CONCEPTUAL ENERGY MODELING FOR ARCHITECTURE, PLANNING AND DESIGN: IMPACT OF USING BUILDING PERFORMANCE SIMULATION IN EARLY DESIGN STAGES

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ABSTRACT

Architecture practice is on the front line directly applying best-case evidence-based solutions to conserve energy. Conserving resources through energy efficiency rely on energy modeling software to simulate performance, evaluate energy use, and optimize energy savings in building designs. Today's powerful building performance simulation tools can be leveraged for energy modeling during early design phases. To further reduce building energy consumption, energy simulations done during conceptual design has potential to impact longterm energy use in architecture. This paper reviews early or conceptual building energy modeling research identifying what is simulated when in building design, provides design examples that utilize evolutionary modeling and proposes recommendations for further energy simulation research in early design.

INTRODUCTION

Primarily energy modeling is performed as a post-design energy evaluation validating building performance. The post-design validation of energy savings is used as a compliance check for various green building rating systems and to predict a building's energy consumption. Because energy modeling is used post-design, occurring after design completion just prior to construction, energy modeling plays a minimal role in the architect's mind during design. Further, limiting energy modeling to the domain of experts isolates performative results from influencing building planning and design. Kanters et al. (2012) survey and interview results strongly indicate the need for further development of design tools for solar architecture.

In the report Unlocking Energy Efficiency in the U.S. Economy, what is needed to "reach our full [economic] potential is an integrated analysis of energy efficiency opportunities that simultaneously identifies the barriers and reviews possible solution strategies" (Granade, 2009). The barriers and solutions, according to the National Science Board (2009), "to meet near-term needs [sustainable energy economy] include: developing mechanisms for conserving energy; encouraging energy efficiency; and identifying, developing, demonstrating, and deploying both existing and emerging sustainable energy technologies". One technology that serves as a best practice mechanism for conserving energy is building performance simulation (BPS) in architecture.

BPS for energy modeling at the conceptual level is not new (Xia et al, 2008). During building design "the objective is to achieve the best equilibrium between the essential design parameters versus a set of criteria that are subject to specific constraints" (Kolokotsa et al, 2009). For conceptual and early building planning the energy specific constraints include such things as building orientation, building mass, glazing type and ratio, and shading (Gero et al, 1983). Using these constraints for energy modeling enables the architect to understand the thermal behavior of the building affecting the conceptual design. The conceptual planning and design scope of simulation parameters are different from whole-building energy modeling which provides users with feedback on building performance such as energy use and demand, temperature, humidity and costs (Crawley et at, 2008).

Uses of whole-building energy modeling can be summarized into four approaches, ordered by frequency of use.

1. **Post-design validation** benchmark modeling for performance verification prior to construction. Primarily used to establish performance baseline during the construction document (CD) phase for certification against Energy Star, LEED or other green building rating system.
2. **Discrete modeling** verification completed as iterative modeling during design development (DD) phase.
3. **Schematic design** (SD) phase modeling verifies conceptual design decisions such as massing, site orientation and building form.
4. **Pre-design** energy goal setting establishes how to meet performance targets.

Major use of whole-building energy modeling focuses on post-design validation and discrete modeling largely completed later in design; therefore, missing out on energy savings potential gained by BPS during conceptual design operations. Conceputal design similarly defined as part of the "energy design process" (Hayter et al, 2007) or called early design (Xia et al, 2008), (Donn, 2009), (Bambardekar and Poerschke, 2009), is part of the schematic design (SD) phase.

Typically whole-building energy modeling is used to simulate mechanical (HVAC) and electrical systems in buildings. This information is relevant later in design, during construction documentation (CD), but does not inform planning or design considerations made by architects. Furthermore, BPS used for energy validation, is primarily executed after the design development (DD) phase where the majority of building decisions are made. Thus, whole-building energy modeling considerations are not integrated into planning or design decision-making early.

In an extensive review of energy modeling software by Drury Crawley, et al. (2008) twenty different energy simulation tools were evaluated. However, in their analysis the energy modeling categories reviewed simulated building technologies and systems determined later in design development phases (DD and CD) ideal for post-design validation and discrete modeling verification. In order to evaluate the dependencies of performance criteria on building form, orientation, massing and other design decisions determined in schematic design, not specific systems and technical components identified during DD, building performance simulation has to be seamlessly integrated earlier into the design process (Schlueter and Thesseling 2008). Hypothetically the earlier building designs are modeled the more energy saving potential can be realized later in the building project.

Therefore, BPS as part of the energy design process (Hayter 2007) begins with the SD phase and energy considerations evaluated iteratively throughout the following phases of DD, using discrete verfification and finishing CD with post-design validation. This sequence and repetition of energy modeling is what makes simulation important and as discussed by Hayter (2007) is part of an integrated design approach. Further, Xia (2008) outlines the following simulation functions important in the preliminary conceptual design. First, understanding an architectural design's energy efficiency potential and its cost. Second, comparing the energy savings of different building design schemes. Third, analyzing the influence of different parameters on the building performance. Fourth, helping to clearly make design decisions for later design sub-stages, especially the detailed design of the material. To understand more clearly formal considerations in conceptual design and the architectural energy savings potential, what and when to use BPS to energy model is important.

METHODS

The methods section has three parts. First, a review of energy modeling processes identifies when various energy-modeling considerations impact building planning and design. Second section identifies conceptual design elements to model during early design. Finally, the last part on design process provides examples that combine evolutionary modeling and energy simulations speculating on the impact BPS has in conceptual design. Following the methods section is a discussion to understand what to simulate, when to complete BPS during design and how BPS impacts early design stages.

Energy Modeling Processes

A comparative analysis based on four approaches of post-design validation, discrete modeling, schematic design an pre-design completed in Table 1 presents what design activities constitute early planning and design decisions. Comparing energy design processes by various authors includes items such as sketch design, brainstorming, layout design, conceptual design and simulating design solutions. It is important to recognize the need for simplicity in the conceptual design phase (Bambardekar and Poerschke, 2009). As part of the decision making process BPS plays an important role in optimizing complex building design objectives. Therefore, four phases outline when during design to complete an energy model to assist building planning decisions from conceptualization.

BPS incorporated into the phases of building project delivery, Pre-Design, Schematic Design (SD), Design Development (DD), Construction Documentation (CD), Construction Administration (CA) and Post-Occupancy (AIA 2012) establishes a foundation for improving energy efficiency and impactful whole-building energy conservation. Important is the planning process used in building design for energy conservation in the pre-design phase.

First, prior to decisions regarding building layout or form is the identification of energy goals to drive these future design decisions. During pre-design, setting energy goals enables the design team to embed critical energy savings goals informing the BPS and proper energy model. Next, schematic design decisions where building form (figure 1 for example), orientation, massing, interior layout, and other decision are made provide simulation potential for energy performance embedding these conceptual strategies into the later phases. During DD iterative modeling of discrete design elements or parameters optimizes the buildings design development such as HVAC, electrical systems, and building fenestration, figure 3 for example. Finally, during the CD phase post-design benchmark modeling simulates the full scope of energy consumption in a building against an established standard.

In one study, Xia (2008) separated the conceptual design phase into four parts for simulation. Table 1 overlays the four phases identified earlier to organize the modeling protocols that authors Xia calls conceptual design, Hayter's (2007) energy design process, Bambardekar's (2009) framework and

Table 1 Comparison of the various phases identified for use of BPS.

WARREN (2002)	**HAYTER ET AL. (2000)**	**BAMBARDEKAR ET AL. (2009)**	**XIA ET AL. (2008)**	
	Pre-design	Programming Stage		4. Pre-design Goal Setting
	Best-case building model Parametric Analysis			
		Early Schematic Design	Sketch Design	3. Schematic design
	Brainstorming Simulation Design Solutions		Layout Design	
Conceptual Design	Conceptual Design	Late Schematic Design	Preliminary Conceptual Design	
Preliminary Design			Detailed Conceptual Design	2. Discrete Modeling
Detailed Design	Design Development			
Construction				1. Post-design Validation
Tender Evaluation	Bid Documents/Specifications			
Commissioning	Commissioning			
Facilities Management	Post-Occupancy Analysis			
Renovation				

Warren's (2002) diagram of the idealized building design process. Table 1 aligns these authors various phases of when energy modeling is completed with the four approaches of whole-building energy modeling discussed in the introduction. The commonality is a wide range of early simulation options for the schematic design phase. However, omitted from this comparison is a look at energy modeling during the later phases as these authors primarily discuss energy modeling early in design.

Conceptual Design Elements

Energy modeling as a design application is discussed in the conceptual design phase (Hopfe et al, 2005), (Hong et al, 2000); early design (Donn et al, 2009), (Bambardekar, 2009), (Pollock et al, 2009); as well as the simulation software tested for applicability (Riether and Butler, 2008). Other energy modeling considerations include the proper use and application of the simulation tool (Donn, 2009), (Hong 2000); resolution of the energy model and solving the proper question (Hensen, 2004), are all critical. As argued by Hensen (2004) "a first and paramount requirement for the above is sufficient domain knowledge by the user of the software". However, as noted by Schlueter and Thesseling (2008) "this expert knowledge is limited by the accumulation of knowledge and current workflow directed to the energy modeler". Due to this, energy modeling remains primarily the domain of specialized engineers.

In contrast to the highly specific nature of energy modeling, design software is more intuitive and equipped with 3D modeling capabilities. In comparing ten "architect friendly" simulation tools Attia et al. (2009) outlined that design users value an intelligent information knowledge base and software usability. The software tools should be able to produce initial results from a "rough building representation and then allow for detailing parts of the building" (Hopfe, 2005). To design energy efficient buildings, requires validation of energy performance that is primarily done with energy modeling software. The majority of energy modeling software available on the market is not design oriented but evaluative in nature.

For the architecture community, one goal is to gain expertise in the evaluative aspects of BPS and improve and maximize a buildings energy performance. This impetus for energy modeling "beginning the design in this simulation environment is a means by which the architecture profession can address its responsibility, for the betterment of all involved." (Butler, 2008). Architecture needs to gravitate towards a more effective use of energy modeling (Hensen, 2004) and requires simulation of the proper information (Donn, 2009). In 2012 the American Institute of Architects (AIA) issued a guide for architects to integrate energy modeling in the design process. Primarily an overview of why energy modeling benefits practice and the role Architects play in determining building performance. The report provides a good snapshot of why, how and where to ingrate energy modeling in the design process (AIA, 2012). Therefore, to expand the use of energy modeling in architecture, understanding when and what to simulate is critical in order for widespread adoption.

This paper provides design clarity on what to model (Bambardekar, 2009) in order to produce meaningful energy performance simulations (Bazjanac et al, 2011) and expand energy simulation by Architects (Attia, 2009). Based on several papers, Table 1 identifies when to use energy modeling in the planning and design of buildings.

Several previous examples of early design simulations raise questions about what is simulated and when. Riether and Butler (2008) discuss the use of Ecotect as "a one-tool solution for providing early phase performance analysis to designers." However, their testing method was limited and omitted design variables typically considered in conceptual design. Xia's (2008) example of natural ventilation to prove the conceptual design approach uses natural ventilation in a case study. Natural ventilation is just one design factor and is not widely applicable to energy savings in many hot/humid and cold climates where ventilation is not useful. Additionally, not all projects may utilize natural ventilation as an energy saving strategy; therefore, the purpose of this methods section is the identification of what design elements to model shown in Table 2. Reviewing existing literature on early and conceptual design Table 2 identifies a range of design elements that contribute to energy conservation. The what, schematic design elements, along with the when, design process, provides a design-centered process that simplifies the simulation protocol (Bambardekar, 2009), which is necessary in early building planning.

Software comparision by Bambardekar (2009) compared Ecotect, IES and Green Building Studio as part of evaluating the energy simulation protocols in early design. What they found was a need to define the simulation scope to guide the energy modeling to address in order to make more intelligent design decisions based on energy saving features (Wilde and Augenbroe, 2002).

Looking at several authors who discuss energy modeling as a process in design are Warren (2002), Hayter (2007), Xia (2008), Attia (2009), Bambardekar (2009) and Gero (1983). Table 2 compares design elements they identify for schematic design with potential for energy simulation.

Design Process

For early design decisions during schematic design, information distilled from the comparison in Table 2 includes passive design elements of building orientation, size, massing, function, geometry/shape, envelope materiality/resistance, window to wall ratio, interior spaces, shading, natural ventilation, thermal mass, daylight, renewable energy and infiltration. A design process for BPS in schematic design requires maintaining energy simulation settings as close as possible with each run limiting changes to selected schematic design elements above. By limiting variation and maintaining operational, HVAC, and electrical system settings during the simulation variation within the schematic design energy model becomes more meaningful producing simulation feedback informing design considerations. Two design examples serve as a proof of concept to demonstrate in what ways BPS linked to design can impact conceptual design decisions.

Table 2 Conceptual design elements identified to simulate (excluding HVAC, Electrical and Alternative Technologies.)

	Warren (2002)	Hayter et al. (2000)	Xia et al. (2008)	Attia (2011)	Bambardekar et al. (2009)	Gero (1984)
Orientation	X	X	X		X	X
Massing			X	X	X	X
Function			X			
Geometry/Shape		X	X	X	X	X
Envelope	X	X		X	X	X
Window to Wall Ratio		X		X		X
Interior Space	X	X	X		X	
Shading		X		X	X	
Natural ventilation	X	X	X	X	X	
Thermal Mass		X		X	X	
Daylight	X	X		X	X	
Renewable Energy	X			X	X	
Infiltration				X		

Design Examples

Performance-based design can use energy modeling to set formal priorities for the design related to building mass and building orientation two fundamental tenants of passive solar design. Therefore, one methodology is to start with performance-based design where formal decisions are based on performative [energy] results (figure 2). Different from the broad definition of performance-based design (Becker, 2008), in performative modeling of design, "performance is formally prioritized as a shaping force" (Oxman, 2009). Once planning for building massing issues the design process can continue using whole-building optimization early and iteratively throughout the design process.

As a starting point, one simulation goal to evaluate design is solar insolation (kWh/m2) or the amount of solar radiation energy striking the building surface (Hachem 2011), (Kampf et al, 2010) helping designers understand the thermal performance of the building mass as affected by site orientation or shading. Examples discussed by Hachem (2011) and Kampf (2010) demonstrate simulation protocols that impact schematic design decisions from simulating incident solar insolation/radiation. Both papers identify the need for a parametric model or multi-object optimization algorithm to balance the complex design decisions across a spectrum of possibilities. Hachem identifies several types of buildings and typological differences to test against solar radiation values. The simulation was completed, we assume, from iterative simulations based on the research constraints. Additionally, Kampf evaluates the aggregate massing and roof heights. In this case due to the large range of urban typological differences, Kampf uses an evolutionary solver to test different urban forms and their radiance values.

Parametric modeling and evolutionary solvers are recent advancements in the field of software-development. As design tools they enable shortening the distance between the schematic design and BPS. In other words, by establishing the necessary communication between our software of choice we can achieve a parametric model that instantly reflects the energy performance of our design (Jakubiec and Reinhart 2011). Moreover, if too much data is a problem we can pass the data through an evolutionary algorithm to reach a desired level of optimization.

Technically, design objectives are a collection of parameters that we provide for the algorithm (genes). Objectives are tested to reach a target optimization level (fitness level) to produce results. In evolutionary computing we transform our data into form and shape through our parametric design scheme. This kind of planning for energy-performance in our design (as a more ideal process) is the subject of our next examples where the optimization of the numeric data leads to a range of alternatives with close approximation to the optimized performance.

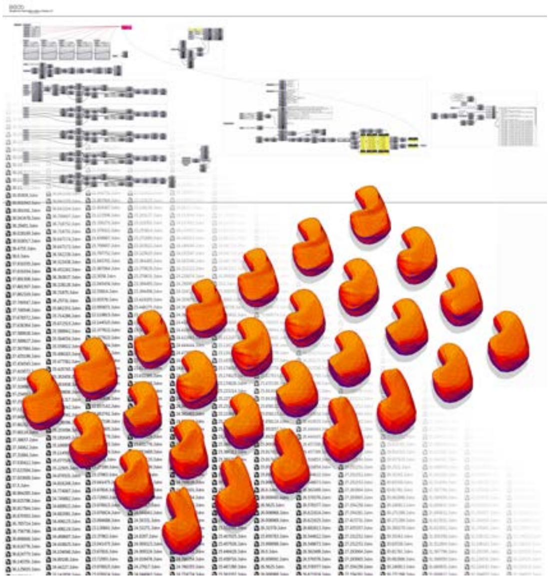

Figure 1 Performance-based optimal form finding based on incident solar radiation by Thibault Schwartz, House project, EZCT Architecture & Design Research Energy, sunlight analysis and optimization, 2011.

Two design examples show how to optimize a building solution early during the schematic design phase. First is building form, figure 1, derived from a parametric-model linked to energy simulation using an evolutionary solver and, second, window locations within a typical suburban house are optimized for daylight, figure 2. If we look at when these simulations occur, the window example could occur during early schematic design and the building shape during planning or best-case building model (Hayter, 2000). Next, considering what is measured, the building form example derives its form based on minimizing solar insolation to reduce the solar radiation energy received.

Parametric modeling environments derive geometry from explicitly embedded relationships. Performance targets can be defined inherently in the modeling environment and multiple variations can be tested. A performance-based approach that uses BPS of irradiation shown in figure 1 verifies during conceptual design energy can be embedded into the formal building massing. The second example, formal designs evolve from window location variables to maximize interior daylight, figure 2. The experiment uses BPS to measure the daylight factor on the interior until it has reached a predetermined or desired design level. A generic housing mass is virtualized and locations of windows are iteratively tested with a genetic algorithm to maximize interior daylight levels. This could further be expanded to synchronize interior daylight with internal programs

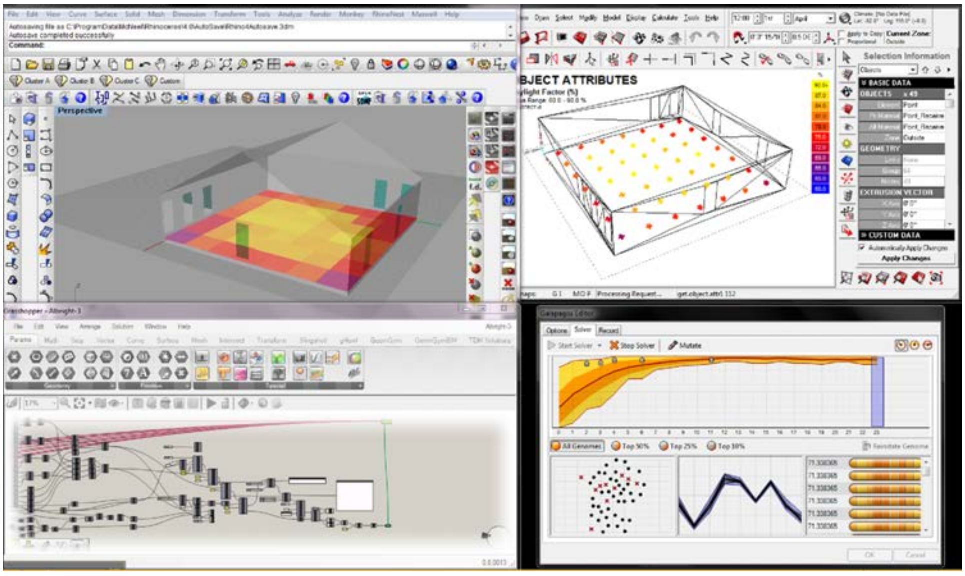

Figure 2 Parametric optimization of window locations based on interior daylight factor.

and operations. The daylight example linked together design (Rhinoceros 3d) and evaluation software (Ecotect) to discretely test window locations maximizes the interior daylight levels. The parametric simulation is an example of both discrete and performance-based simulation. Discrete due to the software samples various window locations against others to maximize daylight. Performance-based because the final solution is the optimal fit for the performance parameters tested.

DISCUSSION

In BPS, specifically energy modeling, one problem is too much information to compare especially during the early phases of design. Authors who outline a methodology for early phase design (Xia 2008); (Donn 2009); (Gratia, Herde 2003) overlook the reality of what information architects have to make decisions. To better serve the design industry, what information should we simulate to understand the impact of conceptual design decisions? The most comprehensive framework to date (Bambardekar, 2009) identifies forty different analysis items keyed to design process. Their framework is part of Table 2 and further outlines what items various authors have identified that can be modeled in the schematic/conceptual or early design.

*Table 3: Building performance simulation methodologies used in conceptual/early design phases. *Not explicitly stated but inferred from article's language.*

	Hachem, et al (2011)	Kampf, et al. (2010)	Kanters (2012)	Gratia, Herde (2003)	Morrissey et al. (2011)	Example in Figure 3
Software Used	Energy Plus	Radiance	Ecotect	TAS	AccuRate	Ecotect
Simulation/Analysis Performed	Solar Irradiation	Solar Irradiation	Incident Solar Radiation	Thermal Performance	Thermal Performance	Daylight Factor
Period	One summer and winter degree day	Six months from Nov-Apr	Annual	Annual	Annual*	Single Day
Design Element	Shape and Orientation	Massing	Massing	WWR, Shape and Orientation	Geometry and Orientation	Daylight
Context	Urban	Urban	Urban	Unknown	Residential	Residential
Program Type	Residential	Residential	Residential	Commercial	Residential	Residential
Location	Montreal, Canada	Switzerland	Sweden	Belguim	Melbourne, Australia	Lincoln, Nebraska

Additionally, the American Institute of Architect's report on energy modeling (2012) identifies broad goals and benefits that energy modeling has in various design phases and levels of modeling fidelity. With clear information such as this it is possible to expand the comparison of when in the design process and what design elements are important to simulate with energy modeling. Another issue is not having adequate information to produce meaningful simulation results (Bazjanac 2011). For example, expert level modeling programs require extensive inputs to produce meaningful results therefore are the domain of expert modelers beyond a designers expertise and knowledge.

In order for energy modeling to have a significant impact for Architects in design, usable intuitive software tools (Attia, 2009) would allow early conceptual energy decisions. As we know, simulations approximate building performance and not the actual operational performance (Augenbroe, 2011). However, evidence-based decisions derived from BPS establish analytical measures to check whether designs meet intended energy conservation goals and are important in design.

Based on the examples and background outlined in this paper there are four recommendations to discuss for early energy efficient building planning and design decisions.

1. Design is a process that changes and is in flux, so using the same tool throughout design can disassociate where a design might be with what information is available. From the design examples discussed, their success relies on the **use of multiple tools** to evaluate the right information early and often. Consider what and when to simulation energy performance and which tool is best to use (Crawley, 2008), (Attia, 2009). This is counterintuitive to those who believe using one energy-modeling engine from beginning to end for a high fidelity simulation. A proper BPS is about performing the right type of virtual experiment with the right model/tool (Augenbroe, 2011).

2. **Establish iterative protocols for optimization** of the design at the right time as part of the energy design process (Hayter, 2000). Energy modeling at the end or just at the beginning ignores larger design changes that might occur during the design phase. Energy modeling early on establishes important project goals. The earlier goals are set is important because functional, scope, or design changes will likely occur and using BPS to set energy goals increases the likelyhood they remain relevant through all design phases. The bulk of BPS tools for energy modeling ignore early formal design considerations, due to their purely evaluative nature. Therefore, energy modeling later in the design process limits consideration of formal strategies to reduce energy early on.

3. **Explore multiple simulation outcomes to find the right information.** It is hard to know what energy performative factors will be appropriate for the project. The best method in one project might not be the same one in another. Often energy saving features are predominantly selected without computational support (Wilde and Augenbroe, 2002); therefore, BPS completed early and appropriately is valuable to the design process. Additionally, the variety of BPS tools available opens up multiple perspectives to consider in order to conserve energy. Simulating incident solar irradiation informs photovoltaic active potential (Hachem, 2011) as well as which building surface has the most passive gain (Kampf, 2010). Project location and climatic considerations also affect a buildings morphological or formal design strategies (Olgyay, 1963).

4. **Integrate energy into formal design considerations** at the beginning of the project. Without integrating energy into the conceptual form of the building it is easily forgotten, ignored and omitted throughout the process. Success is built on appropriate application of the first three recommendations providing the greatest leverage in the design process.

CONCLUSION

This paper identifies BPS energy modeling for building design processes and conceptual design elements showing early design decisions impact on energy conservation. Improving energy conservation decisions early in building planning and design helps to optimize whole-building performance. When to use energy modeling processes in designing a building informs the BPS protocol in pre-design, schematic design, discrete modeling and post-design validation. Highlighted is what design elements to simulate, specifically for early design energy considerations that involve building orientation, size, massing, function, geometery/shape, envelope materiality/resistance, window to wall ratio, interior spaces, shading, natural ventilation, thermal mass, daylight, renewable energy and infiltration. Finally, critical to improving a building's energy performance are proper BPS protocols completed at the right time in the design process and modeling the right design elements to conserve energy in buildings.

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