a different manner to layer and relate the relevant energy data.

The plan view used the base image with a grid in the central space. The site image was layered in the central space with the sun path layered next and then the building plan, from the BIM tool, was overlaid on the site at the relevant scale and position.

The space being analyzed was deleted using a photo-editing tool and this allowed the grid to fill in the space being analyzed. Using the daylighting analysis generated in the ESS and the colour scale, developed for the orientation analysis: daylighting analysis step, the grid was filled in with the relevant daylight factor colors. The sun position for the relevant date, generated in the ESS was used to plotted on the sun path. Using the photo editing software, a line was drawn from the sun to the window of the space being analyzed to represent a sun ray. In this way, the horizontal analysis was developed for the shading analysis.

To develop the vertical analysis, the research initially developed a arc like grid (Figure 5.15), which was placed above the constant section line. The different arc represented different times of the day while the angled lines represented the sun angle at the solstices and equinoxes. Thus, the intersection of the arc and angled grid represented the sun position on a particular date and time. Depending on the chosen date, the sun position was marked using the grid system. The building
section was layered on this grid and using the photo-editing tool, a line was drawn from the sun to the window of the space being analyzed, to represent the sun ray. Using the ESS daylight analysis the space being studied was filled in with relevant colours from the daylight factor scale. Though the section line allowed the two analysis to be related, the system for reading the sun angles was incorrect (Figure 5.15). This was because as the relevant spaces changed, the sun angle in the visualization for the same day and time would change. This however is not true as the sun angle would stay the same for a certain date and time irrespective of which part of the design was being analyzed.

Figure 5.15 : Proposed Shading Analysis showing error with sun angles
In order to resolve this issue, the research developed another grid for the vertical analysis which still used the section line as a constant to relate it to the horizontal analysis. Instead of using grid lines within the axes, the research created notches on the top of the grid to signify the grid lines which were absent within the central space. The notches had smaller notches between them to provide the designer with flexibility to use only the large notches or use all the notches to overlay the sun ray data. The section was then layered into the blank central space at a scale and position in relation to the plan in the horizontal analysis below. The space being analyzed was filled with the relevant daylight factor color.

Using the ESS, the research was able to generate the sun position, sun angle and ray for the chosen date and time. The sun ray at the relevant angle, from the ESS, was placed within the space using the notches as a reference point. As the angle of the sun ray did not change, it was copied using the photo-editing tool and repeatedly pasted at all the notches. This represented the sun rays for the chosen date and time. Thus, the designer was able to see how the sun rays strike the building, what rays can enter the space and how this affects the interior daylighting.
Inferences:
- Glare and low daylight factor around windows but this space is not used.
- Daylight factor of 2 in the central usable portion of the living room.

Conclusions:
- Better daylighting with glare limited to unused regions of the space.
Inferences:
- Glare cut out by horizontal shading device
- Lower daylight factor of 1.5 in central usable space as compared to previous option

Conclusions:
- Since glare is not a major concern in the cold climate, the recessed windows option was used as it offered superior daylighting
5.5.3 ENERGY DESIGN DECISIONS BASED ON VISUALIZATION

Based on the visualization, the research was able to analyze the design and the impact of shading on it. As the building was located in State College with a latitude of 40.8 N, there was high summer sun and a low winter sun. Due to the cold weather, the research examined the potential of using the low winter sun to warm the interior spaces. As the sun was low, there was no glare and thus allowing the sun in during the winter served the dual purpose of lighting and warmth without requiring to cut out glare. The high summer needed to be kept out due to the potential for glare.

The research used the visualizations to study how the design would respond to the sun in terms of shading. The living room space was studied with two options, one with recessed windows and a second with shading devices above the windows. Using the visualizations, it was seen that recessed windows option provided the living room space with a daylight factor ranging between 1.5 – 2 in the center of the space while the regions around the window were in the range of 0.5. The recessed windows were also able to limit the glare due to the high sun to a region around the windows which was not used by the occupants. In contrast, the option with shading device provided better protection from the glare by totally cutting out the high summer sun. However, the shading devices decreased the daylighting within the space to a daylight factor of 1 in the central space. The design concept consisted of a series of vertical layers of massing and the introduction of horizontal shading devices was in opposition to this.

Contextually too (Figure 5.17,5.18), recessed windows were the preferred method rather than shading devices as the glare and high sun were not a major concern in the cold climate of State College. Thus, the visualizations supported informed design decision. The decision to keep recessed windows was not only an energy decision but also suited the design concept and context.
Figure 5.18 Local Building Typology 1  Figure 5.19 Local Building Typology 2
CHAPTER 6 : PROPOSED FRAMEWORK AND RELEVANT WORKFLOW

Using the feedback the existing steps of the framework were refined and two additional steps were added. These five steps comprised the visual framework integrating BIM-ESS at the EDS. This framework was documented for future use by designers in early design. The documentation for each step included:

1. Aim of the visualization
2. Relevant BIM-ESS data required for integration
3. Workflow to integrate data and create visualization.

The documentation for the five steps is detailed as follows:

6.1 PROPOSED SITE ANALYSIS VISUALIZATION.

AIM:

The Site Analysis visualization was the first proposed step for the framework. At this step, the visualization allowed the designer to analyze the site with respect to different energy parameters such as the wind, shadows and solar path. Using this information, the designer was able to exploit site conditions as well as identify what could prove problematic. By layering the different data, the designer could study how they impact each other rather than study the data in isolation.

RELEVANT BIM-ESS DATA:

The relevant BIM data for the visualization was the model of the surrounding environment which was used to generate shadows which impact the site. To generate the relevant ESS data a local weather file was required. This was available in .wea, .tmy3 and .epw formats at the D.O.E. Energy Plus website, (http://apps1.eere.energy.gov/buildings/energyplus/cfm/Weather_data.cfm) The
relevant ESS data was the wind roses, sun path, solar radiation and shadow range.

**WORKFLOW:**

Using this step, the research was able to develop a system and base image for layering the data, which was then used for the rest of the visualizations. For this visualization, the research also developed a colour scale for wind temperatures which was later used for the thermal comfort and ventilation visualizations. The visualization was generated at a scale suitable to accommodate the relevant surroundings which would impact the site. For the workflow please refer to Appendix A.
6.2 PROPOSED ORIENTATION ANALYSIS VISUALIZATION.

**AIM:**
This step was developed to allow designers evaluate an optimum orientation for the design with respect to climate, energy efficiency and the surrounding context. The optimum orientation was evaluated on the parameters of daylighting and thermal comfort.
For this purpose this step had two separate visualizations for thermal comfort and daylighting analysis respectively. Using these parameters and other energy data such as wind and the solar path, the designer was able to analyze how different orientations impact the daylighting and thermal comfort of the design. Based on this analysis and studying the context, the designer was able to select an optimal orientation.

**RELEVANT BIM-ESS DATA:**
The relevant BIM data for this step was the building plan for both visualizations and the model of the surrounding environment to generate shadows for the daylight visualization. For the daylight visualization, the ESS data identified was the daylighting analysis, sun path, shadow range and solar radiation. For the thermal comfort, wind and thermal analysis were required.

**WORKFLOW:**
To generate this visualization, the base image was used to layer the relevant data. A colour scale was developed by the research for daylight and thermal comfort. The visualization was at a scale suitable to accommodate the building, site and only immediate surroundings. For the workflow please refer to Appendix A.
6.3 PROPOSED BUILDING SKIN OPTIMIZATION VISUALIZATION.

AIM:
With the site analyzed and optimum orientation decided, the next step optimized the building materiality for internal thermal comfort. In this step, the designer evaluated how different materials would affect the thermal comfort of the design. Along with analyzing internal thermal comfort, the designer also studied how wind of varying temperatures struck the building and what effect this had on the thermal comfort. Using this visualization, the designer was able to optimize the building form and materiality.

RELEVANT BIM-ESS DATA:
The relevant BIM data for this step was the detailed building plan showing the materiality. The ESS data required were the wind roses to show wind temperature and frequency and the thermal comfort analysis.

WORKFLOW:
The base image was used to layer the relevant BIM-ESS and the temperature colour scales developed for wind temperature and thermal comfort were used. The visualization was at a scale suitable to accommodate the building plan and show details of the materiality. For the workflow please refer to Appendix A.
6.4 PROPOSED NATURAL VENTILATION VISUALIZATION.

AIM:
The next step analyzed the ventilation potential within the design by studying prevailing winds and how they flow through the building. This visualization allowed the designer to see which winds could be used to promote natural ventilation and how they influenced the interior. By studying the direction of prevailing winds, the designer was able to decide window locations and the internal airflow was studied to decide the window sizes. Thus, using this visualization the designer was able to locate and size windows to influence natural ventilation.

RELEVANT BIM-ESS DATA:
The relevant BIM data for this step was the building plan and section as the horizontal and vertical airflow were studied. The ESS data required were the wind roses to show wind direction, temperature and frequency and the ventilation analysis.

WORKFLOW:
The base image was used to layer the relevant BIM-ESS data on the horizontal analysis, however an additional vertical grid was developed to layer information for the vertical analysis. The section line, a constant, was used to establish a relationship between the horizontal and vertical analysis. A suitable scale was used for the plan and section such that the ventilation data could be layered and read easily. To relate the plan and section, the same scale was used for both. The research developed a colour scale for the internal airflow rate. For the workflow please refer to Appendix A.
6.5 PROPOSED SHADING VISUALIZATION.

AIM:
The last proposed step was used to help the designer develop a design optimized for daylighting and shading. This meant analyzing the solar path and angles to decide how to allow daylighting while cutting out the direct sun and related glare. Using this visualization the designer was able to see how shading devices cut out glare and impacted daylighting within the building. The sun path and angles allowed the designer to see when the sun needed to be cut out and the daylighting analysis showed the effect of the shading on the internal spaces. By studying this data simultaneously, the designer was able to create a shading design which cut out glare but also allowed considerable daylighting.

RELEVANT BIM-ESS DATA:
Similar to the ventilation analysis, the relevant BIM data for this step was the building plan and section. The plan was used to study the movement of the sun and subsequent impact on horizontal shading and daylighting. The section was used to study the sun angles and vertical shading. The ESS data required was daylight analysis, sun path and sun angle for the date and time being analyzed.

WORKFLOW:
The base image with horizontal and vertical grids was used to layer the relevant information as horizontal and vertical analysis were required. Similar to the ventilation analysis, the section line and a similar scale were used to establish a relationship between the plan and section. The colour scale developed for the daylighting analysis was used. For the workflow please refer to Appendix A.
CHAPTER 7: CONCLUSIONS

7.1 SUMMARY

The research incorporated feedback from designers who had used or were expected to use the framework and was able to refine the framework. The framework is still not comprehensive as it was developed using only two relatively simple designs. However it identified five basic steps which would help designers make informed energy design decisions at the EDS by combining BIM and ESS data. By documenting the relevant workflows, the research allows designers to replicate the framework as well as use the system for other analysis if required. Overall, the framework seems successful in achieving the aim of visually integrating BIM and ESS data to allow informed design decisions at the EDS. Though the research primarily used Autodesk Revit and Ecotect, it was able to recommend alternative, in some cases free sources, to generate the relevant BIM-ESS data for integration. This allows the framework to be flexible and not constrain the designer due to lack of available tools. Even the required workflows were documented as text and video tutorials to allow designers to choose whichever method they were comfortable in following. In addition this allows the designer additional references incase one method is not clear enough. The recommended workflow also proved to be helpful as the framework was used not only by the researcher but also by external designers for energy analysis and subsequent design decisions. However, despite the successes, there were certain limitations to the framework as well as potential for it to be further developed.

7.2 LIMITATIONS

Despite being refined based on multiple feedback, the final framework still has certain limitations. Some of these are not within the researcher's scope while some are. These limitations will be identified and ways to resolve them will be explored. These include the need for programming certain variable data and the
choice of BIM-ESS software used to generate the data. Certain limitations like the complexity of CFD simulations for ventilation analysis were identified but could not be resolved.

7.2.1 CHOICE OF SOFTWARE

The framework was developed to allow designers to use BIM and ESS at the EDS to make design decisions. In order for it to be applicable to all designers, the sources used to generate relevant BIM-ESS data need not have been limited to Autodesk Revit and Ecotect. These were chosen as the research did not have time nor expertise to test all the available BIM and ESS software. They were also chosen as the BIM and ESS tools respectively as the researcher was familiar with them, their popularity within the architectural community (Figure 7.1) and the advantage of using Revit to export a gbXML file for analysis in Ecotect.

![Figure 7.1](image.png)

Figure 7.1 : Distribution of BIM tools used by designers

7.2.2 PROPOSED STEPS OF EARLY DESIGN

The research proposed five steps of early design for visually integrating
BIM-ESS data. These steps are not the only relevant steps as they were decided using only two test designs and time constraints did not allow the research to explore additional steps. However, these steps cover a range of energy parameters and analyze the site, building form as well as means to optimize the building. Thus, though only five steps are proposed, they provide the designer with a comprehensive way of analyzing the design at the EDS. In addition, the documented workflows and photoshop file help define a system to layer BIM and ESS data and this can be used by designers to layer data and create visualizations for steps other than those proposed by the framework.

7.2.3 NEED FOR PROGRAMMING VARIABLE DATA

From the BIM and ESS data identified for integration, certain data was constant whereas certain data was variable. This presented the research with the problem of dealing with this variable data and finding a way to layer it in the visualization. The variable data included resizing the central grid squares to layer thermal and daylight data as well as controlling the size of the ventilation and shading vertical analysis grid. The constant data included the sun path and site image and building plan. The programming expertise required for this was outside the scope of the research and was done by the Penn State ITS.

In addition to the Photoshop file developed to layer the integration, the research also proposed a web based interface, which is described in detail in Chapter 7.3.2. This was proposed to extend the applicability of the research to other designers using the internet as a medium and thus making the research software independent. This approach would also allow the researcher to program data which was available online for free such as site images from Google Earth and sun angles from the Sun angle calculator. Though programming the website was not within the scope of the research, a prototype was developed with assistance from the Penn State ITS.

7.2.4 IMPROVED INTEGRATION BETWEEN EXISTING BIM-ESS TOOLS

Using the literature review, the research identified various attempts being
made by design firms as well as software developers to integrate energy analysis into the design process. While design firms are attempting to create workflows incorporating the BIM and ESS tools they currently use, software developers are exploring flexible file formats and plug-ins as means of integration. Currently none of these attempts allow layering of different data nor do they integrate the data in a visual manner. However, due to the expertise and experience on hand, they may be able to develop a method of integrating this data at the EDS. This would be more widely used by design firms who can purchase BIM and ESS tools.

However the framework developed in this thesis used certain sources like the sun angle calculator and University of Oregon sun path tool and Weblakes Wind Roses which are available to everyone and thus would still be applicable to smaller design firms as well as students.

### 7.2.5 VENTILATION SIMULATION ISSUES

A major reason designers avoid using ESS in the EDS is the complexity involved in modeling and the subsequent analysis. For a majority of the steps, the research was able to identify sources to easily generate the relevant energy data. However, for the ventilation analysis, the researcher was unable to identify a suitable tool. This was due to the fact that the ventilation analysis required computational fluid dynamic (CFD) modeling and all the relevant tools were designed for engineering rather than architecture. Certain ESS like Ecotect have made attempts to use the existing geometry and volume of gbXML files for the ventilation analysis, however this still required an external CFD tool. The research explored numerous other CFD tools recommended for ventilation analysis but was unable to carry out the analysis. This was also due to the fact that these tools were suited for modeling spaces rather than entire buildings. The research was finally able to carry out the analysis using FLUENT though this was done with assistance from the Penn State ITS Research Group and only the living room space was analyzed. The research identified the ventilation analysis
as an area for further development and documented the issues faced with the different CFD tools.

7.3 FUTURE DIRECTIONS

Over the course of the research, several issues and limitations were encountered while developing the integrated framework. The research accounted for these, refined the framework accordingly and identified issues which could not be tackled due to the above mentioned limitations. The refined framework was successfully used by designers external to the research and proved effective in allowing informed design decision making at the EDS. However, the steps and method recommended by the research were not absolute and the research identified areas for further improvement in the future to increase the usefulness of the framework.

7.3.1 PHOTOSHOP FILE FOR STUDENTS

Using the photoshop file format, a prototype file was created with pre-assigned layers to enter the recommended BIM-ESS data. This file was successfully used by designers for site and orientation analysis. The feedback regarding this system of layering the data was used to improve the file and create the remaining three steps. The research proposed getting an external designer to use all the steps to analyze a design and thus obtain feedback not only for the individual steps but the research as a whole. Currently, the research is attempting to use the Arch 497B BIM Studio (Figure 7.2) for this purpose. This file could also be made available to Penn State students via a central server to analyze their designs as they are familiar with Photoshop and have the required BIM-ESS tools.
7.3.2 WEB INTERFACE FOR GENERAL APPLICABILITY

The photoshop file was not the only system of integration explored. A website was also proposed which would enable designers create integrated visualizations irrespective of the BIM and ESS tools used. Having a website would also make the framework available to a larger set of designers and thus increase its applicability. In addition, the website would use other online resources to generate some of the required data such as the site image from Google Earth, Sun path from the UO SRML (Figure 7.3), solar angle from the Sun angle calculator (Figure 7.4) and wind information from www.windfinder.com (Figure 7.5) Using such resources to generate variable data would also help resolve the problem faced with integrating variables in the visualizations. As programming the website was not within the scope of the research, it was done with assistance from the Penn State ITS.
Early prototypes of the website tried incorporating site analysis (Figure 7.6) and solar radiation potential (Figure 7.7). These were then integrated with other steps, the base image and the Photoshop method to create the most current prototype. This prototype allowed creation of the site and orientation analysis visualizations. The research was unable to develop it further due to time constraints.
constraints but it is an example of the future potential and application of the framework.

![Site Analysis Toolset for PennState Architecture Students (Prototype) Not for public use](image1)

**Figure 7.6**: Initial Web Prototype for Site Analysis

![PSU Campus Solar Radiation Test](image2)

**Figure 7.7**: Initial Web Prototype for Solar Radiation

The prototype website (*Figure 7.8*) allowed designers to enter the coordinates of the site to generate a site image to layer in the central space. The designer had the option of scaling this image to a suitable size. The website allowed designers to upload images of the site and building plan to layer the
energy data on. Using the wind color scale, the designer could select relevant colors and fill them into the circular grid. A scribble tool allowed the designer to sketch the region with solar radiation. For the daylight analysis, the central space had a grid which could be filled with relevant colors from the color scale. This grid was programmed such that the designer could adjust the cell size thus determining how many cells required to be filled. These visualizations could then be saved as image files for future reference by the designer.

Despite being a prototype, the website displayed the future potential of the framework and a way of increasing its applicability within the design community.

Figure 7.8 : Proposed Web Interface for Site and Daylight Analysis

7.3.3 AUTODESK IDEA STUDIO PROPOSAL

Every summer, Autodesk invites proposals for the IDEA Studio which promotes research using its products in innovative ways. As the research used Autodesk Revit and Ecotect as the BIM and ESS tools respectively, a proposal was submitted to further the research by using the expertise of Autodesk employees and the facilities at the IDEA Studio. This opportunity would be used
to explore better ways to incorporate ventilation analysis using Autodesk ALGOR, a new CFD simulation tool developed by Autodesk. An attempt would also be made to further develop the web based interface and integrate it with Autodesk Project Butterfly (Figure 7.9). Project Butterfly is an online collaboration tool developed by Autodesk to allow designers to create, edit and share drawings online and only requires a web browser. The ventilation analysis and web based interface were existing areas of the research identified for future development using the expertise of Autodesk employees at the IDEA studio. A proposal for the same has been submitted to Autodesk and a decision is awaited.

Figure 7.9 : Autodesk Project Butterfly, showing integration of design drawing and Google Earth
BIBLIOGRAPHY OF CITED WORKS


Marsh, Andrew (1996) Integrating Performance Modelling into the Initial Stages of Design. [ANZAScA Conference Proceedings, Chinese University of Hong Kong, Hong Kong, China]


APPENDIX : Framework Workflows
## PROPOSED SITE ANALYSIS VISUALIZATION WORKFLOW

<table>
<thead>
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<th>AIM</th>
<th>WORKFLOW</th>
<th>VISUALIZATION</th>
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</thead>
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<td>1</td>
<td></td>
<td></td>
<td>Use base image to layer relevant data</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Site Image</td>
<td>Google Earth</td>
<td>Give context, orientation and surrounding environment to the site</td>
<td>Place relevant site image with correct orientation in the central blank space.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Scale</td>
<td>Sun Path</td>
<td>Wind Roses</td>
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</tr>
<tr>
<td>3</td>
<td>User</td>
<td>Autodesk Ecotect</td>
<td>Autodesk Ecotect</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Establishes a relationship between the site and proposed design.</td>
<td>Layer the generated sun path around the site with correct orientation.</td>
<td>Use given wind temperature scale to pick relevant colour and fill into circular grid around site with reference to already generated wind rose.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sun Path</td>
<td>Autodesk Ecotect</td>
<td>Wind Roses</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Track Sun movement in relation to design and interior layout.</td>
<td>Identify local winds, temperature, duration and how they impact the site.</td>
<td></td>
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<tr>
<td>5</td>
<td>Wind Roses</td>
<td>Autodesk Ecotect</td>
<td>Wind Roses</td>
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<tr>
<td></td>
<td>Shadow Range</td>
<td>Autodesk Ecotect</td>
<td>Autodesk Revit</td>
<td>To study how surrounding environment casts shadows on the sites and affects solar potential.</td>
<td>Layer shadow range generated in ESS and paste into relevant location on site image.</td>
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<tr>
<td>7.1</td>
<td>Solar Radiation</td>
<td>Autodesk Ecotect</td>
<td></td>
<td>Establish solar potential by studying solar path and how surrounding environment's shadows affect it.</td>
<td>For solar radiation, Mark start and end of sun position on Sun Path for time period being studied</td>
</tr>
<tr>
<td>7.2</td>
<td></td>
<td></td>
<td></td>
<td>This can help decide solar strategies like location of a photovoltaics and sun spaces.</td>
<td>Extend points to site and create polygon for range of Solar Radiation</td>
</tr>
<tr>
<td>7.3</td>
<td></td>
<td></td>
<td>Use given solar radiation scale to pick relevant colour and fill the polygon with it.</td>
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</tbody>
</table>
**PROPOSED ORIENTATION ANALYSIS : THERMAL COMFORT VISUALIZATION WORKFLOW**

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</thead>
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<td></td>
<td>Use base image to layer relevant data</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Site Image</td>
<td>Google Earth</td>
<td>Give context, orientation and surrounding environment to the site</td>
<td>Place relevant site image with correct orientation in the central blank space.</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>3</strong></td>
<td>Site Image Scale</td>
<td>User</td>
<td>Establishes a relationship between the site and proposed design. If scale is known, enter scale.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>4</strong></td>
<td>Sun Path</td>
<td>Autodesk Ecotect UO SRML</td>
<td>Track Sun movement in relation to design and interior layout. Layer the generated sun path around the site with correct orientation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>5</strong></td>
<td>Building Plan</td>
<td>Autodesk Revit</td>
<td>To study the effect of different orientations on thermal comfort in interior spaces. Place the building plan with the correct orientation and size.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>7</td>
<td>Cut out the relevant zones where daylight analysis is required.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td><strong>Thermal Comfort Analysis</strong></td>
<td>Autodesk Ecotect</td>
<td>This allows the designer to see the thermal comfort of internal spaces and how it changes depending on different orientations. Use the thermal colour scale and reference grid to fill in the relevant colours for daylight in the required zones.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td><strong>Wind Roses</strong></td>
<td>Autodesk Ecotect</td>
<td>Analyze how local winds can impact the thermal comfort of internal spaces. Use given wind temperature scale to pick relevant colour and fill into circular grid around site with reference to already generated wind rose.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Data</td>
<td>Source</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>----</td>
<td>------</td>
<td>--------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Site Image</td>
<td>Google Earth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Site Image</td>
<td>Google Earth</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Visualization Workflow**

<table>
<thead>
<tr>
<th>No</th>
<th>Workflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Place relevant site image with correct orientation in the central blank space.</td>
</tr>
<tr>
<td>2</td>
<td>Give context, orientation and surrounding environment to the site.</td>
</tr>
</tbody>
</table>

**Proposal Orientation Analysis - Daylighting Visualization Workflow**

1. Use base image to layer relevant data.
2. Site Image Google Earth

Give context, orientation and surrounding environment to the site.
<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Site Image Scale</td>
<td>User</td>
<td>Establishes a relationship between the site and building plan. If scale is known, enter scale.</td>
</tr>
<tr>
<td>4</td>
<td>Sun Path</td>
<td>Autodesk Ecotect UO SRML</td>
<td>Track Sun movement in relation to design and interior layout. Layer the generated sun path around the site with correct orientation.</td>
</tr>
<tr>
<td>5</td>
<td>Building Plan</td>
<td>Autodesk Revit</td>
<td>To study the effect of different orientations on daylighting in interior spaces. Layer the building plan with the correct orientation and size.</td>
</tr>
<tr>
<td></td>
<td>Daylighting Analysis</td>
<td>Autodesk Ecotect</td>
<td>Cut out the relevant zones where daylight analysis is required.</td>
</tr>
<tr>
<td>---</td>
<td>---------------------</td>
<td>------------------</td>
<td>-------------------------------------------------------------</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Daylighting Analysis</td>
<td>Autodesk Ecotect</td>
<td>This informs the designer of the daylighting potential of the relevant potential. Various orientations can be tried and the daylighting potential compared.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Use the daylight colour scale and reference grid to fill in the relevant colours for daylight in the required zones.</td>
</tr>
<tr>
<td>8</td>
<td>Shadow Range</td>
<td>Autodesk Ecotect</td>
<td>To study how shadows cast by the surrounding environment affect daylighting of the interior spaces</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Copy shadow range generated in Ecotect and paste into relevant location on site image.</td>
</tr>
<tr>
<td>9.1</td>
<td>Solar Radiation</td>
<td>Autodesk Ectotec</td>
<td>Establish solar potential by studying solar path and how surrounding environment’s shadows affect it.</td>
</tr>
<tr>
<td>-----</td>
<td>----------------</td>
<td>------------------</td>
<td>----------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>9.2</td>
<td></td>
<td></td>
<td>This can help decide the locations of spaces which require daylighting and solar gain such as a greenhouse.</td>
</tr>
<tr>
<td>9.3</td>
<td></td>
<td></td>
<td>Using the visualization, the designer can evaluate daylighting and solar potential of different orientations.</td>
</tr>
</tbody>
</table>
# PROPOSED BUILDING SKIN OPTIMIZATION WORKFLOW

<table>
<thead>
<tr>
<th>NO</th>
<th>DATA</th>
<th>SOURCE</th>
<th>AIM</th>
<th>WORKFLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>Use base image to layer relevant data</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Site Image</td>
<td>Google Earth</td>
<td>Give context, orientation and surrounding environment to the site</td>
<td>Place relevant site image with correct orientation in the central blank space.</td>
</tr>
<tr>
<td>Step</td>
<td>Description</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Establishes a relationship between the site and proposed design. A suitable scale is chosen to allow the designer see the materiality in the building plan. If scale is known, enter scale.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>To study the effect of different materiality on internal thermal comfort. Place the building plan at the relevant location, orientation and scale.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Cut out the relevant zones where daylight analysis is required. Cut out the relevant zones where daylight analysis is required.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>User</th>
<th>Autodesk Revit</th>
</tr>
</thead>
</table>
6. Rotate and resize the grid as required.

7. **Thermal Comfort Analysis**
   - Autodesk Ecotect
   - This allows the designer to see the impact of different materiality on internal thermal comfort.
   - Use the thermal colour scale and reference grid to fill in the relevant colours for daylight in the required zones.

8. **Wind Roses**
   - Autodesk Ecotect
   - Analyze local winds which affect the building and can have an impact on thermal comfort.
   - Use given wind temperature scale to pick relevant colour and fill into circular grid around site with reference to already generated wind rose.
### Proposed Ventilation Analysis Workflow

<table>
<thead>
<tr>
<th>No</th>
<th>Data</th>
<th>Source</th>
<th>Aim</th>
<th>Workflow</th>
<th>Visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Use base image to layer relevant data</td>
<td><img src="image1.png" alt="Diagram 1" /></td>
</tr>
<tr>
<td>2</td>
<td>Site Image</td>
<td>Google Earth</td>
<td>Give context, orientation and surrounding environment to the site</td>
<td>Place relevant site image with correct orientation in the central blank space.</td>
<td><img src="image2.png" alt="Diagram 2" /></td>
</tr>
<tr>
<td>Step</td>
<td>Task</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>------</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Establishes a relationship between the site, building plan and section.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Place the building plan with the correct orientation and size.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Cut out the relevant zones where daylight analysis is required.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**User**

**Site Image Scale**

**Building Plan Autodesk Revit**
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Internal Airflow</td>
<td>FLUENT</td>
</tr>
<tr>
<td></td>
<td>Allows the designer to see how air moves through a space. This helps establish if the layout promotes ventilation.</td>
<td>Use the airflow rate colour scale and reference grid to fill in the relevant colours for airflow in the required zones.</td>
</tr>
<tr>
<td>7</td>
<td>Wind Roses</td>
<td>Autodesk Ecotect</td>
</tr>
<tr>
<td></td>
<td>The designer can see the temperature and duration of winds which enter the space.</td>
<td>Use given wind temperature scale to pick relevant colour and fill into circular grid around site with reference to already generated wind rose.</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>To establish a relationship between the horizontal and vertical analysis.</td>
<td>Rotate the circular grid such that the section line cuts through the plan where the section was taken.</td>
</tr>
<tr>
<td>9</td>
<td>Building Section</td>
<td>Autodesk Revit</td>
</tr>
<tr>
<td>---</td>
<td>------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Internal Airflow</td>
<td>FLUENT</td>
</tr>
</tbody>
</table>
Use given wind temperature scale to pick relevant colour and fill into circular grid around site with reference to already generated wind rose.
# Proposed Shading Analysis Visualization Workflow

<table>
<thead>
<tr>
<th>NO</th>
<th>DATA</th>
<th>SOURCE</th>
<th>AIM</th>
<th>Workflow</th>
<th>Visualization</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Use base image to layer relevant data</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Site Image</td>
<td>Google Earth</td>
<td>Give context, orientation and surrounding</td>
<td>Place relevant site image with correct orientation in the central blank</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>environment to the site</td>
<td>space.</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Site Image Scale</td>
<td>User</td>
<td>Establishes a relationship between the site, building plan and section.</td>
<td>If scale is known, enter scale.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sun Path</td>
<td>Autodesk Ecotect UO SRML</td>
<td>Study sun movement with respect to shading potential of the design.</td>
<td>Layer the generated sun path around the site with correct orientation.</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Building Plan</td>
<td>Autodesk Revit</td>
<td>To study how sun enters internal spaces throughout the day and influences daylighting.</td>
<td>Place the building plan with the correct orientation and size.</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>Cut out the relevant zones where daylight analysis is required.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Page</td>
<td>Task</td>
<td>Software</td>
<td>Description</td>
<td>Instructions</td>
<td></td>
</tr>
<tr>
<td>------</td>
<td>-----------------------</td>
<td>----------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Daylight Analysis</td>
<td>Autodesk Ecotect</td>
<td>To study how shading devices impact internal daylighting with respect to the sun's movement throughout the day.</td>
<td>Use the daylighting colour scale and reference grid to fill in the relevant colours for daylight in the required zones.</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Sun Position</td>
<td>Autodesk Ecotect</td>
<td>To establish what time the analysis is being carried out for.</td>
<td>Place Sun at relevant position on Sun Chart with respect to time and date being used for analysis.</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>To establish a relationship between the horizontal and vertical analysis.</td>
<td>Rotate the circular grid such that the section line cuts through the plan where the section was taken.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Building Section</td>
<td>Autodesk Revit</td>
<td>To study how shading deals with sun angles.</td>
<td>Layer the section in the central vertical grid and resize it to the same scale as the plan.</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>------------------</td>
<td>----------------</td>
<td>--------------------------------------------</td>
<td>------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Daylight Analysis</td>
<td>Autodesk Ecotect</td>
<td>To study how shading devices impact internal daylighting.</td>
<td>Cut out the relevant zones where daylight analysis is required. Use the daylight colour scale and reference grid to fill in the relevant colours for daylight in the required zones.</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Sun Angle</td>
<td>Autodesk Ecotect Sun Angle Calculator</td>
<td>Establish sun angle for the relevant day and time and see how shading device deals with different sun angles.</td>
<td>Use the notches on the grid to layer the sun ray generated in the ESS. This gives the angle o the sun at the relevant date and time.</td>
<td></td>
</tr>
<tr>
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<td>---</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>To see how the sun angle for a specific day and time impacts the overall design.</td>
<td>Copy the sun ray and paste in on all the notches to see how the sun strikes all the surfaces.</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>