Graduate Student Project and Report:

Leveraging BIM for Sustainability:

An Analysis of Ability to Evaluate Building Performance, Facilitate LEED Certification and Monitor Resource Flows with Selected Software Tools From Autodesk and Integrated Environmental Solutions

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INTRODUCTION

Problem Statement

Building Information Modeling (BIM) is driving an unprecedented revolution in the Architecture, Engineering and Construction (AEC) industry. It involves digital engineering, modeling and simulation, sometimes referred to as "Virtual Design and Construction," used to predict and manage construction projects. Software developers such as Autodesk, Bentley and Nemetschek are producing intelligent and highly capable "BIM platforms" to replace traditional 2D drafting and design. However, BIM is much more than a software package or a digital model. It is a new methodology and process of data management, information distribution, risk mitigation and project delivery. Alongside this transformation are other trends in the AEC industry. Construction projects are increasingly complex, owner expectations are increasing, and environmental consciousness is wonted. Specifically, the green building or sustainability movement is rapidly gaining momentum. Several green rating and certification systems exist, perhaps the most prevalent of which is LEED – the Leadership in Energy and Environmental Design Green Building Rating System. Although LEED does not yet consider civil engineering work such as highways and bridges, the criteria attempt to evaluate a building's performance with respect to certain fundamental characteristics, such as water and electricity consumption, VOC (volatile organic compound) emissions, content of recycled materials, and use of natural light.

As BIM and LEED mature, it seems there is an inevitable relationship between the two; both are tools to promote sustainability in the built environment. Thus, there is the issue of how to use BIM to facilitate LEED certification. If BIM can evaluate a building's performance, and LEED credits correspond to certain performance criteria, it should be possible to ease or automate LEED credit tracking with BIM. Therefore, can any existing BIM platforms monitor which LEED criteria are satisfied by a specific building design? If so, which platforms are best suited to accomplish this task? Furthermore, do any existing BIM platforms have the capacity to track significant resource flows and evaluate a building's performance throughout its entire lifecycle? These questions form the foundation of the following project and report.

Statement of Intent

The purpose of this Project and Report (P&R) is to investigate possibilities of leveraging BIM for sustainability in the AEC industry. The scope of this P&R is to identify opportunities to use software tools to facilitate and enhance sustainable practices within the design, construction, and operations and management phases of a construction project. The Project and Report objective is to gain and disseminate knowledge of ways to use existing BIM platforms and analysis tools to promote sustainability in the AEC industry. In particular, this report analyzes several Autodesk and Integrated Environmental Solutions products with respect to ability to evaluate building performance, facilitate LEED certification, and monitor significant resource flows throughout the design, construction, and operations and maintenance phases of a facility lifecycle. The products that are analyzed include: Autodesk *Revit Architecture* (Revit), Autodesk *Green Building Studio* (GBS), Autodesk *Ecotect*, and Integrated Environmental Solutions Virtual Environment: *Architectural Suite Plus* (IES VE), which includes a Sustainability Toolkit and advanced energy analysis capabilities. This P&R is significant because achieving a sustainable facility lifecycle is an effective way to mitigate the potentially negative effects of the built environment, LEED is rating system that attempts to measure or mitigate these effects, and BIM is an excellent tool to facilitate sustainable building design and analysis in the AEC industry. Neither BIM nor LEED nor the sustainability movement is going away; rather, their existence is already prevalent and they are rapidly gaining momentum, so it is beneficial to understand and optimize the relationship between them.

Research Method and Objectives

This P&R attempts to identify opportunities for the AEC industry to use BIM processes and tools to facilitate and enhance sustainable practices within the design, construction, and operations and management phases of construction projects. The methodology of this P&R is to review and amalgamate significant information about existing opportunities for facility designers, builders, owners and users to exploit BIM software's ability to promote a sustainable facility lifecycle. However, it is out of the scope of this P&R to access and use each of the analyzed software tools, so a majority of this information is from extensive literature reviews, and primary resources for this P&R include previously published research and other information from books, case studies, conference proceedings, websites, and software-specific product information. In general, the table below summarizes the primary data sources for each software tool analyzed in this P&R.

Table 1. Information Sources for the Selected Software Tools

INFORMATION SOURCE	PRODUCT			
	Autodesk Revit Architecture	Autodek Ecotect	Autodesk Green Building Studio	IES VE Architectural Suite Plus
Product Website	X	X	X	X
Product Documentation	X		X	X
Product User Guide	X		X	X
Rick Rundell Tutorial		X	X	X
Customer Review		X		
Other	X	X	X	X

There are four relevant sections of this P&R. The first section is the Introduction, which identifies the P&R topic, intent and methodology, defines sustainability and BIM, and identifies a relationship between the two. This section also defines the LEED rating system and criterion, and identifies several major resource flows for construction projects considered in this P&R. The second section of the report identifies available BIM platforms and building performance / sustainability analysis software tools, and then selects the platform and software for use in this P&R. The third section reviews the capabilities of the selected BIM platform and analysis software to enhance sustainability in the design, construction, and operations and management phases of a facility lifecycle, with particular focus on ability to facilitate LEED credit tracking and resource tracking. The fourth and final section of this report summarizes significant capabilities and deficiencies of the selected BIM platform and analysis tools and alludes to the future roles of sustainability, BIM, and software in the AEC industry.

The specific objectives of this P&R are as follows:

- Conduct sufficient research and literature reviews to understand Sustainability, BIM and other analysis software tools, LEED criteria, construction project resource flows, and the relationships between each of these
- Identify major available BIM platforms and Sustainability Analysis Tools
- Identify three major Sustainability Analysis Tools that are compatible with one major BIM platform and review their capabilities
- Create a matrix to analyze the selected software's abilities to facilitate sustainability in the AEC industry, with particular focus on building performance modeling, LEED certification, and resource flows throughout a facility lifecycle
- Perform a gap analysis to identify software strengths and weaknesses

Definition and Overview of Building Information Modeling

BIM is defined as "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 and Nies 2008)." BIM makes a reliable digital representation of the building available for design decision-making, high-quality construction document production, construction planning, performance predictions, and cost estimates. The ability to keep information up-to-date and accessible in an integrated digital environment gives architects, engineers, builders, and owners a clear overall vision of all their projects, as well as the ability to make better-informed decisions faster.

However, BIM is much more than a digital model or software. Rather, BIM is a methodology and a building information model is merely a product of that methodology. BIM goes beyond traditional 3-Dimensional (3D) drawings and models by attaching a wealth of additional information to 3D parametric models. As an integrated database of coordinated information, a BIM model goes far beyond traditional 3D representations of objects used primarily for visualization. Instead, a BIM model can encompass much more information – graphical, non-graphical and linked – such as building system relationships and interdependence, material composition and performance properties, time and cost attributes, system installation methods and operation requirements, and impacts to and from the local environment.

Although risk perception and liability issues currently plague the industry by hindering project participants' willingness to share information, the inherent adversarial nature of the construction industry in the United States will inevitably change. The inefficiencies and costs of designing, construction and operating facilities today are becoming more and more inflated due to legal issues and malpractice insurance; at some point, the industry will be forced to change or nothing will be able to be built. In fact, the beginnings of that change are already evident, with more and more design-build firms coming into existence, and more owners realizing the major source of a facility's cost and looking for ways to eliminate them. So, liability issues aside, putting more information into a building model has the potential to benefit consultants and collaborators during the design and construction processes, and can further benefit customer, the building owner or manager, once the project is complete (Dillon 2005). The following are current capabilities and uses of BIM:

- Site Selection, Utilization and Building Orientation
- Design Optimization and Constructability Review
- Integration of Design, Manufacturing and Construction
- Visualization and 4D Scheduling
- System / Trade Coordination and Sequencing
- Cost Estimating
- Daylighting Analysis and Thermal Assessments
- Energy Analysis
- Water Analysis
- Wind Analysis
- Materials Computation / Quantification
- Specification Integration and Document Generation
- Waste Reduction / Waste Stream Forecasting
- Operations and Management Optimization and Automation

The optimal result of these capabilities is a seamless facility performance assessment throughout its entire lifecycle. Thus, BIM gives the AEC industry greater potential to effectively support sustainability in facility lifecycle management.

Definition and Overview of Sustainability

Although it was not until the early and mid-90's that terms like *green* and *environmentally friendly* gained popularity among architects to describe their projects, the concept of sustainability is not a new one. Many ancient civilizations built structures with local materials to meet performance needs in a specific environment, such as Egyptian pyramids and Native American teepees. Igloos created thermal mass and wind resistance, and ancient Pueblo peoples utilized natural cliffs and caves as the location for some of the first sedentary civilizations (Krygiel and Nies 2008). Thus, the notion of *green* design or construction is not necessarily a new one. However, as civilizations evolved, the inherent *greenness* of the built environment dissipated and buildings took on significance other than shelter. Many created elaborate structures as a symbol of power and authority, among other things, and eventually the building industry moved away from design that was specific to climate, culture, and place, and toward uniform standards for all situations. Today, for example, the majority of heating and cooling operations are achieved using mechanical systems, sources of interior light are mostly artificial, and globalization has encouraged the industry to obtain our building materials from anywhere in the world (Krygiel and Nies 2008). As a result, the built environment of our time is not as sustainable as that of ancient civilizations. Exactly how and why this change occurred is not the focus of this P&R, though these issues raise interesting thoughts and concerns. Rather, this report focuses on identifying ways to use BIM to mitigate the result of this change, which is the necessity of a paradigm shift within the AEC industry – a shift towards sustainability, but what is *sustainability*?

To understand sustainability, first consider the difference between *sustainability* and *green building*. The Office of the Federal Environmental Executive defines green building as the practice of 1) increasing the efficiency with which buildings and their sites use energy, water, and materials, and 2) reducing building impacts on human health and the environment, through better site selection, design, construction, operation, maintenance, and removal – the complete building lifecycle (Federal Environmental Executive 2003). Groups like the American Institute of Architects (AIA), the United States Green Building Council (USGBC), and others have essentially defined *green buildings* as those that have a less negative impact on the natural environment than traditional buildings. For example, green building design and operation intends to create healthier and more productive environments by utilizing natural light and improved air quality. However, industry language recently transitioned from using the term *green* to *sustainable*, which is a definite improvement in how we think about the built environment. A *sustainable* design is better than a *green* one, because sustainability takes into account a much broader array of impacts than just those that burden the natural environment (Krygiel and Nies 2008). The World Commission on Environment and Development (also known as The Brundtland Commission) exemplifies this notion by identifying a concern "about the accelerating deterioration of the human environment and natural resources and the consequences of that deterioration for economic and social development." This report defines *sustainable development* as development that "*meets the needs of the present without compromising the ability of future generations to meet their own needs* (Assembly 1987)." Moreover, one may conclude that in order to be truly sustainable, a construction project must not deplete any significant resource base, and we must ultimately move beyond projects that are neutral to projects that are regenerative.

Sustainability is important for many reasons. In a global context, future generations deserve to live in a world that is in the same condition, if not better, than it is today. Locally, sustainability is important to ensure stability in the social, environmental and economic systems that make up a community in order to provide a healthy environment and a prosperous life. Without question, the decisions made today pertaining to the construction of new structures and the modification of existing structures will impact generations for several decades. Within the AEC industry, the built environment has a profound impact on our natural environment, economy, health, and productivity. In the United States alone, buildings account for the following (USGBC 2008):

- 72% of electricity consumption
- 39% of energy use
- 38% of all carbon dioxide (CO_2) emissions
- 40% of raw materials use
- 30% of waste output (136 million tons annually)
- 14% of potable water consumption

Thus, it is not hard to establish buildings as one of the primary sources of the greenhouse gases contributing to global warming and climate change (AIA 2007). Today these issues combine with other issues of environmental sensitivity, economic disaster and energy crises throughout the world. It is for these reasons that all engaged in building the fabric for future generations must become true stewards of environmental responsibility (Kose and Sisel).

Definition and Overview of LEED

The USGBC is a non-profit organization that coordinates the establishment and evolution of a national consensus effort to provide the industry with tools necessary to design, build and operate buildings that deliver high performance inside and out. Following the formation of the USGBC in 1993, members quickly realized that the sustainable building industry needed a system to define and measure green buildings. The USGBC began to research existing green building metrics and rating systems and less than a year after formation, members established a committee to focus on this challenge. The committee, comprised of architects, real estate agents, a building owner, a lawyer, an environmentalist and industry representatives, offered a "cross section of people and professions that added a richness and depth to both the process and to the ultimate product - the Leadership in Energy and Environmental Design (LEED) Green Building Rating System (USGBC 2007)." An open, consensus-based process led by LEED committees provides input to develop the LEED rating systems. Each volunteer committee is composed of a diverse group of practitioners and experts representing a cross-section of the building and construction industry. The key elements of the USGBC consensus process include a balanced and transparent committee structure, technical advisory groups that ensure scientific consistency and rigor, opportunities for stakeholder comment and review, member ballot of new rating systems, and a fair and open appeals process (USGBC 2007). The first LEED Pilot Project Program, known as LEED Version 1.0, debuted at the USGBC Membership Summit in August 1998; however, several key AEC industry players were not included in the USGBC committee, such as scientists, engineers/designers, and builders/construction managers. The absence of these industry representatives raises interesting questions about the intent, content, and validity of the LEED rating system; however, that is not the focus of this P&R.

LEED encourages global adoption of sustainable green building and development practices through the creation and implementation of universally understood and accepted tools and performance criteria. It is a third-party certification program and the nationally accepted benchmark for the design, construction and operation of high performance green buildings. LEED gives building owners and operators the tools they need to have an immediate and measurable impact on their buildings' performance. LEED promotes a whole-building approach to sustainability by recognizing performance in five key areas of human and environmental health: sustainable site development (SS), water efficiency (WE), energy efficiency and atmosphere preservation (EA), materials and resources selection (MR), and indoor environmental quality (IEQ). A sixth category for "innovation" (ID, IO) addresses sustainable building expertise as well as design and operation measures not covered under the five other categories. Architects, real estate professionals, facility managers, engineers, interior designers, landscape architects, construction managers, lenders and government officials all use LEED to help transform the built environment to sustainability. State and local governments across the country are adopting LEED for public-owned and public-funded buildings. Furthermore, there are LEED initiatives in federal agencies, including the Departments of Defense, Agriculture, Energy, and State; and LEED projects are in progress in over

40 different countries, including Canada, Brazil, Mexico and India.

Multiple different LEED rating systems exist, including Commercial Interiors, Core and Shell, Schools, etc., but this P&R focuses on LEED for New Construction (LEED NC) and the LEED for Existing Buildings: Operations & Maintenance (LEED EB: O&M). LEED NC intends to guide and distinguish high-performance commercial and institutional projects, including office buildings, high-rise residential buildings, government buildings, recreational facilities, manufacturing plants and laboratories. LEED EB: O&M is a new version of LEED for Existing Buildings (LEED EB), which helps building owners and operators measure operations, improvements and maintenance on a consistent scale, with the goal of maximizing operational efficiency while minimizing environmental impacts. It also addresses whole-building cleaning and maintenance issues (including chemical use), recycling programs, exterior maintenance programs, and systems upgrades. It can be applied both to existing buildings seeking LEED certification for the first time and to projects previously certified under LEED for New Construction, Schools, or Core & Shell. As of January 1, 2006, all LEED NC projects must register under LEED NC Version 2.2, and as of September 1, 2008, all projects registering for LEED EB must do so under the current LEED EB: O&M version. Furthermore, after LEED Version 3 launches in April 2009, all LEED certifications must meet the requirements in the new suite of LEED 2009 rating systems. The table below shows the current certification level requirements for LEED NC and LEED EB: O&M.

Table 2. LEED Version 2.2 Certification Levels and Point Requirements

LEED VERSION 2.2 CERTIFICATION LEVELS AND REQUIREMENTS				
	CERTIFIED	SILVER	GOLD	PLATINUM
LEED NC	26-32 points	33-38 points	39-51 points	52-69 points

Definition of and Overview of Resource Flows

In terms of sustainability, it may help to view a built facility as a complete, but open system. This system has boundaries, such as the site limits or the building envelope, but resources constantly flow within and across these boundaries throughout the facility's lifecycle. The resources vary in type, from material resources (wood, water, energy, etc.) to human resources (construction workers, facility employees, etc.), to intangible resources like data and knowledge. However, in terms of mitigating environmental impacts, the significant resources are measurable and it is necessary to track them in order to quantify system / facility sustainability. This is because an ultimate goal of sustainability is to leave resource bases and natural ecosystems as unchanged or improved as possible, while maintaining standards of living at least as high as the ones that currently exist (Pearce and Fischer 2001). Thus, one must characterize how a building impacts its context by verifying resource consumption and system performance, not only during the construction phase, but also throughout each phase of the entire facility lifecycle. To better understand how a facility consumes or provides resources, consider the "Interfaces of Built Facilities with External Systems" diagram on the following page, which illustrates several ways resources flow into and out of a facility throughout its lifecycle (Pearce and Fischer 2001).

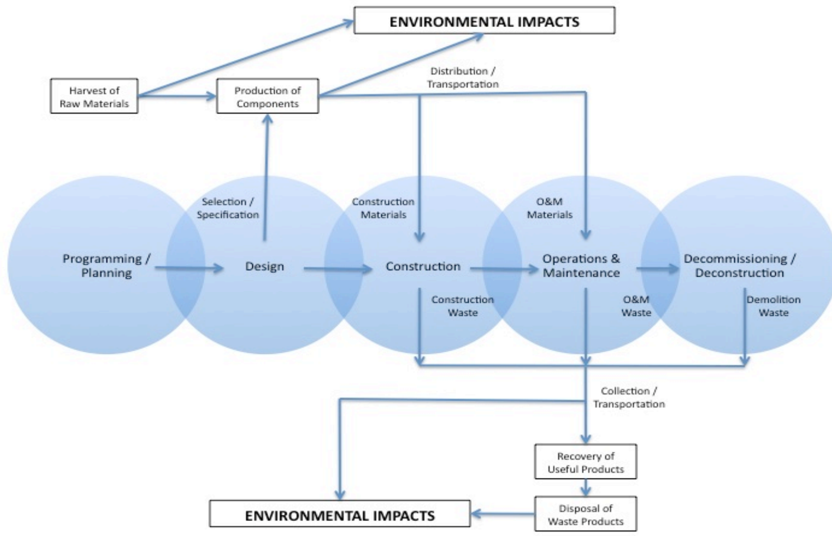

Figure 1. Interfaces of Built Facilities with External Systems (Pearce and Fischer 2001)

By using this diagram as a starting point for measuring resource flows, it is possible to identify several major resources or types of resources present in each of the depicted flows. Furthermore, by considering the main categories of the LEED criterion, it is possible to map these categories onto the depicted flows and identify several major resources that serve a relevant purpose when measuring system or facility sustainability. Although LEED considers many other factors and criterion, several primary elements evaluated in the LEED categories are as follows: water, energy or electricity, materials (such as wood, steel, concrete, recycled content/post-consumer content, etc.), and airflow volume and contaminants (such as ventilation rates and VOC emissions). These elements form the basis for the selection of the resources analyzed in this report. Specifically, this report attempts to identify which of the following resources can be tracked or monitored with the selected software tools: money/costs, carbon, water, energy and electricity, solar and thermal resources, and specific material quantities and recycled content/waste.

Relationship Between BIM and Sustainability

Sustainable building design is an activity predicated almost entirely on the ability to gain insight into construction outcomes through analysis, prediction and optimization of the design. In fact, one might argue that achieving real sustainability is only possible when you can accurately predict the behavior of the building and its effect on the environment before that building is built (Bernstein 2007). In current practice, many digital building models do not contain sufficient information for building performance analysis and evaluation – the building blocks of sustainable building design. As with traditional physical models and drawings, evaluating building performance based on the geographic representations of conventional CAD (Computer Aided Drafting/Design) solutions requires a great deal of human intervention and interpretation, which renders the analyses too costly and/or time consuming (Autodesk 2005). However, recent innovations in BIM are making sustainable practices more accessible to the industry.

Perhaps the greatest advantage of BIM in sustainable building design is building analysis. Sustainable building design hinges on the ability to gain insight into a building's performance through design analysis and optimization, and BIM naturally captures much of the data needed to support performance analysis as design proceeds, and designers can analyze how a building will perform in the early stages of design (Middlebrooks 2008). With this information, one can evaluate design alternatives quickly and make better decisions for greener designs. By streamlining the design and analysis processes, BIM facilitates the calculations needed to optimize building performance.

A BIM-based design model also carries a wealth of information necessary for many other aspects of sustainable design. For example, the ability to create drawings and details directly from a model, particularly while the software automatically coordinates these drawings and details within the model, improves efficiency and accuracy of green certification. Many software programs can generate schedules of building-material quantities from a model to determine percentages of material reuse, recycling, and salvage, which indicates BIM provides an opportunity to monitor resource flows. It is possible to pursue various design options for sustainability in parallel and automatically track performance variations in a model for comparison, as well as perform advanced visualization techniques for solar studies and produce 3D renderings and construction animations of a project. These, among other capabilities lend BIM to behoove LEED certification by analyzing certain LEED criteria.

From many perspectives, adopting BIM will play an increasingly important role in supporting the creation and maintenance of sustainable buildings, and links between building information models and analytic tools enable designers to assess proposed designs to determine whether or not a completed project will achieve the necessary performance outcomes (Hoffer 2007). A digital 3D model supports better understanding and collaborative communication among the various stakeholders in a green partnership (architects, owners, consultants, builders. review bodies, etc.) (Autodesk 2008a). Therefore, an accurate digital simulation of a building is a logical prerequisite for sustainable building design.

BIM PLATFORMS AND ANALYSIS TOOLS

Overview of Existing Software

Many BIM platforms and associated analysis software programs already exist, but as interest and contractual requirements of BIM evolve, these numbers will likely continue to rise. Many existing BIM platforms have similar capabilities and modeling structure, however some software is for specific building types, such as industrial plants or building with extremely complex geometry. Some sustainability analysis tools claim to be "comprehensive," in that they can easily facilitate the design of a sustainable building. While this is true to a limited extent, most of the tools do not analyze all necessary building parameters to be truly comprehensive from a sustainability analysis standpoint. On the other hand, some software is specific to one particular type of analysis, such as daylighting or thermal performance. For now, the lists below identify several available BIM platforms and sustainability analysis tools, respectively.

Several available BIM platforms:

- ArchiCAD 12 produced by Graphisoft Virtual Building Solutions
- AutoCAD Architecture and MEP produced by Autodesk
- Digital Project produced by Gehry Technologies
- Microstation, GenerativeComponents produced by Bentley Building Products
- Pro/Engineer produced by Parametric Technology Corporation
- Revit Architecture, Structure and MEP produced by Autodesk
- Vectorworks 12 produced by Nemetschek
- 5D Virtual Construction Software Suite 2008 produced by Vico Software

Several available Sustainability Analysis Tools:

- Department of Energy-funded DOE-2
- EnergyPlus

- Ecotect
- Green Building Studio
- Integrated Environmental Solutions <Virtual Environment>
- Radiance

The abundance of potential combinations of BIM platforms and analysis software makes it beyond the scope of this Project and Report to study each one. Rather, this report focuses on a narrow selection of software from two primary software producers in the AEC industry: Autodesk and Integrated Environmental Solutions. Autodesk is a major competitor in the BIM software market, and many AEC industry professionals use their products, thus Autodesk is a rational choice for analysis. Furthermore, Autodesk produces Revit (a BIM platform), as well as Green Building Studio and Ecotect (two building analysis tools), which provides a unique opportunity to analyze multiple software tools from one provider. This P&R analyzes several products from the same software manufacturer because of the assumption that interoperability issues between the BIM platform and the analysis tools would be minimal. Furthermore, there is inherent "fairness" in comparing products from the same manufacturer, thereby reducing any biases. The additional building analysis tool chosen for investigation is Integrated Environmental Solutions Virtual Environment (IES VE) Architectural Suite Plus. This software is an ideal candidate because IES VE offers a Revit plug-in tool that allows Revit Architecture users, as well as Revit MEP and Revit Structure users, to import 3D BIM models into IES VE's software and undertake sustainable performance analysis. Specifically, IES VE provides a Sustainability Toolkit within the Architectural Suite that is unique to the Revit platform, so interoperability and compatibility issues between Revit and IES VE should be minimal. In general, these software programs have a significant presence in the AEC industry and provide opportunities to investigate

BIM's ability to facilitate sustainable building through building performance analyses, LEED certification, and resource flow management.

Revit Architecture 2009

From capturing conceptual studies through the development of the most detailed construction drawings and schedules, Autodesk Revit-based applications help provide immediate competitive advantage, deliver better coordination and quality across project phases and disciplines, and can contribute to higher profitability for a project team (Autodesk 2008a). The Revit platform is a purpose-built solution for building information modeling and Revit Architecture 2009 is Autodesk's primary BIM platform, which attempts to capture the real-world attributes and performance characteristics of buildings in a virtual environment. It is a complete, discipline-specific building design and documentation system that supports all phases of design, construction documentation, and even fabrication. At the heart of the platform is the Revit parametric change engine with "bidirectional associativity," which automatically coordinates changes across the project. Parametric Components, also known as families, are the basis for all building components designed in Revit Architecture. They offer an open, graphical system for design thinking and form making as well as an opportunity to express design intent at increasingly detailed levels (Autodesk 2008a). Revit Architecture also has the following features (Autodesk 2008a):

- Ability to develop and study multiple simultaneous design alternatives
- Schedule views with automatic updating
- Extensive detail library and detailing tools
- Ability to calculate detailed, accurate material quantities
- Revit Building Maker provides a better workflow for common tasks
    - Easily create expressive forms to produce an overall massing study
    - Import conceptual massing from other applications
- Capture design ideas in a photorealistic state with the mental ray rendering engine
- Use interference checking to scan models for collisions between elements
- Autodesk 2D and 3D .dwf file integration to publish in those formats

This report focuses on Revit Architecture as the BIM platform and it is important to note that other Revit products, such as Revit MEP and Revit Structures, are not part of the Revit Architecture software. While many Revit Architecture users also have access to these other Revit products, Autodesk sells Revit MEP and Revit Structures separately; thus, the software abilities mentioned in this P&R are specific to Autodesk Revit Architecture 2009. Revit Architecture is widely used in the AEC industry and it is compatible with the other chosen software products. In particular, Autodesk, which produces Revit, also produces Ecotect and Green Building Studio, so interoperability and file-exchange issues between these should be minimal. Furthermore, a computable Revit design model is a great fit for the analyses needed for sustainable design – even during schematic design. As soon as the layout of a building's walls, windows, roofs, floors, and interior partitions (elements that define a building's thermal zones) are established, a Revit model is ready for whole-building analyses. Performing these analyses in a traditional CAD workflow is a difficult undertaking, because users must export and carefully massage the CAD model in order for it to work with analysis software programs. In addition, most analysis software is complex and requires special training, and the provided output is often complicated, making such programs unsuitable for casual users like architects or designers (Autodesk 2007). However, using Autodesk's Green Building Studio web-based service to analyze building design from a Revit BIM workflow can simplify this process. The following section provides a description of the Green Building Studio web service.

Green Building Studio

Autodesk Green Building Studio (GBS) is an energy schematic simulation plug-in for Revit and other BIM platforms. GBS provides a web-based service with XML connectors, which gives users quick, reliable estimates of a building's energy costs during the early stages of conceptual design (Autodesk 2008c). It creates a geometrically correct equivalent thermal energy model and provides almost immediate feedback on the energy implications of different architectural design scenarios. With the GBS web-based energy analysis service, architects and designers can perform whole-building analysis, optimize energy efficiency, and work toward carbon neutrality earlier in the design process (Rundell 2008a).

In particular, GBS enables whole-building energy, water, and carbon emissions analyses of a Revit building model within the design environment, directly over the Internet. Based on the building's size, type, location (which drives electricity and water usage costs), the web service determines the appropriate material, construction, system and equipment defaults by using regional building standards and codes to make intelligent assumptions. GBS uses precise hourly weather data, as well as historical rain data, that are accurate to within a few miles of any given building site. It also uses emission data for every electric power plant in the United States and includes a broad range of variables needed to assess carbon neutrality (Rundell 2008a). The software determines a building's carbon emissions and displays the results in a web browser, including the estimated energy consumption and cost summaries, as well as the building's carbon neutral potential. The output also summarizes the water and electricity usage and costs, calculates an EPA EnergyStar score, estimates photovoltaic and wind energy potential, calculates points towards the LEED daylighting credit, and estimates natural ventilation potential. Architect's can view the easy-to-understand output and explore design alternatives by updating the settings used by the web service and rerunning the analysis, and/or revising the building model itself in Revit and then rerunning the analysis. The design data resulting from a Revit BIM workflow and the whole building analysis provided by GBS work in combination to reduce the cost and time to perform the modeling and analyses required to optimize energy efficiency, work towards carbon neutrality, and ultimately mitigate the carbon footprint of the built environment (Autodesk 2008c).

Ecotect

Built specifically by architects and focused on the building design process, Autodesk Ecotect is an environmental analysis tool that allows designers to simulate the performance of their building projects right from the earliest stages of conceptual design. Acquired by Autodesk in June 2008, the software provides a wide array of analysis functions, including shadows, shading, solar, lighting, thermal, ventilation, and acoustics. However, perhaps the most unique aspect of the software is its highly visual and interactive display that presents analytical results directly within the context of the building model, including shadow animations resulting from shadow casting analysis, surface mapped information such as incident solar radiation, and spatial volumetric renderings such as daylight or thermal comfort distribution in a room (Rundell 2008b). This visual feedback enables the software to communicate complex concepts and extensive datasets, and helps designers engage with multifaceted performance issues early in the design process.

Ecotect has its own basic modeling environment that is best suited for generating basic layouts, but it is not quite as intuitive as a CAD or BIM system. However, the model is editable and tasks such as resizing or inclining walls, manipulating complex curves, rearranging zones, moving apertures, or adding or deleting surfaces are all straightforward (Marsh 2003). Each material in Ecotect can store a wide range of information, including basic thermal and surface properties, detailed layer descriptions, acoustic response, and environmental impact data.

Users can export Revit-based design models to gbXML format and import them directly into Ecotect for analysis throughout the design process. At the onset of the design process, early-stage Revit-based massing models can be used in combination with the site analysis functionality and visualized in an openGL format with overlaying sun-path diagrams, shadowing information, lighting grids, etc. This can help users determine the optimal location, shape, and orientation of a building design based on fundamental environmental factors such as daylight, overshadowing, solar access, and visual impact. As the conceptual design evolves, whole-building energy solutions such as Green Building Studio can benchmark energy use and recommend areas of potential savings. Once these fundamental design parameters are established, user can access the model again to rearrange rooms and zones, to size and shape individual apertures, to design custom shading devices or to choose specific materials based on environmental factors such as daylight availability, glare protection, outside views, and acoustic comfort (Rundell 2008b). Specifically, Ecotect can evaluate or perform the following (Autodesk 2008b):

- Acoustic Analysis
- Building Regulations Compliance
- Lighting Design
- Photovoltaic Array Sizing and Load Matching
- Photo Gallery with Screenshots
- Resource Management
- Right-to-Light
- Shadows and Reflections Analysis
- Shading Design
- Solar Analysis
- Thermal Analysis
- Visualization and Data Import/Export

Integrated Environmental Solutions

Established in 1994 and headquartered in Glasgow, Scotland, Integrated Environmental Solutions produces the Virtual Environment Architectural Suite Plus (IES VE), which is the first commercially available system for the integrated analysis of a building's performance, generating detailed data for a range of analyses such as thermal simulation, load calculations, daylight assessment and solar studies (Rundell 2007). The IES VE plug-in for Revit Architecture provides a direct link to IES VE software and enables easy analysis of energy efficiency and building performance at early stages of the design process. Furthermore, there is no need to recreate the building geometry, because users can pass the BIM room data directly from Revit to the IES VE software and run a variety of analyses. This tight integration allows Revit users to quickly and easily analyze alternative green designs. For example, users can perform thermal and daylighting studies in minutes and display the results in a HTML report. The quality and speed of the technical feedback enables users to actually use the building analysis tools for sustainable design, rather than just equipment sizing (IES 2008).

The Sustainability Toolkit is an analysis package within the IES VE software that is unique to the Revit platform. It lets architects conduct a variety of analyses, including ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) load calculations, dynamic thermal analysis and daylighting assessment, and produce a LEED daylighting credit report, all based on a Revit building model. The toolkit has two kinds of thermal assessments, the first of which is an ASHRAE steady-state load calculation that determines how much energy the building will consume during peak heating and cooling situations. Users can perform this type of analysis to size and specify mechanical systems very early in conceptual design, perhaps during design charrettes, to gain quick insight into a building's carbon footprint. The second thermal assessment is a more rigorous analysis that uses advanced dynamic thermal simulation to evaluate a building's performance over time. It provides a more comprehensive analysis, but the time required to run this type of analysis may be ten to twenty times greater than the steady-state ASHRAE method, so it's better suited for more detailed designs (Rundell 2007). The Sustainability Toolkit also contains point-to-point daylighting simulation for evaluating how natural light can be used to illuminate the interior of a building design, and the integration of the IES VE daylighting tools and the Revit building model allows designers to evaluate daylight levels from within their design environment as a routine part of the design process. The software displays results in both graphic and tabular forms, or in a format required for LEED submittal, which could ease the LEED certification process. In general, the IES VE Architectural Suite Plus can evaluate or perform the following (IES 2008):

- Annual / Monthly Energy and Carbon Performance
- Thermal Comfort Assessment
- Lighting and Daylighting Analysis
- Solar Shading Animations
- Airflow and ASHRAE Load Calculations
- Egress Assessment
- 2030 Challenge Assessment
- LEED, BREEAM, and UK Building Regulation Compliance
- Value and Capital / Lifecycle costs

INVESTIGATION OF SOFTWARE TOOLS

EXPLANATION OF ANALYSIS

This P&R intends to investigate the abilities of the selected software tools with respect to three primary considerations: modeling and analyzing building performance characteristics, facilitating LEED certification, and monitoring resource flows throughout a facility lifecycle. Extensive literature reviews reveal building performance modeling and analysis capabilities, as discussed in the specific software sections on the following pages. However, to systematically identify which LEED credits and resource flows can be tracked with the specific software tools, three matrices were created: one for LEED NC, one for LEED EB: O&M, and one for resource flows. There is a section within the LEED matrices for each of the LEED categories, and there are similar sections within the resource flows matrix. Individual software evaluation within these matrices identifies which LEED credits and resource flows, and associated costs, the software can track.

Each row in the LEED matrices corresponds to a specific LEED credit. The first three columns in the LEED matrices identify each LEED credit number and type, and describe the criteria for achieving the credit, respectively. The fourth column indicates the required inputs, calculations, and/or capabilities for a software tool to be able to determine specific LEED credit achievements. The fifth column is broken into sub-columns for each specific software tool analyzed in this report. If a software tool can receive the indicated inputs and/or can perform the indicated calculations or functions necessary to track a specific LEED credit, then an "X" is in the cell for that software tool and credit. If the software cannot aid in tracking the LEED credit, then the cell is blank. The final column in the LEED matrices represents the costs associated with achieving each LEED credit. Examples of these costs include energy costs or operational costs, material costs, and so on. If the software tool can track cost-related information for a LEED credit, then the corresponding software symbol is in the cell. For example, consider LEED NC Version 2.2 Energy and Atmosphere Credit 1: Optimize Energy Performance; also consider that Green Building Studio can track energy consumption and associated cost attributes. As a result, an "X" is in the cell for the EA Credit 1 and a "G" is in the cost cell, followed by a description of the particular cost attribute the software can track (i.e. "cost of energy consumption"). The final rows in each LEED category, and at the bottom of the matrices, indicate the total number of points tracked by each software tool, the total number of points with at least one associated cost tracked, and the total number of points possible. This same logic applies to both the LEED NC matrix and the LEED EB: O&M matrix.

It is important to note the LEED point totals identified in this P&R differ slightly from most other LEED documentation. This P&R considers LEED prerequisites and required credits as additional points in order to portray a true reflection of the "total possible points" within a LEED category. For example, consider the EA category in LEED EB: O&M. Formal LEED documentation indicates 30 total possible points and 3 prerequisites for this category; it also indicates one required credit within the Optimize Energy Efficiency Performance credit category. However, the matrix for this category cites 34 possible points, because this P&R considers prerequisites and required credit as additional points.

In the Resource Flows matrix, each row corresponds to a specific resource. The first two columns in the resource matrix identify resource flows into and out of a building project, respectively. The third column is broken into sub-columns for each of the three primary phases of a facility lifecycle: design, construction, and operations and maintenance. The final column corresponds to costs associated with the resource flows. If a software tool can track a specific resource flow in one of the lifecycle phases, then the software symbol is in the cell under that phase for that resource, and the same logic applies to costs. For example, if GBS can track the amount of electricity required for building lighting during the design phase, then an “G” is under the design phase column in the row labeled “Electricity for Lighting.” If GBS can also track energy costs for lighting, a “G” is placed in the cost column followed by a description of the specific cost parameter tracked (i.e. “G – Cost of energy consumption for lighting”). The final rows in each section indicate the total number of resources tracked and the total number of resources with at least one associated cost tracked by each software tool.

Results From Analysis

This P&R analyzes each of the selected software tools for the following specified criteria: LEED NC points and associated costs, LEED EB: O&M points and associated costs, and resource flows and associated costs. The tables on the following four pages summarize the results of these analyses. The first two tables provide detailed descriptions of the analysis results for the LEED credits and associated costs, respectively. The next two tables provide a more general overview to summarize the LEED credit and cost results for LEED NC and LEED EB: O&M, respectively. The final table summarizes the results for the resource flows and costs. These tables, as well as the matrices used for each analysis, are also in the appendix section of this P&R.

Detailed Summary of LEED Points

The table below provides a detailed summary of the LEED point analysis results for each of the software tools. The results for each specific category within the LEED certification criterion precede a total summary for each type of LEED certification.

Table 3. Detailed Summary of LEED Points Facilitated by Each Software

DETAILED SUMMARY OF LEED VERSION 2.2 POINTS THAT CAN BE TRACKED						
		Ecotect	**Green Building Studio**	**IES Virtual Environment**	**Revit**	**TOTAL POSSIBLE POINTS**
LEED NC POINTS THAT ARE TRACKED	SS POINTS	1	0	2	**4**	15
	WE POINTS	0	**5**	0	0	5
	EA POINTS	0	**15**	**15**	0	20
	MR POINTS	0	0	**12**	**12**	14
	IEQ POINTS	2	1	**14**	6	17
	ID POINTS	**4**	**4**	**4**	0	5
	TOTAL POINTS TRACKED	7	25	**47**	22	76
LEED EB: O&M POINTS THAT ARE TRACKED	SS POINTS	1	0	**2**	1	12
	WE POINTS	0	**7**	0	0	11
	EA POINTS	0	**22**	**22**	0	34
	MR POINTS	0	0	**3**	2	16
	IEQ POINTS	2	2	**6**	2	22
	IO POINTS	0	**4**	**4**	0	7

	TOTAL POINTS TRACKED	3	35	**37**	5	102

*Note: Totals include prerequisites and required credits.

Bold font indicates software that can track the most LEED points.

Detailed Summary of LEED Points With Costs

The table below provides a detailed summary of the results of each LEED cost analysis for the software tools. The results for each specific category within the different LEED certification types precede a total summary for each LEED certification type.

Table 4. Detailed Summary of LEED Points with Costs

DETAILED SUMMARY OF LEED VERSION 2.2 POINTS WITH ASSOCIATED COSTS THAT CAN BE TRACKED						
		Ecotect	**Green Building Studio**	**IES Virtual Environment**	**Revit**	**TOTAL POSSIBLE POINTS**
LEED NC POINTS WITH AT LEAST ONE COST TRACKED	SS POINTS	0	0	2	**5**	15
	WE POINTS	0	**5**	0	2	5
	EA POINTS	0	**15**	**15**	0	20
	MR POINTS	0	0	**12**	**12**	14
	IEQ POINTS	0	1	**14**	8	17
	ID POINTS	0	**4**	**4**	**4**	5
	TOTAL POINTS WITH AT LEAST ONE COST TRACKED	0	25	**47**	31	76
LEED EB: O&M POINTS WITH AT LEAST ONE COST TRACKED	SS POINTS	0	0	**2**	1	12
	WE POINTS	0	**7**	0	0	11
	EA POINTS	0	**22**	**22**	0	34
	MR POINTS	0	0	**3**	2	16
	IEQ POINTS	0	2	**6**	4	22
	IO POINTS	0	**4**	**4**	**4**	7

	TOTAL POINTS WITH AT LEAST ONE COST TRACKED	0	35	**37**	11	102

*Note: Totals include prerequisites and required credits.

Bold font indicates software that can track the most points with costs.

General Summary of LEED Points and Points with Costs

The table on the following page provides a summary of the results for the analysis of LEED NC and LEED EB: O&M points and points with costs. Notice that Ecotect and Revit can track more or less points than points with costs. For Ecotect, this is because the software does not have stand-alone capability to track significant cost information associated with LEED points. For Revit, this is because Revit is more adept at tracking costs than at facilitating LEED point achievement. For example, consider the interior daylighting requirements of LEED NC credit 8.1. GBS can measure interior area exposed to the required daylighting levels, but it cannot monitor changes in cost due to alterations in window configuration, or other design changes, needed to achieve the credit; however, Revit, which cannot monitor daylight levels, can track such costs.

Table 5. General Summary of LEED Points and Points with Costs

GENERAL SUMMARY OF LEED VERSION 2.2						
		Ecotect	Green Building Studio	IES Virtual Environment	Revit	LEED POINTS POSSIBLE
LEED NC	POINTS THAT CAN BE TRACKED	7	25	47	22	76
	POINTS WITH AT LEAST ONE COST THAT CAN BE TRACKED	0	25	47	31	76
LEED EB:	POINTS THAT CAN BE TRACKED	3	35	37	5	102

O&M	**POINTS WITH AT LEAST ONE COST THAT CAN BE TRACKED**	0	35	37	11	102

*Note: Totals include prerequisites and required credits.

Bold font indicates software that can track the most points with costs.

Summary of Resource Flows and Associated Costs

The table below summarizes the results for the resource flows and costs analysis of each software. The final two rows in the table summarize the total number of resources and number of resources with at least one cost that the software can track throughout the facility lifecycle. It is important to note that none of the selected software tools has ability to track resources or costs past the design phase of a facility lifecycle; there is no direct way to monitor progress, operational performance or resource consumption during the construction phase or during the operations and maintenance phase. Thus, from a lifecycle standpoint, none of the selected software tools can comprehensively track resource flows and costs, which are key parameters in sustainability evaluation.

Table 6. Summary of Resource Flows and Costs

SUMMARY OF RESOURCE FLOWS AND COSTS					
LIFECYCLE PHASE	**Ecotect**	**Green Building Studio**	**IES Virtual Environment**	**Revit**	**TOTAL RESOURCES POSSIBLE**
DESIGN	4	**16**	14	4	33

CONSTRUCTION	0	0	0	0	26
OPERATIONS & MAINTENANCE	0	0	0	0	33
TOTAL RESOURCES THAT CAN BE TRACKED	4	**16**	14	4	92
TOTAL RESOURCES WITH AT LEAST ONE COST THAT CAN BE TRACKED	0	**16**	14	5	92

*NOTE: Bold font indicates software that can track the most resource flows and costs.

Autodesk Revit

The Autodesk Revit software provides a substantial backbone for consideration of LEED credits, resource flows, and the costs associated with each. In particular, Revit can track the highest number of LEED NC SS points and Revit ties with IES VE for tracking LEED NC MR points. Much of Revit's ability to track LEED credits is a direct result of the software's ability to identify specific material types, characteristics and quantities, which also allows Revit to track four of the resources identified in the resource flows. However, one noticeable lacking feature is Revit's ability to consider the construction and operating costs of a facility. Revit can calculate material cost estimates internally from a Bill of Materials for most building elements, or users can export this information to estimating software such as Timberline for more detailed cost estimating, but it does not have internal ability to monitor facility construction or operation costs. Nonetheless, the modeling and design functions of Revit are fully capable of producing building models with sufficient detail to export to other analysis software. In general, Autodesk Revit can create most building components and systems in sufficient detail to perform relevant and accurate sustainability analyses, but Revit alone is not sufficient for facilitating LEED accreditation, resource flows, or costs.

Autodesk Ecotect

In terms of tracking LEED credits, resource flows, and the associated costs, Ecotect seems to be the least capable software analyzed in this P&R. Generally, Ecotect offers a wide range of internal functions that analyze performance characteristics and environmental impacts on a building, particularly by providing feedback on parameters related to acoustics, lighting, and solar and thermal performance. The software is useful during early stages of design, but much of the analysis is relatively simplistic and it cannot internally evaluate several characteristics, such as airflow and ventilation rates. Ecotect can evaluate heating and cooling loads for a room, but the software does not provide data on the operational costs or requirements for an HVAC system to accommodate those loads. However, Ecotect does have significant import and export capabilities to convey data to other software, such as EnergyPlus for detailed energy analysis or computational fluid dynamics software for ventilation and airflow analysis (Marsh 2003). Users can then import the analysis results back into Ecotect and display them visually inside the Ecotect model. This is a very powerful capability, which allows users to modify the Ecotect model based on the displayed analysis results, then re-export the model to analysis software and iteratively design a building to meet desired performance and other criteria (Autodesk 2008b). Nevertheless, in terms of stand-alone, comprehensive sustainability analysis capability, Ecotect is the least adept software.

It is important to note that users who formally subscribe to Ecotect Analysis automatically gain access to the GBS web-based service; consequently, those Ecotect users have increased analysis capability over users who do not have a formal subscription to Ecotect Analysis – particularly with respect to analysis of energy and water consumption and costs. However, if Ecotect cannot perform a specific function without an analysis subscription (i.e. without accessing the GBS web-based service), then this P&R does not identify that function as an Ecotect capability.

Autodesk Green Building Studio

Autodesk Green Building Studio (GBS) is the best software for tracking resource flows and associated costs, and is second best software for tracking LEED points and associated costs. GBS is the only software that can track water resource flows and associated costs, so it can also track the most Water Efficiency (WE) credits and associated costs. GBS can track the most resource flows and associated costs, and it ties with IES VE for ability to track Energy and Atmosphere (EA) credits and associated costs, as well as Innovation credits and costs, both for LEED NC and LEED EB: O&M.

GBS provides accurate and easy-to-understand summary information on building energy and resource use, carbon emissions, simulation assumptions, performance metrics, and costs that can be used to compare multiple design scenarios at the conceptual design phase of a building project. The analysis results pages provide detailed summaries and breakdowns of building performance parameters, which allows users to target specific building systems or components and monitor or modify them independently. For example, GBS provides annual energy costs for the building as a whole, but also breaks down the annual energy costs for HVAC, lighting, and other systems. This allows users to monitor system-specific and overall building impacts of changes to the HVAC system, for example, which is a very powerful feature. The ability to calculate renewable energy and natural ventilation potential is also unique and beneficial for sustainability analyses. In general, GBS is an adequate stand-alone performance analysis tool that can compare multiple design alternatives simultaneously and offers multiple file export capabilities. Furthermore, the ability for GBS to access Google Maps provides unique ability to extract weather data, geographic information, and other data accessible through the Internet (Autodesk 2008c). Although GBS is not the best-suited software to facilitate generative design of specific building components, it provides substantial building performance analyses capabilities and is a logical choice for use with Autodesk Revit software when performing sustainability analyses.

Integrated Environmental Solutions

Architectural Suite Plus

The IES Virtual Environment (IES VE) Architectural Suite Plus outperforms the other software with respect to the specified criterion. IES VE can track the highest number of LEED points and associated costs for both LEED NC and LEED EB: O&M. IES VE can track the highest number of LEED NC IEQ points and associated costs, and the highest number of LEED EB: O&M MR and IEQ points and associated costs. IES VE is the only software that can track a cost associated with every LEED point it tracks; similar to GBS, IES VE can also track a cost associated with every resource it tracks.

The IES VE Architectural Suite Plus offers specific design and analysis tools for multiple building systems and performance/sustainability parameters. IES FlucsPro, LightPro, and RadianceIES perform advanced daylight analysis and artificial lighting design, SunCast performs advanced solar analysis and ApacheSim performs detailed energy simulation and analysis. PiscesPro and IndusPro provide facilities to draft pipe and duct systems, respectively, and then size the systems appropriately within the IES VE environment. LifeCycle and CostPlan predict building lifecycle costs and capital costs, respectively, with significant cost breakdowns and other data. Other tools exist within the software, including the Sustainability Toolkit, which considers energy consumption, carbon emissions, ASHRAE load calculations, and a 2030 Challenge assessment, among other things (IES 2008). In general, the IES VE software can simulate a building as a complete entity and perform qualitative and quantitative analyses to optimize the integrated elements of the building design. It offers a very holistic approach that provides more in-depth access to specific design elements and performance characteristics than the other software analyzed in this report. Thus, the IES VE software provides the most comprehensive stand-alone sustainability analysis tool.

CONCLUSION

Summary of Findings

Overall, the results of this P&R indicate that current capabilities of the selected software tools are inadequate for comprehensively tracking LEED points, resource flows, and costs associated with them. Ecotect is adequate for performing general building analysis early in the design phase, particularly if the primary concern relates to acoustics, lighting or thermal performance; although it provides superb visualization of analysis results, Ecotect cannot perform all analysis function internally and is best suited for a more “quick-and-dirty” approach to building performance analyses. GBS and IES VE provide relatively similar capabilities, however GBS is more adept at tracking water-related points, resources, and associated costs. IES VE seems to be the most comprehensive; it provides highly detailed analysis and design functions and can track the most LEED points.

In terms of LEED certification, none of the analyzed software tools can facilitate any level of formal certification. IES VE can facilitate 47 credits, which is enough for basic LEED NC certification, and both GBS and IES VE can facilitate enough credits for basic LEED EB: O&M certification. However, no software tool can facilitate achieving all LEED points or all the prerequisites and required credits; therefore no software tool can truly facilitate any type of LEED certification without additional resources. These results are significant, because LEED is currently the most widely used green building certification / measurement tool in the United States.

The results for tracking resource flows and costs are similar to those for LEED criterion. None of the selected software tools can track resource flows or associated costs during the construction or operations and maintenance phases of a facility lifecycle, and the maximum number of resources tracked by any software in the design phase is only sixteen out of the ninety-two identified. GBS is the most adept at tracking resource flows and the associated costs, while IES VE ranks a close second. Surprisingly, Revit cannot track many of the resource flows. However, it is important to note that Revit is very adept at tracking specific building material quantities and costs, but this capability is not accurately reflected, because material quantities are not broken down by specific material type; if this were the case, the number of resources tracked by Revit would likely increase dramatically.

Although it depends on the specific preferences, needs and objectives of a particular user, it seems that the IES VE Architectural Suite Plus is the best software for performing building performance and sustainability analyses. However, there is still a need for substantial improvement within this software and others. One notable absence in the IES software is the ability to track Water Efficiency (WE) credits and other water-related parameters. The IES website indicates ongoing research with respect to developing a LEED-specific toolkit, and perhaps water resources will be addressed, but the contents of the toolkit are not yet available.

In general, software developers must work closely with architects, engineers, constructors, building owners and users, and others in the AEC industry to determine where, when and how BIM and related analysis software tools are applicable. Primarily, the area in most need of improvement is resource management through the entire facility lifecycle. Each of the software tools analyzed in this report can track at least some LEED credits and some resources during the design phase, but none has ability to monitor resources or costs during the construction phase or the operations and maintenance phase of a facility lifecycle. This is a substantial deficiency because most of a building's costs, environmental impacts, and resource consumption occur after the design phase is complete.

It is important to note that this P&R methodology does not include use of or access to any of the software programs studied in this report. Thus, the software capabilities mentioned in this report are not the result of direct interaction with the software; rather, information regarding software capabilities is from second-hand user experiences, product reviews and reports, and product-specific documentation, such as user guides and software manuals. This limits the accuracy of the P&R, because it is not possible to verify software capabilities first-hand; however, software access and utilization exceeds the scope of this P&R. Perhaps an appropriate follow-up to this P&R is to document personal experiences during software utilization and conduct interviews with other software users.

Conclusion

Growing awareness of the environmental impact of buildings and infrastructure has increased the need for AEC industry professionals to embrace sustainable practices. Sustainable design is a major trend driving process change within our industry, requiring a workflow that provides more information earlier in the design process. BIM is poised to facilitate this change, because it enables an integrated workflow, linking design with analysis and construction to promote design-awareness and understanding throughout a building's lifecycle. In this light, sustainability is part of the larger trend toward more predictable, accurate, and responsible outcomes through integration in the AEC industry. As this trend progresses, BIM will also evolve and become an integral tool to enable the cost-effective design and delivery of healthy, resource-efficient buildings and to realize the true potential of the AEC industry to facilitate a sustainable built environment.

As the relationship between sustainability and BIM matures, industry focus on facility performance will shift beyond minimizing negative impacts to reaching net-zero impact, and ultimately to creating facilities that contribute to regeneration. Some define this type of facility, often referred to as a *living building*, as having zero net annual impact on the environment from an operational standpoint (Krygiel and Nies 2008). It provides its own energy and water, cleans it own wastes, and emits no pollution. However, a *truly* sustainable facility mitigates all environmental impacts and prevents depletion of any natural resource throughout the *entire* facility lifecycle. In that sense, none of the software reviewed in this report has stand-alone ability to facilitate truly sustainable buildings. However, will BIM methodology and technology be adopted and evolve to such an extent that realizing such buildings is commonplace for the AEC industry? Furthermore, it seems LEED is not the most adept rating technique for evaluating the sustainability of a construction project or building, and there may be a need for new sustainability evaluation criterion for the AEC industry. Perhaps these topics should be goals or research areas for software developers, practitioners, and others in the AEC industry.

APPENDICES

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