VIRTUAL FACILITY PROTOTYPING FOR SUSTAINABLE PROJECT DELIVERY

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SUMMARY: *The delivery of facilities which incorporate a high degree of sustainable characteristics requires extensive collaboration and coordination between many professionals early in the design process. One challenge related to the design of sustainable projects is the ability for each professional to understand the impact of one building system on the performance of the building as a whole. Advanced visualization applications and display systems allow professionals to gain a better understanding of a facility including the 3D product model, the construction process, and the facility performance. This paper presents a case study of the design of an Early Childhood Development Center and the application of various modeling tools and media to display the developed models. This case helps demonstrate the value of visualizing design and construction information in virtual prototypes to improve decisions relevant to achieving sustainable design goals.*

KEYWORDS: *sustainability, visualization, immersive display system, virtual reality, building simulation.*

1. INTRODUCTION

Interdisciplinary collaboration and coordination is critical to developing sustainable projects. With recent advancements in computer display technology, it is now possible to place the project team within a large-scale, immersive projection display system that allows the team to experiment with a 3D, full-scale virtual prototype of a building project. This advanced visual communication can provide a common graphical language for team members from multiple disciplines to understand project design information and draw upon their experience and tacit knowledge to provide more efficient and effective facility designs. A virtual prototype allows disciplines to interact in a common model and critically evaluate various design options from multiple perspectives. This can significantly improve the total building energy performance due to the simulation of different building environmental systems. Additional information can also be added to the model including Computational Fluid Dynamics analysis; luminance distributions; thermal gains and losses; and graphical representations of other data. For example, one can color code objects to represent the recycled material content or the thermal properties of a material. These capabilities provide the core tools needed for experienced design, construction, and facility operation team members to perform high quality design, construction, and operation reviews.

This paper presents the value and application of a collaborative visualization process through a detailed case study of a sustainable building project. The project is the design of a new day care center for Chief Dull Knife College in Montana, USA. This project is seeking a LEED® Gold rating and is being developed through a collaborative effort between the American Indian Housing Initiative based at Penn State University and Chief Dull Knife College. The design and construction planning process for this project focused on a highly collaborative process with many different professional and student groups seeking innovative design and construction methods. The ability to visualize the various prototypes of this project throughout the design and construction planning phases was critical for effective collaboration.

A description of the systems and methods used to develop and review the virtual facility prototypes for this sustainable project are included in this paper. Guidelines for effectively using advanced visualization tools to achieve more sustainable project delivery are also developed from the lessons learned on this project.

2. SUSTAINABLE BUILDINGS

Green or "sustainable" buildings place value on minimizing the environmental impact of the built environment through strategies focused on 1) sustainable site design; 2) water efficiency; 3) energy efficiency; 4) green materials and resource efficiency; 5) indoor environmental quality; and 6) innovation and design process. The demand for green buildings is increasing rapidly around the world as private and public faculty owners become more attuned to the financial benefits of sustainable design to energy efficiency and improved health and productivity of occupants. The introduction of the LEED® (Leadership in Energy and Environmental Design) rating system in the U.S. by the U.S. Green Building Council (2005) has accelerated the demand for green buildings and sustainable design in the U.S. by providing metrics for evaluating the levels of sustainability achieved, and also, more importantly, providing targeted and focused design goals for project teams.

Green buildings require close integration of building systems and more intense energy, daylighting, and material analysis during design. Most building simulation and analysis tools require a three dimensional (3D) representation of building surfaces and properties. These virtual facility models can be time consuming to produce. As designs evolve, the need to repeat and exchange analysis results between various design disciplines becomes complex and labour intensive. In many cases, these challenges often result in building designs that proceed without the full benefit of building simulation and analysis information and as a result, less than optimal energy and daylighting solutions.

3. VIRTUAL FACILITY PROTOTYPING

Virtual prototyping incorporates the concepts of product models and building information models. Through the application of 3D modeling tools, virtual prototyping provides a means of rapidly developing a graphical representation of a design and provides an opportunity to analyze the design for form, fit, logistics, human factors integration, and general feasibility analysis (Schaaf and Thompson 1997). The US Department of Defense defined a virtual prototype as 'a model or simulation of a system placed in a synthetic environment, and used to investigate and evaluate requirements, concepts, system design, testing, production, and sustainment of the system throughout its life cycle'(Department of Defense 1995).

Several researchers have proposed the use of virtual prototyping in the construction industry. According to Issa, a Virtual Reality Integrated Construction System should have (Issa 2003):

- the capability to enable designers, developers and contractors to virtually test a proposed project before its construction;
- a 'walk through' to view the project so as to solve the problems in the early stage;
- free flow of information between CAD systems and other applications work packages; and
- the ability to select alternative designs by allowing different plans to be tested.

Maver and Petric (2003) have addressed the value of using computer models for design as:

- Widening the search for solutions;
- Improved integration in decision making;
- Improved design insights;
- Differentiation of objective and subjective judgement; and
- Verisimilitude of visualizations.

A virtual prototype can be displayed within a number of medium. The medium used to interact with the virtual model is important. The core components of virtual reality (VR) have been defined by Burdea and Coiffet (2003) as:

1. Immersion: Immersion has been defined as a sensation of being in an environment. This immersion can be physical (e.g., immersion within a large, stereo display system) or mental (e.g., being deeply engaged in the virtual world).
2. Interaction: The user has the ability to interact in real time with the virtual world and receive visual, audio, tacit, smell or taste feedback.

3. Imagination: The user can imagine items that may not be shown within the model

Much focus from application vendors that support the Architecture, Engineering and Construction (AEC) Industry is placed on the development of applications that can be used to develop model content. This content may be in the form of 2D or 3D geometry, and may also contain additional information regarding the facility. This information (e.g., cost, schedule, product characteristics) have been broadly discussed as nD modeling (Lee et al. 2003) or Building Information Modeling (Ibrahim and Krawczyk 2003). These modeling efforts and the applications that support these efforts provide vehicles to improve the design process for sustainable projects since they can provide better information to the decision makers throughout the process.

In addition to the model development, it is imperative that the model content be communicated to the decision makers in a format which promotes effective decision making. This model presentation is through some medium of communication. This medium may be a text document, 2D drawings on paper, the electronic display of 3D models on a screen, or using immersive projection display systems to view models in an immersive environment. This medium of communication is critical to the communication process. A progression of modeling methods and media for communicating models is shown in Fig. 1.

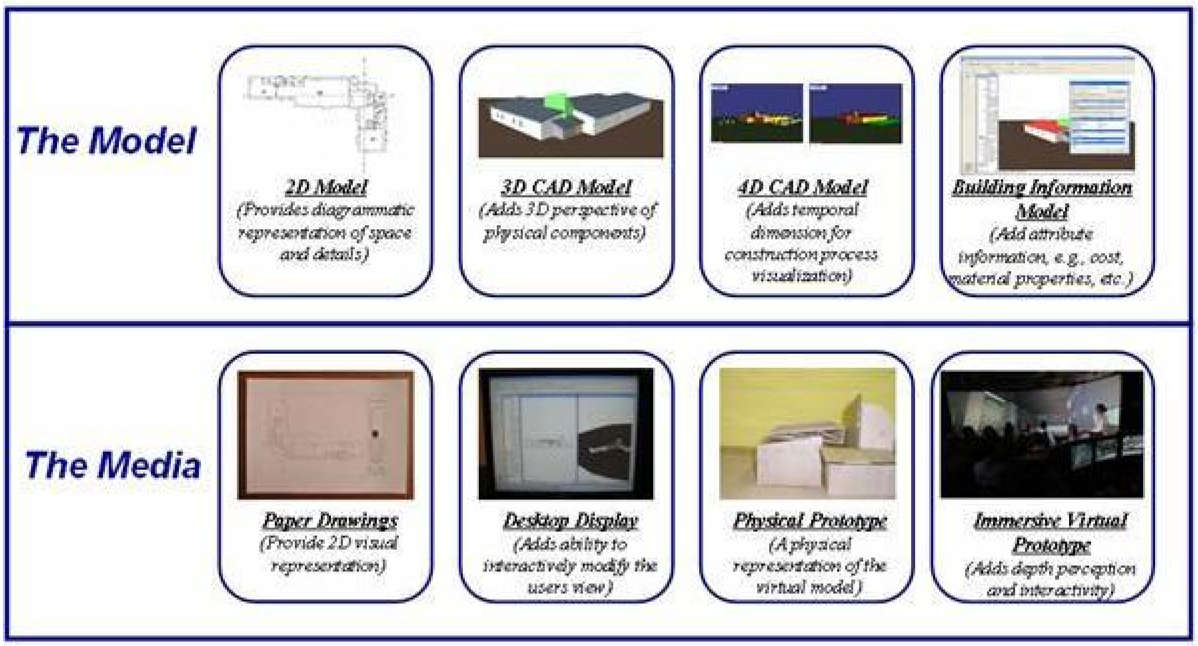

FIG. 1: Models and Media for Prototype Visualization

The use of a virtual reality display system which provides physical immersion can provide several valuable benefits when compared to other media for communicating a product or process model. The immersive nature of the display system through large scale, stereo viewing adds a dimension of realism for the viewer (also referred to as a sense of presence (Slater and Wilbur 1997)). This added realism has been shown to improve the confidence level of users when reviewing design and construction information; increase the identification of design and construction conflicts; and improve the overall understanding of a project design (Yerrapathruni et al. 2003). Another important benefit to viewing virtual prototypes in immersive projection displays is that they engage the users. This can increase the amount of time that users spend reviewing the models which can ultimately increase the quantity of feedback.

4. CASE STUDY: EARLY CHILDHOOD LEARNING CENTER

To illustrate the current capabilities of virtual facility prototyping tools, a detailed virtual facility prototype was developed for the Early Childhood Learning Center which was built in the summer of 2005. This prototype included physical product information, process information, and simulation information. The prototype evolved throughout the design phase of the project and has been used, in many different versions, as the project design matured to make important decisions related to the sustainability of the project. This section will describe the project information; the prototype development and evolution; and conclude with comments regarding the value of using the virtual prototype.

4.1 Project Description

The Early Childhood Learning Center (ECLC) is the seventh building to be constructed through a collaborative effort of universities and Northern Plains Indian Tribes called the American Indian Housing Initiative (AIHI). Each year, students and faculty at Penn State and participating universities including the University of Washington, University of Wisconsin, and most recently, the University of Texas, collaborate in the design and planning of a sustainable housing or community building. These facilities are then constructed by students in two three week blitz-build workshops during the summer. To date, four homes and three community buildings have been completed featuring strawbale construction methods and other energy and resource efficient materials and technologies.

The ECLC project was initiated through a partnership with Chief Dull Knife College (CDKC) on the Northern Cheyenne reservation in Montana. One of the many challenges facing tribal members and residents in this region interested in attending college is finding adequate childcare. In 2003, AIHI partners helped acquire a U.S. Housing and Urban Development (HUD) TCUP grant for a new center for early childhood learning on the campus of CDKC. This 4,000 square foot (372 m^2) facility will double the current childcare capacity at the college. Due to the extreme temperatures and high energy costs in the region, and the desire to create a healthy learning environment for children, the ECLC was targeted to be a LEED® Gold Certified Facility.

After initial design charettes on the campus of CDKC in the summer of 2004, an initial schematic design was developed by a studio class at the University of Washington. The initial design was then developed further at Penn State through the integration of the project into three graduate courses and the AIHI course series. A brief description of the courses used to develop the design is provided below.

Sustainable Building Methods (Graduate): Students in this graduate class conducted an initial LEED point review of the project, and performed feasibility analysis of several sustainable building features, including rain water catchment and evaporative cooling.

Virtual Design and Construction (Graduate): Students in this class helped to create 3D surface and solid models of the building, in addition to 4D and VRML simulations of the construction process. One student group also performed a daylighting analysis of the design.

Production Planning (Graduate): Students in this class helped to develop detailed short interval construction schedules for the three week summer blitz build.

Design-Build Montana (Integrated): Undergraduate and graduate students in this class performed materials research and construction planning for the ECLC, and eventually travelled to Montana to lead other students, volunteers, and tribal members in the construction of the ECLC superstructure.

The final design of the ECLC included the following key building elements and sustainable design features:

- Load-bearing strawbale walls,
- Structural Insulated Panel walls and roof,
- Custom fabricated insulated translucent wall panels,
- Triple glazed windows,
- Radiant floor heating,
- Evaporative cooling,
- Low VOC paints and finishes,
- Digital climate control and CO2 monitoring,
- Energy Star appliances,
- Low-flow water fixtures, and
- Rough-in for future solar hot water collectors.

4.2 Virtual Models of the Early Childhood Development Center

A variety of virtual modeling tools have been used throughout the one year design process for the Early Childhood Learning Center. Initially, a 3D model of the facility was developed using SketchUp, a rapid 3D modeling application. Fig. 2 illustrated an early design concept sketch of the floor plan accompanied by a 3D rendering using SketchUp by @Last Software. Later, during design development, a different design team member developed a concept rendering of the ECLC using for the center using form·Z by auto·des·sys, Inc. (Fig. 3). During the latter stages of design development, the design team agreed upon the use of Autodesk Architectural Desktop and Revit models which continued to be used throughout the design process.

A key element of the design process was the development of a footprint that minimized the intrusion of the building into the courtyard of Chief Dull Knife College, while still allowing the code-required play space outside the facility. An "L" shaped configuration emerged, which effectively wrapped the ECLC around an existing cultural center (building with the green roof shown in Fig. 2).

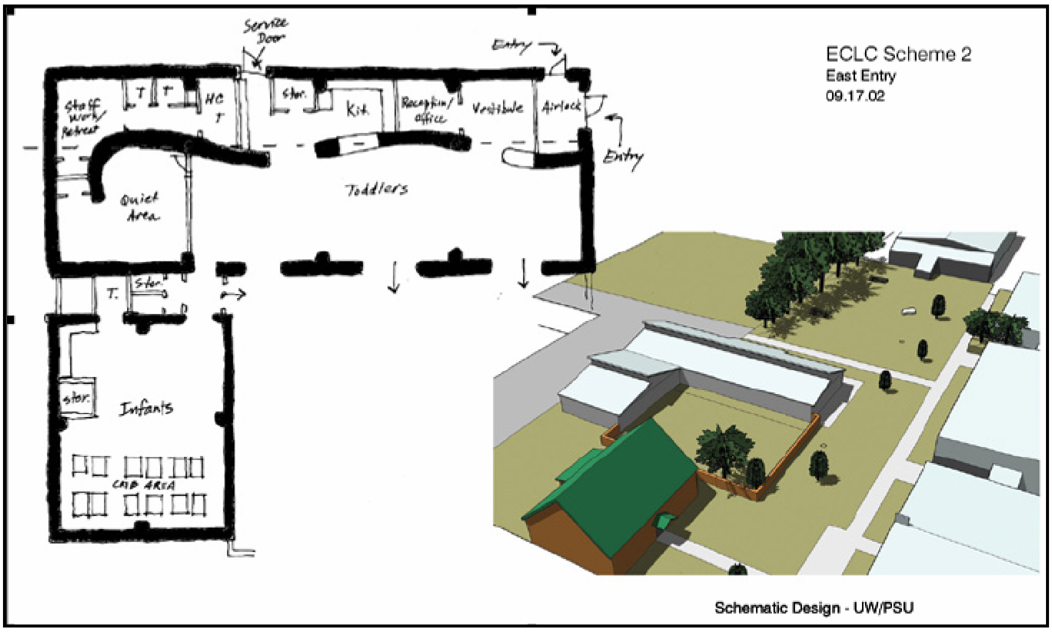

FIG. 2: Initial rendering of ECLC using SketchUp®

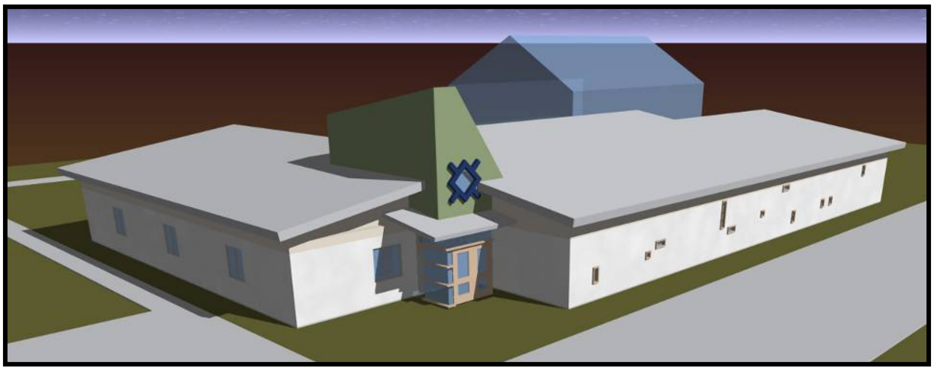

FIG. 3: Design development model generated in form·Z

The use of visualization software during conceptual and schematic design proved valuable for two main reasons. First, the fact that a 3D electronic version of the rendering existed permitted the concept models to be distributed quickly to all team members, including consultants in various disciplines such as daylighting, energy modeling, and the leadership at Chief Dull Knife College. In addition, having these renderings in 3D expedited the ability of team players to understand and evaluate the geometry of the building, and the impact of the building on the site in terms of views from various positions in the courtyard, the shadows cast from and to neighbouring buildings, and the proximity of the building to the cultural center.

4.2.1 Building Information Model

A building information model (BIM) of the facility was then developed in Autodesk Revit. The BIM includes product data for the physical elements contained within the building. Fig. 4 shows a perspective of the BIM developed in Autodesk Revit. This model includes the building properties for each of the product model elements. One advantage of using the BIM application instead of a 3D CAD application is the ability to generate a more comprehensive product model of the facility with limited added effort. For example, the model includes information regarding the visual properties of the building (e.g., color, textures, etc.), but also includes information regarding additional material properties (e.g., structural and mechanical properties). This additional information can be exported in a format that is readable by other applications. While the interoperability of the parametric modeling applications which allow for building information modeling is still somewhat limited, many of the modeling applications can currently export Industry Foundation Classes (IFCs) or other standard data formats. There were many frustrations throughout this project related to the most appropriate methods for exporting and importing data from the various applications used, and significant efficiency could be gained from a more extensive adoption of standard data models for interoperability between modeling applications.

FIG. 4: Autodesk Revit Model of ECLC

4.2.2 Surface Model

One of the challenges facing design teams on a sustainable or high performance building project is the need to perform energy and daylighting analysis of alternate early design concepts to assess the impact of various configurations on daylight levels and energy use. Quite often these analyses require individual consultants to develop 3D models of the designs independently. As the development of models is often the most time consuming part of the consulting hours, a shared surface model was developed for the purposes of providing consultants with the information needed, such as surface geometry and respective U values, reflectance and transmittance values for the materials used on the ECLC façade. After an initial meeting with consultants to understand the requirements of the surface models needed for eQUEST and RADIANCE lighting simulation software, a combined surface model was generated and transmitted to each consultant (Ward 1994). In addition to the 3D surface model generated in AutoCAD, a table listing the key properties of each surface material was developed to allow consultants to quickly import necessary data for their respective analysis. AutoCAD was used due to the limited export capabilities of Revit Version 7.0 although many of the features have been improved in the recently release Revit Version 8.0. Fig. 5 illustrates the initial surface model generated for daylight and energy analysis during the schematic design phase of the project.

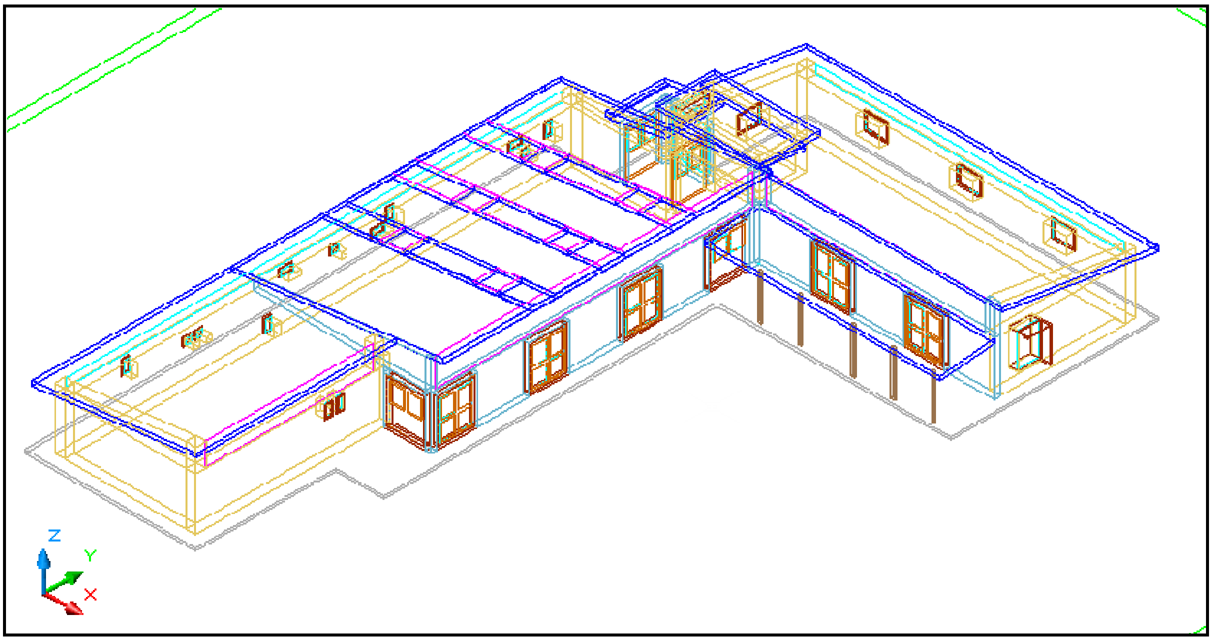

FIG. 5: Initial surface model of ECLC distributed to design consultants for energy and daylighting analysis

4.2.3 Daylight Simulation Model

The introduction of daylighting was an important criterion for the design of the building. However, the extreme climate in Montana (which can vary between -50 degrees F (-60˚ C) in the winter and 110 degrees F (29˚ C) in the summer) demanded that the use of windows be limited to control heat loss and gain. During the early stages of design the concept of south facing clerestories was introduced. This concept was carried forward as much as possible while the building design progressed. Unfortunately, the constraints of the site limited the ability for the design to embrace the path of the sun. Fig. 6 illustrates an initial evaluation of a schematic design concept using the RADIANCE lighting simulation and rendering system (Ward 1994). This image helps illustrate the levels of light that fall on different surfaces of the building, and can provide valuable information during the early stages of design for selecting elevations that can provide maximum daylighting gains. Irradiance simulations are based on actual hourly weather data for Billing, MN using the Perez sky model (Perez et al. 1993).

Windows in extreme climates such as Montana should be strategically placed for maximum daylight availability, maximum solar gains during the winter, and minimum solar gains during the summer. This required maps showing the monthly average solar and diffuse irradiance on each exterior building surface, based on hourly weather data. As a rule for sustainable buildings, windows should be located in the areas with low solar irradiance in the summer, high solar irradiance in the winter, and high diffuse irradiance year round. Fig. 6 and Fig. 7 show that the south-south-east facing walls fulfil both requirements, whereas the east-south-east facing walls should be avoided due to low thermal gains in the winter and generally low diffuse year-round illuminance levels. These initial maps based on actual weather data give the designers important feedback on passive solar and daylighting strategies, and they allow for easy communication with the other members in the design and construction team.

Clerestories on both facades generate the interior average monthly illuminance pattern for March as shown in Fig. 8 from RADIANCE. A daylight model for the facility was also developed using AGI 32 by Lighting Analysts, Inc. This model helped everyone understand the impact of daylighting throughout the facility along with the material selection which will maximize the benefits of the daylighting. An interior image from the daylighting model is shown in Fig. 9. This model was exported from AGI 32 as a VRML 97 formatted file which can be loaded in any VRML compliant viewer. Additional interaction was then embedded into the model to allow a user to interactively switch the flooring material and see the variation in the daylighting based on the properties of the various flooring materials including concrete, carpet, and tile. This interactive model can be viewed on a desktop computer or in the immersive environments lab through a stereo VRML viewer.

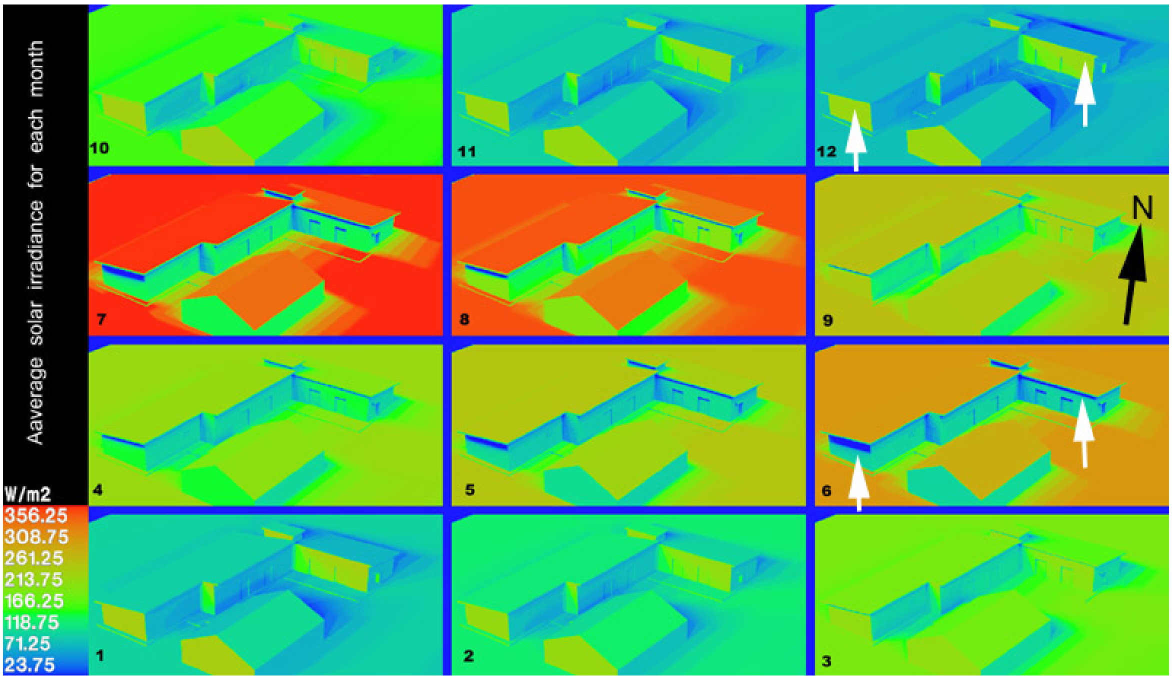

FIG. 6: Monthly average solar irradiance on the different surfaces from East to West. White arrows indicate surfaces with beneficial low solar gains in the summer and high solar gains in the cold months.

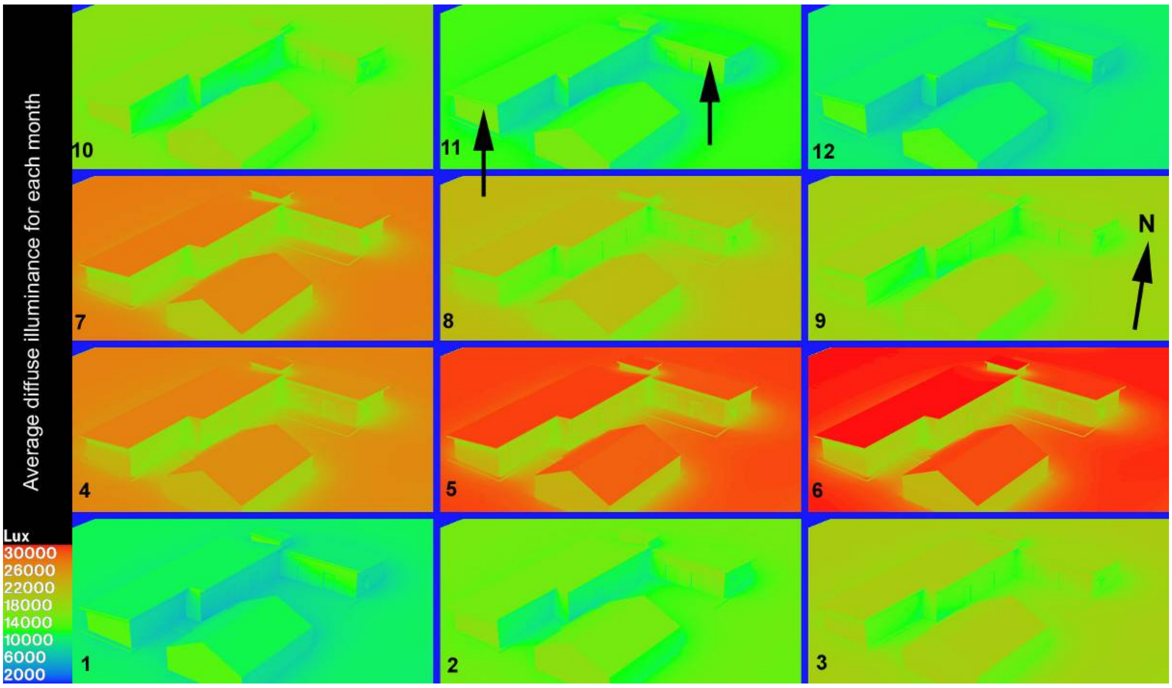

FIG. 7: Monthly average diffuse illuminance on the different surfaces from East to West, due to diffuse sky only. Black arrows in picture 11 indicate the maximum diffuse illuminance with the most beneficial locations for windows.

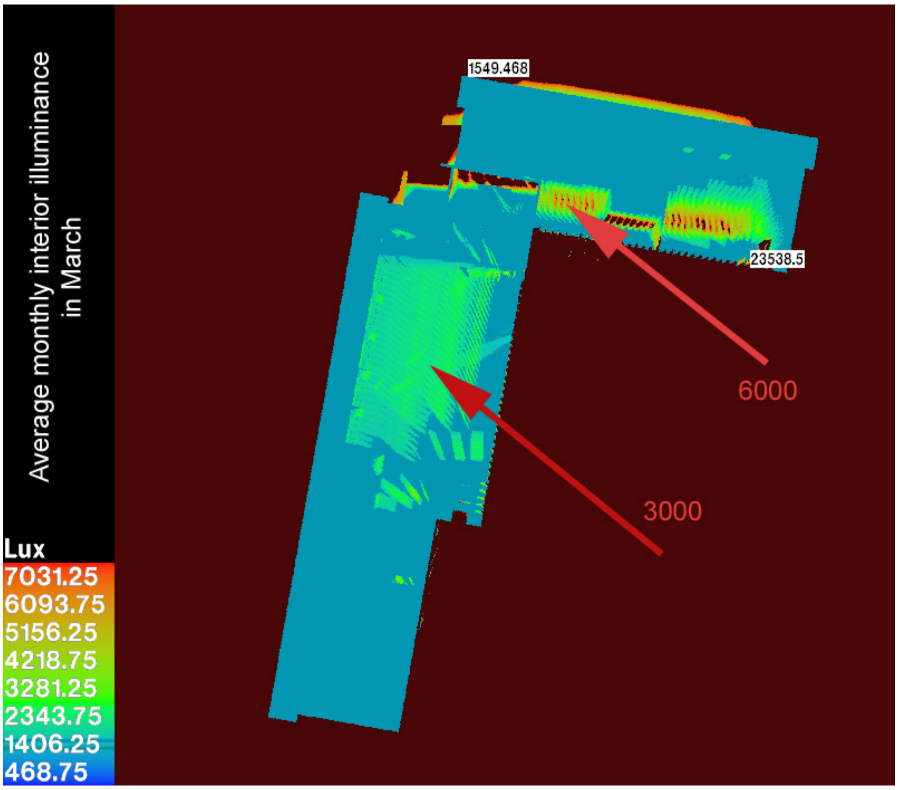

FIG. 8: Interior Daylight Illuminance in March

FIG. 9: Interactive Daylighting Model in VRML format

4.2.4 Energy Modeling

The use of energy modelling during the prototyping process is critical to making informed design decisions about the envelope of the building. Several interactions and types of energy analyses are needed throughout the building design process. Initially, schematic representations of a facility can be used to evaluate alternative energy saving strategies. Later in the process, as the design evolves, energy models help to estimate energy requirements and size mechanical equipment. In the final stages of a project, energy models and performance monitoring sensors are used to verify the performance of mechanical system designs.

In the case of the ECLC, Energy-10™ (Sustainable Building Industry Council 2004) software was used during preliminary stages of design to compare benefits of daylighting and energy use strategies. This analysis helped show that any use of daylighting would result in net energy loss in the building, as the solar gain through windows was insufficient to make up for the energy lost through windows. Since daylighting was still an important feature goal for the design team, strategies to minimize heat loss were developed through the use of energy efficient translucent panels instead of windows on several surfaces of the building. Fabricated on site, these low-cost panels made from Polygal plastic also provided adequate financial savings to allow highly energy efficient triple glazed windows to be used at other key locations in the facility to allow for additional daylighting.

After the selection of mechanical systems that were proven to be effective in the region of the facility, further energy modelling was performed to verify the building performance with the various potential systems during times of extreme temperatures. The results of this analysis were then used in the final development of a controls strategy for the building in which initial set-back times and control logic was developed for the ECLC.

The energy modelling used in the design of the ECLC was less than optimal, and hindered by the labour intensive efforts needed to revise the model as late changes were made to the building façade, and indecision about the use of façade materials pushed the modelling late into the design process. As a result, many design decisions had to be made without the benefit of energy simulation data. This common problem found often in the building design process clearly demonstrates the need for not only improved interoperability between building simulation tools and 3D modelling tools, but also a better understanding of energy modelling analysis results by design team members. While not implemented on the ECLC project, new and more integrated building simulation tools capable of producing graphical output exist and have been found to improve the communication of the results of energy modelling analysis (VEL Engineering 2004). Also, interoperability methods such as the Green Building XML initiative which developed the gbXML schema allows for the integration of building information modeling applications and energy modeling applications. One application that is available via the internet is the Green Building Studio by Geopraxis, Inc. (2004).

4.2.5 Construction Process Simulation Model

A construction process visualization model was also developed for this project. This model integrated the construction schedule with the 3D model to develop a 4D CAD model. This 4D CAD model was used to analyze and improve the schedule and to review constructability issues related to sequencing that could impact the facility design.

The complete 4D CAD model includes the physical building products along with temporary staging locations for large and bulk materials (see Fig. 10 for snapshots of the model on different days). Fig. 10a illustrates the initial structural insulated panel elements of the construction sequence that were to be completed by a contractor. Figure 10b illustrates the construction of the straw walls (red indicating “in progress”). Figure 10c illustrated the erection of trusses starting in the north wing. Figure 10d illustrates the completion of the structural insulated panel roof on the south wing.

The 4D CAD model provided several benefits during the design process. It was critical for the design team to understand the sequence of construction so that the connection details were accurately developed based on assembly sequence. It was also valuable for the construction team to be able to investigate the most appropriate location for the material storage and staging onsite, especially since it is a congested site and many activities must occur simultaneously.

In addition to the value of the model in the design and construction planning phases, the model is also very valuable for communicating the construction sequence to a large number of volunteer workers that will be constructing the project. The 4D model can quickly communicate the construction sequence and staging area locations to a large workforce in a very efficient and visual manner. This can be valuable to make sure that material deliveries and work staging areas are properly located on site and it can ensure that the large workforce is working on the most appropriate activities throughout the construction period. In additional, the model will be valuable in future years for documenting the construction process. Data was collected to clearly illustrate the actual schedule and the 4D model will be used in future years to evaluate the actual schedule.

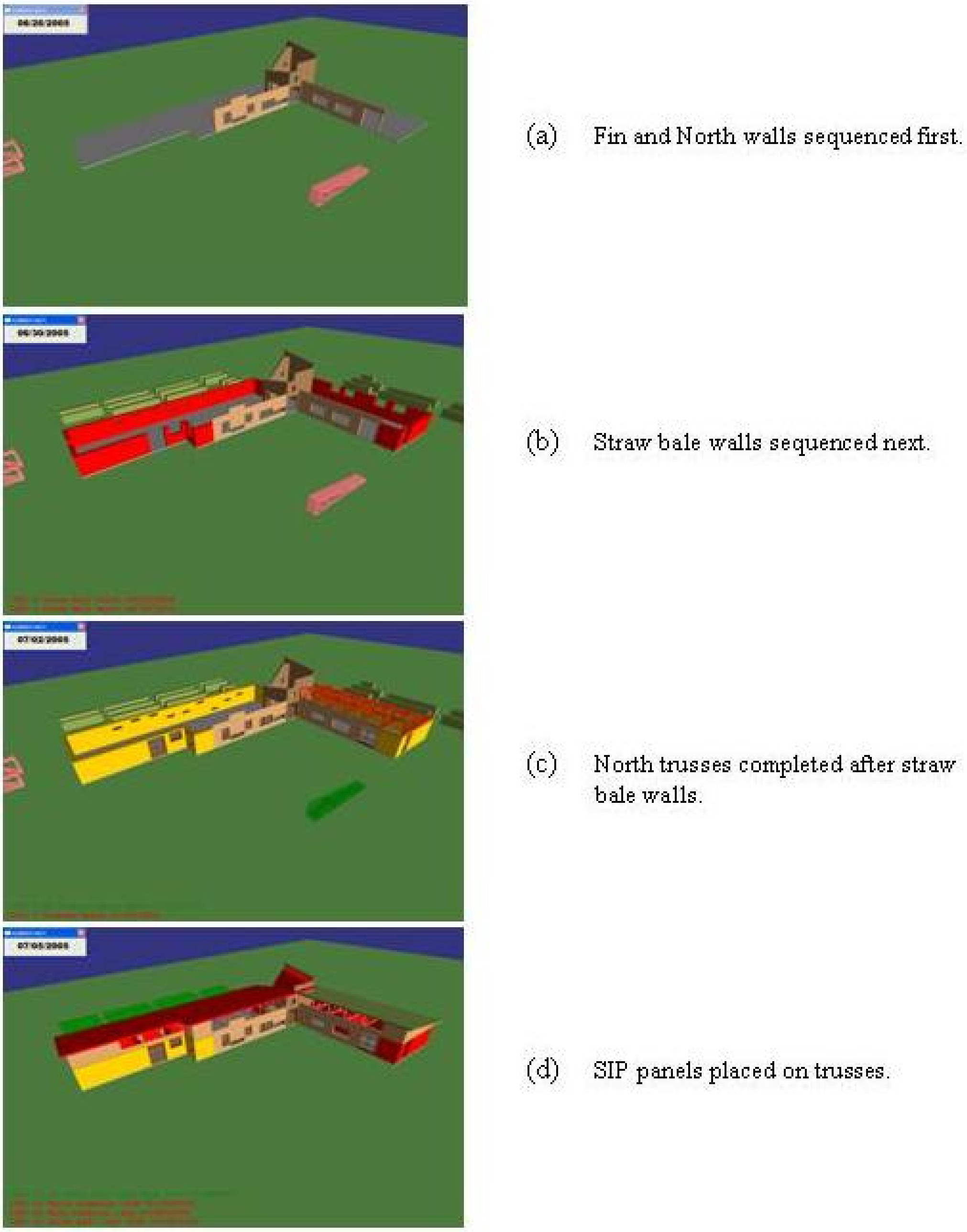

FIG. 10: Construction Process Model from Common Point Project 4D™

4.3 Advanced Media for Visualization

In additional to the development of the various models, it is important to consider the nature of the media used to view, navigate, and interact with the models. In addition to typical media for viewing facilities designs, including paper drawings and computer screen displays, the virtual models for the ECLC were visualized in a large immersive display system as well as a scale physical model that was developed directly from the virtual model.

4.3.1 Virtual Facility Prototype Visualization in an Immersive Environment

Several virtual facility prototypes for the ECLC were reviewed within the Immersive Construction (ICon) Lab during the design phase of the project. The ICon Lab is a projection-based immersive virtual environment (see CIC Research Group (2006) for additional details on the display system components). The ICon Lab is a large format, three screen, stereo display system which was developed from previous work at Penn State to construct the Immersive Environments Lab (Otto et al. 2005). The ICon Lab allows for the viewing and navigation of models at full or modified scales. The ICon Lab includes three backlit, passive stereo projection screens which allow for the stereoscopic visualization of virtual models. The ICon Lab will seat up to 30 people who can navigate and view models using a joystick, gyromouse, or remote keyboard. One goal for the ICon Lab development was to use a familiar computing environment and simple input devices to encourage users to engage with the friendly environment. This facility is used by students for navigating models and providing presentations for their course projects. The facility has also been used for presenting models to industry practitioners such as the models used in the ECLC project.

Several models were viewed in the ICon Lab throughout the design phase of the ECLC project. Initially, the surface model of the building along with surrounding buildings were imported, in the form of a VRML model, into the facility for navigation. Later in the design process, the 4D CAD model was displayed to the volunteer students for input and educational purposes. The detailed daylighting prototype which clearly displays the various daylighting levels in the facility for different times of year and different building materials was also displayed in the lab (see Fig. 11). Once the virtual models were developed, it was easy to export these models into VRML 97 format and load them into the ICon LAB. Additional interactivity was embedded into several prototypes through the use of a VRML editor.

FIG. 11: Immersive Construction Lab with Student Presentation of the Daylighting Prototype

4.3.2 Digital Fabrication of the Physical Model and SIP Panels

While the value of virtual models and analysis tools to the design process for sustainable buildings is undeniable, the use of physical models during design and construction planning is often still appropriate. In the case of the ECLC, the planning of the wall assembly and the panelization of the roof frame were analyzed through the fabrication of a scaled physical model of the building on which each structural panel was annotated based on size and installation sequence. Unlike conventional model building, the scaled model of the ECLC was created using a laser-cutting digital fabrication machine.

CAD files of building elevations and roof plans were utilized as inputs to the physical model development (see Fig. 12). Laser-cut sections of the façade were then cut and at the same time, inscribed with panel numbers and façade materials. The physical model was then assembled to evaluate the sequence and configuration of panels on the roof frame. In a second round of digital fabrication, individual panels were cut to help the planning team develop staging plans for the manipulation and pre-assembly of panels on the site. Once the plan for partitioning the structural wall and roof panels was developed, the CAD files used by the design team were transmitted to the SIP manufacturer, which used the files to generate shop drawings and ultimately the digital fabrication of the actual panels to be used in the building construction. Fig. 13 illustrates the digitally fabricated model elements used to help plan the construction sequence of the model.

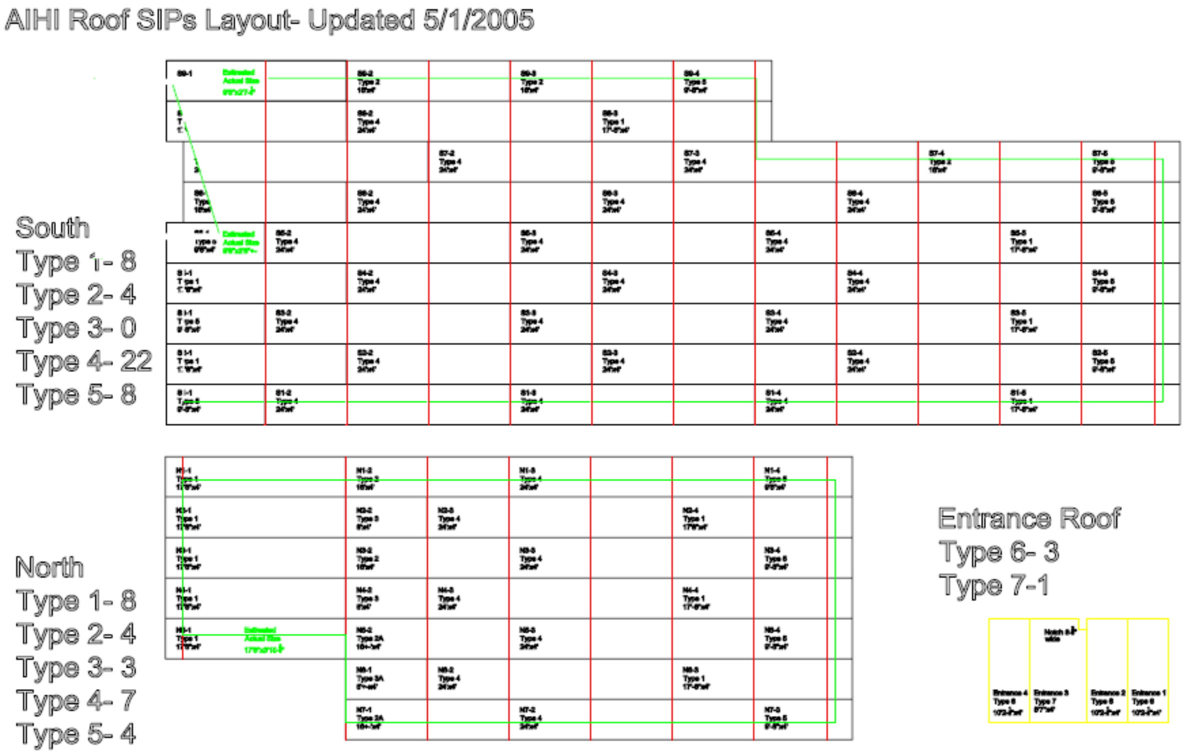

FIG. 12: Layout Drawing for SIPs Panels used in Laser Cutter for Physical Prototype

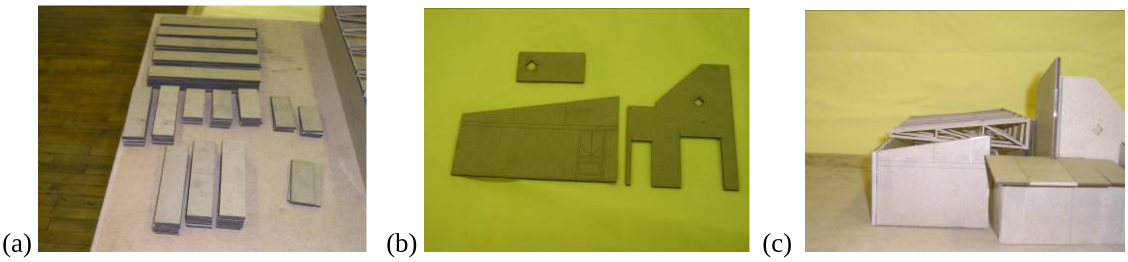

FIG. 13: Digitally fabricated physical model elements including (a) SIP Panels, (b) Wall Elements, and (c) a Partially Assembled Model

The growing use of digitally fabricated building components used in curtain wall systems, building partitions, and modular building systems promises to further amplify the value of virtual building models. In the ECLC case, virtual models used in the design process were very valuable in both the design and construction planning phases of the project, as the partitioning of the complex façade design into individual structural panels could be simulated and optimized. In addition, when the digital model of the building was proven to be accurate through the development of physical models, the virtual models helped expedite the fabrication of the actual panels and reduced material waste through optimizing the panel shapes.

5. SUMMARY OF CASE STUDY

This case study demonstrates an attempt to utilize a variety of virtual facility prototyping technologies and strategies in the design of a LEED certified facility. Throughout the ECLC project design, appropriate uses of various modeling applications and media for visualizing the models were documented. Table 1 includes a description for using various virtual design applications and media along with their corresponding contributions toward achieving sustainable design and construction objectives on the project.

Table 1: Summary of Virtual Model Applications and Media with Contributions toward Sustainable Goals

Virtual Prototyping Strategy	***Description of Use***	***Contributions Toward Sustainable Goals***
Virtual Models		
Conceptual Design Model	Develop conceptual and schematic models	Aided in rapid distribution of design alternatives to various design disciplines during early stages of design.
		Visually demonstrated the impact of the building on the site and adjacent facilities.
Building Information Model	Included building surface information in virtual building model	Helped to communicate building features to different analysis consultants.
	Developed standard coordinated document of surface geometry and attributes for energy and lighting analysis	Minimize the time for energy and daylighting consultants to perform an analysis of early design concepts.
Energy Analysis Model	Early modelling	Helped to compare energy efficient design strategies for ECLC configuration in the region.
	Design Development Modelling	Helped to select between alternative envelop materials and demonstrate payback of highly insulating g materials.
	Final energy simulation and analysis	Helped to develop control system design and logic.
Daylighting Analysis Model	Analysis of lighting intensity levels for building geometry	Helped to assess potential window locations.
	Analysis of daylight factor achieved in design	Helped to visualize areas of the building in which daylight factors were sufficient to reduce artificial light levels.
	Evaluation of lighting design	Helped to simulate lighting design to ensure the accent of unique building features.
Construction Process Model	4D modelling of building details and sequence	Helped to develop a detailed construction sequence in support of the blitz-build construction method.
	VRML version of 4D model	Helped to communicate the construction sequence to students and volunteers not familiar with traditional scheduling tools.
Media of Display		
Immersive Visualization	Visualize models at full scale	Aided in the visual display of developed 3D and 4D CAD models in design and construction review as well as presentations to students volunteers.
Digital Fabrication	Digital fabricated scale model	Helped produce a digitally fabricated facility prototype used for planning the staging of roof trusses and panels.
	Supply-chain integration of CAD data	Helped to develop scaled panels diagrams used in the manufacturing process of structural insulated panels (SIP).

6. CONCLUDING COMMENTS

This paper has presented a practical case study and lessons learned from the development of various models and virtual prototypes for the design of the Early Childhood Learning Center in Billings, Montana, U.S.A. These model applications and virtual prototyping techniques were used to perform advanced performance simulations for the project that minimized energy usage while improving the indoor environment quality.

It was apparent throughout the design process that the use of visualization tools for design tasks improved collaboration and communication between the various design and construction parties. The case study examples have shown how visualizing project information through virtual facility prototypes can:

- assist owners by providing improved early feedback for a project which can increase overall facility quality, minimizing change orders, and reduce waste due to changes;
- improve overall systems evaluation through simulation modeling;
- allow more parties to understand the interrelationships of the various aspects of design decisions (e.g., reducing the size of a window will reduce the energy costs but will negatively affect the daylighting);
- provide construction process information to all parties; and
- communicate valuable information to the construction workforce.

While many advantages were gained through the use of the prototyping methods, there remain inefficiencies in the rapid development of these prototypes which limit their use within the industry. One clear inhibitor is the lack of interoperability of the various modeling applications. There was much lost data when the models were passed from one application to another. There was also lost information when the models were sent to the immersive visualization environment. Most applications do not support stereoscopic visualization of a model in real time, so the models needed to be converted to a format that could be easily loaded into the virtual environment. Either improvements in exporting capabilities that carry added data or the addition of direct stereoscopic visualization capabilities within modeling applications could improve the quality of the virtual reality experience with limited effort from the users.

Another important lesson that was gained throughout this case study was that the initial data gathering and visualization process is critical. Performing initial condition assessments which graphically illustrate the site conditions, e.g., thermal and illuminance, can help design professionals gain a deeper understanding of the project conditions at early stages of design. Additional investigation into the best means to illustrate this information could greatly improve the quality of designs that support sustainable objectives. An example from the case study included the balancing of indoor environment quality with daylighting and energy efficiency that it greatly impacted by openings. The ability to visualize the site characteristics can allow the architects and engineers to modify the basic shape, orientation, and form of the building to optimize indoor environmental quality and energy performance.

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