HOW CAN AMERICAN AEC FIRMS GET THE LEAD IN SUSTAINABLE BUILDING DESIGN? WHAT A POTENTIAL DESIGN LEADER SHOULD KNOW ABOUT “GREEN-_CONVERTIBLE BUILDINGS.”

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ABSTRACT

Energy-efficient building design and operations reduce the negative impacts of buildings on human health, natural environment, and non-renewable energy resources by reducing waste, pollution, environmental degradation, and energy consumption. However, the number of green residences and commercial buildings is small compared to the number of traditional buildings since the initial costs of energy-efficient buildings are relatively higher than regular buildings. When stricter environmental regulations take place, innovative technologies become available at a lower price, costs of non-renewable resources rise to higher levels, or capital financing becomes ready, energy-inefficient buildings will be required to convert to low-energy green buildings at a certain cost, the green-conversion cost. It is then appropriate to ask what AEC firms can do now to reduce this future green-conversion cost. A possible solution is to develop a systematic approach that helps designers/retrofitters to identify flexible building systems and (dis)assembly methods that facilitate conversion to low-energy green buildings in the future with minimal intervention cost. We present the novel approach of incorporating flexibilities on/in a building or a building system to AEC firms. Considering flexibilities on/in building projects can potentially contribute to transforming the traditional building development and design as the nation confronts the daunting challenge of securing sustainable buildings for future generations and American AEC firms seek the competitive advantage to lead in the global markets.


INTRODUCTION

Buildings account for one-sixth of the world’s freshwater withdrawals, one-quarter of its wood harvest, and two-fifths of its material and energy flows (Augenbroe et al. 1998). The United States Green Building Council (USGBC) states that buildings account for 37% of all energy use and 68% of all electricity use, noting that "the building trades do about six times more damage than automobiles in terms of energy consumption and carbon dioxide emissions” (Stang and Hawthorne 2005). Energy-efficient, green building design and operations have been used as a transformative solution to reduce the negative impact of built environment assets on the human health, natural environment, and nonrenewable energy resources by reducing waste, pollution, environmental degradation, and energy consumption (Guggemos and Horvath 2005; Trusty

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While this transformation is forceful and regulation-driven in Europe (i.e., mandated environmental declarations and labels, building codes, and permitting requirements), it is more gradual and persuasive in the United States (i.e., Environmentally Preferable Purchasing (EPP) helping the federal government "buy green" and incorporation of sustainable building design principles and procedures by government at all levels) (Trusty 2006).

However, the number of green residences and commercial buildings is small compared to the number of traditional buildings. As of October 2008, just 5,709 buildings in the U.S. had been awarded the Energy Star designation, including 2,230 office buildings, and there were just 1,703 buildings certified by the LEED (Leadership in Energy and Environmental Design) program of the USGBC (Eichholtz et al. 2009). This is due to several factors: first and foremost, the initial costs of energy-efficient buildings are relatively higher than of regular buildings. Developers and building owners must commit to these large-scale investments now to receive possible financial benefits, such as energy savings, in future. In both Europe and the U.S., energy policies are being developed that will require new and existing buildings to meet a step change in energy efficiency requirements. Although the current expenses required to design and construct a highly energy-efficient building are known, the future benefits associated with energy conservation are subject to a great amount of uncertainty (Malkawi and Augenbroe 2004; Straube 2009). Initial building design or design of a retrofit is carried out considering uncertainty about several factors:

- Uncertainty about the price of oil and other nonrenewable energy sources.
- Uncertainty about the future cost and efficiency of clean renewable energy generated by innovative technologies, such as photo-voltaic (PV) electricity generation systems.
- Uncertainty about the actual performance and reliability of innovative technologies to produce clean renewable energy and/or conserve energy consumption in buildings after incorporation in buildings, e.g. due to partly unpredictable conditions, change of physical parameters over time, uncertainties in operation and usage scenarios, etc.
- Uncertainty about the cost, actual performance, and benefit of competing technological alternatives to generate clean energy or reduce building energy consumption.
- Uncertainty about the future regulatory environment to impose and support energy-efficient buildings through new taxation policies and/or subsidiaries and tax breaks.
- Uncertainty about the future energy requirements of building owners and users.

Building designers or designers of a retrofit thus face several possible future scenarios when they work on low-energy green building design. Conventional building design is, however, dominated by only one possible future path. It relies on requirements that come from a deterministic view of the environment (de Neufville 2004) in which the building will operate. Typically, no attempt is made prior to operations to recognize environment uncertainty and to consider it in the design process. This approach often results only in a short-term optimal design choice. However, in the medium/long run, when original environment conditions change, the conventional design will perform sub-optimally (Hu and Augenbroe 2009). The effects of uncertainties in regional climate change have been proven to be another major reason to conduct performance studies under uncertainty (Hopfe and Augenbroe 2009). This medium/long-term sub-optimality creates economic inefficiencies which result in a loss of value for the building stakeholders. Building owners must no longer consider only the features of a design that meet today’s needs and requirements, but also keep in mind the future by building-in transformation mechanisms into the building that allow for changes.

When stricter environmental regulations take place, innovative technologies become available at lower price, the cost of nonrenewable resources rises to higher levels, or project
financing becomes available, energy-inefficient buildings will be required to convert to low-energy green buildings at a certain cost, the **green-conversion cost**. It is then appropriate to ask what we can do now to reduce this future green-conversion cost. A possible solution is to develop a systematic approach that helps building designers or retrofitters to identify and select design choices that leave more future options open than others. This should result in flexible building systems and flexible (dis)assembly methods that facilitate conversion to low-energy green buildings in the future with minimal intervention cost and disruption.

In this new perspective, the design and operation of the built environment is more of an opportunity than a problem in which building designers or retrofitters can take realistic and practical steps to conserve fossil energy and reduce greenhouse gas emissions. Therefore, an uncertain future and/or a limited budget will not be an excuse for an energy-inefficient building, which will become a liability in a future energy- and carbon-constrained world (Straube 2009). Instead, available budgets will be allocated to flexible design solutions and/or design decisions that cannot be easily changed in the future. Such green-convertible buildings can be readily improved in energy-efficiency as financing becomes available.

The theory of flexible design and methods for identifying flexible features in systems engineering (Cardin and de Neufville 2008) provide promising applications in the design of buildings. Flexibility has to be understood in that context as “sufficiently equipped with features that facilitate conversion to low-energy green buildings in future.” In addition, the theory of option pricing developed in independent fields of decision science and finance (Borison 2005) provides a proper valuation technique, which is required to determine when it is economical optimal to exercise a flexible option and transform to a low-energy green building. Although not a direct part of the cost based decision criteria of the client, a life cycle assessment should reveal the environmental impacts of any chosen option. In the scope of this research, life cycle assessment will be limited to a life cycle energy consumption analysis (based on building energy simulation) and translation of the outcome into CO2 emissions, using average data for the energy supply network in the USA. This combined economic/environmental analysis helps design decision-makers properly analyze and compare life cycle costs and environmental impacts, as well as benefits of flexible green-convertible buildings to traditional and green buildings, to avoid under- and over-investments. To fully benefit from flexible green-convertible buildings, the following pressing questions require innovative research:

- How can designers identify appropriate technologies that are the most critical in facilitating transition to low-energy green buildings?
- How can designers translate the adoption of these technologies into choices with respect to building systems and their assembly options that provide the flexibility to adapt to future technology trends in generating renewable energy and/or reducing building energy demand?
- What design, construction, and/or operation constraints should be considered by building designers or retrofitters in utilizing flexible building systems?
- How can designers select the level of flexibility that a critical building system must have (i.e., by comparing the up-front cost of incorporating such flexibility to the lower costs of future energy upgrades to achieve a desired level of energy performance)?

**RESEARCH INTENT AND OBJECTIVES**

In current practice, buildings are rarely designed for adaptability, other than the infill. Most adaptable building design research has taken place around the concept of Open Building (Kendall and Teicher, 2000), which centers predominantly around the re-designation of occupant
functions and associated reconfigurations of the infill systems. Much of this work stems from the seminal work done by Habraken (1998). Systematic research of the relationship between retrofit options and design implications is an underdeveloped area. Several trade organizations (e.g. SMACNA, AISC and ASHRAE) have published retrofit manuals with a clear application emphasis but no overall system design focus. The AIA published the Building Systems Integration handbook (Rush, 1986) which, despite its age, is still one of the best studies ever conducted in the field. The lack of a systematic “design to retrofit” framework has led to the situation that “adaptability” or more narrowly “suitability for retrofit” is rarely explicitly addressed as a requirement in the client brief and even less pursued in the actual design development. In the energy retrofit, this lack of a framework is exacerbated by the fact that energy technologies are fairly new and the translation of emerging systems into flexible design configurations have not yet been undertaken.

It is not surprising that current buildings are designed to meet a given level of energy performance without recognition that the building may have to meet stricter targets at a future date. Our research intent is to enable the client and the design team to look beyond the current energy target and reflect on the possibility to meet future stricter targets and prepare for future upgrades. This preparation involves pondering different options which may be enabled by a “design for flexibility” strategy. Our major research goal is to investigate the benefits of flexible design options for building systems. Incorporation of this flexibility will guarantee that a low energy performing building can be readily converted to high energy performing building when it is required by building owners encouraged by funding availability and or tax credits, or mandated by regulatory actions, and/or encouraged by favorable market opportunities. More specifically, our research objectives are:

1) Conduct a comprehensive case study on two types of renewable building energy technologies: Photo-Voltaic (PV) systems and Ground Source Heat Pumps (GSHP):
   a) Summarize major design and operation considerations of using these renewable energy technologies – specifically related to their interactions with other building systems – in existing buildings.
   b) Summarize critical design and construction issues, which should be considered at the time of concept design, design development, site preparation and construction assembly, or should be considered at the planning and execution stage of a retrofit, to facilitate green-convertible buildings.
   c) Identify the associated building systems that are directly affected by the future option to incorporate one of the renewable systems technologies.

2) Position the two renewable energy technologies in a retrofit systems analysis with the two major technology interventions in standard retrofits: Enclosure System (roof and façade) and the HVAC System (all energy conversion components, pumps, fans and control system). The emphasis will be on the discovery of the interplay between the two tandem technologies: (1) PV and Enclosure, and (2) GHSP and HVAC system.
   a) Develop a systems framework, which guides designers to characterize and parameterize the relationships between the four building systems, and more in particular between the PV and Enclosure and GHSP and HVAC system. Their relationships will be studied through a systems engineering design and performance analysis.
   b) Identify flexibility provisions that enable delayed interventions in any of the four building systems.
3) Develop a novel approach for economic and environmental analysis of green-convertible buildings:
   a) Determine what building system(s) is(are) worth the investment to achieve mid- to long-term building energy conservation.
   b) Describe how a limited budget should be allocated to building systems competing to provide flexibility in green-convertible buildings.
   c) Compare the life cycle financial performance (and resulting environmental performance) of a green-flexible building with a traditional and a green building to assess under what circumstances a green-flexible building is a preferred choice in the uncertain world.

HYPOTHESES

A set of hypotheses is designed to examine these research objectives.

- One can reduce the overall economic and environmental impact of buildings by considering a flexible, green-convertible design option. Such green-convertible buildings can be transformed to lower-energy green buildings with minimal costs and interventions whenever (currently uncertain) future trends emerge favorably.
- A green-convertible building provides a transformative solution to achieve mid- and long-term building sustainability objectives at a relatively low cost.
- The development of green-convertible buildings is facilitated by a systematic approach for identifying building systems that are favorable candidates for flexibility.
- An innovative life cycle cost and benefit analysis approach based on the real option methodology, combined with and supported by a life cycle building energy consumption and CO2 emissions analysis, improves the designer's ability to determine under what circumstances green-convertible buildings are good solutions for transformation to energy-efficiency buildings.
- The proposed real option methodology, combined with life cycle energy consumption and CO2 emissions analysis, also improves the building manager's ability to determine if and when to convert the building into a greener building by exercising the built-in flexible options.

PROPOSED RESEARCH

An overview of our proposed research is shown in Figure 1.

Study Building Renewable Energy and Conservation Technologies

Research Background

Renewable building energy technologies provide renewable forms of energy without the reliance on nuclear or fossil fuels (Kelly and Hunter 2009). One of the leading renewable building energy technologies is Photo-Voltaic (PV) electricity generation system. PV panels convert solar radiation into electric power. One of the major advantages of PV systems is that they are modular and can be increased in size over time.

PV systems have a dominant co-engineering relationship through the following outcomes and design parameters that cross influence design choices of both systems:

- Building energy demand profiles, heating, cooling, plug loads; intelligent energy management system
- Roof construction, slope, orientation, structural stability, accessibility, rainwater run-off, and shading provisions
• Building wiring, electric systems, dual AC and DC systems connecting different sets of energy consuming devices and systems
• Space provisions and positioning of energy storage, inverters, and batteries

There is also a joint impact on Utility contracts, as rates, in most markets are determined by peak power load and consumption patterns, both of which are heavily influenced by the PV-Enclosure tandem.

**Ground source heat pumps (GSHPs)** are electrically powered systems that tap the stored energy of the “greatest solar collector in existence”: the earth. These systems use the earth's relatively constant temperature to provide heating, cooling, and hot water for homes and commercial buildings. GSHP systems have a strong co-engineering relationship with the HVAC system as a GSHP in principle displaces many of the standard components in traditional HVAC systems, and have equal impact on the following outcomes and design parameters:

• Building energy demand profiles, heating, cooling, hot water generation
• Building site provisions, soil conditions, geo conditions, site preparation, surface water
• MEP systems in the building
For utility contracting, the same observation can be made as above. The proposed research will focus on the relevant co-design and co-engineering connections between the two renewable energy technologies and standard energy retrofit technologies. From their analysis flexibility measures will emerge as the best enablers of co-engineering methods for future upgrades.

**Proposed Research Approach**

The proposed research approach in this step is based on conducting case studies to investigate the design considerations that impact the later installation of the two identified renewable building energy technologies in relationship to the standard retrofit interventions in building enclosure and HVAC systems. The research processes consist of the following research tasks:

1) Establish contacts with leading companies in the commercial building market which design, specify, and install any of the four energy retrofit technologies addressed in this proposal to receive information about their products, specification methods and services.

2) Describe the four energy retrofit technologies, their components, respective initial costs, life cycle costs, and energy-saving benefits, and their required operation and maintenance.

3) Summarize important design issues and operation considerations related to each retrofit technology according to manufactures’ technical guidelines. Analyze design and retrofit manuals from a systems engineering perspective, establishing system interface and conflict variables.

4) Describe building systems, which will be impacted the most by using renewable energy technologies according to manufactures’ technical guidelines; this leads to the set of co-engineering relationships that drive the discovery of flexibility features; the focus will be on relationships between the two considered tandem technology interventions: PV+Enclosure and GSHP+HVAC

5) Conduct case studies on several commercial office buildings, in which either or both of the renewable energy technologies have been used.

6) Study design documents of these buildings to outline design considerations and issues related to using renewable energy technologies in new buildings.

7) Study design documents of retrofit to outline challenges and issues related to applying renewable energy technologies in existing buildings.

8) Investigate the actual interactions between these innovative technologies and other building systems that must be considered in their implementation.

9) Summarize critical design issues which must be considered at the time of initial building design or the initial design of a retrofit, to facilitate green-convertible buildings.

10) Identify building systems which are good candidate for incorporating flexibility at the time of initial building design or the design of a retrofit to enhance the future utilization of these renewable energy technologies.

Conducting these case studies helps us understand the major design considerations of using renewable energy technologies in existing buildings. More specifically, we find out how various building systems will be affected if it is ever decided to use renewable energies in existing buildings. One possible solution to facilitate this transformation is to design and construct related flexible building systems with an additional initial cost. Therefore, the question becomes, considering the limited budget, what building systems should be designed with an appropriate level of flexibility to facilitate transformation of existing buildings into low-energy green buildings with the enhancement of renewable energy technologies. This research question has two parts: First, we need to develop a systematic approach for identifying the most important building systems for incorporating flexibility. Once the flexibilities are identified, the designer
needs to justify additional upfront costs and select among competing building systems for flexibility inclusion. A complete life cycle economic analysis is required to determine how much flexibility is appropriate and how the value of a flexible design differs from the value of an inflexible design. As long as the appraised value is higher than the cost of acquiring the flexibility, it is beneficial to incorporate it in the building design or the initial design of a retrofit. These two research tasks are described below.

**Study Building Renewable Energy and Conservation Technologies**

*Research Background*

Flexibility is an important attribute for the design of systems operating under uncertain conditions. It provides “the right, but not the obligation” to modify a system in operations to adapt it to its changing environment” (de Neufville 2004). One benefit of a flexible system is to create value to its stakeholders since it can take advantage of unexpected upside opportunities, and/or reduce exposure to downside risks (Cardin and de Neufville 2008; de Neufville 2004). Flexibility can be incorporated in building projects in two shapes: (1) flexibility in terms of an option on a building as a whole or a building system; and (2) flexibility in the form of an adaptable feature embedded in a building system or a Design Option Flexibility (DOF) in a building system. Identifying flexible features embedded in a building system is more difficult than identifying flexible options on a building or a building system since it requires prior technical design inputs. Over the last decade, several methods have been proposed to address the important problems of identifying DOF “in” systems (Cardin and de Neufville 2008). These methods are:

1) **Interview Method (IM):** Expert interviews can help assess the system design change that would be necessary to cope with a change in exogenous factor scenarios (Shah et al. 2008).

2) **Information-Flow Methods (IFMs):** The following three matrix-oriented frameworks are used to model the flow of information between different system components:
   a) **Change Propagation Analysis (CPA):** Describes how changes in design components move through the system (Eckert et al. 2004; Giffin et al. 2007; Suh 2005; Suh et al. 2007).
   b) **Sensitivity Design Structure Matrix (sDSM):** Segregates the system variables that are insensitive to exogenous changes (i.e., platform) from the system variables that are more prone to vary under the same exogenous factors (i.e., DOF) (Giffin et al. 2007; Kalligeros and de Weck 2004).
   c) **Engineering System Matrix (ESM):** Considers the social, environmental, and managerial aspects of engineering systems to find potential sources of flexibility (Bartolomei 2007).

3) **Screening Methods (SMs):**
   a) **Optimization-based method:** This method screens different designs using various combinations of design variables to find the DOF that maximizes value under physical and budgetary constraints (Wang 2005).
   b) **Approximation-based method:** This method screens a smaller set of representative scenarios of uncertainty by limiting the number of possible design configurations to explore (Cardin 2007).

Despite successful applications of the described flexibility identification methods in systems engineering, they have not yet used to enhance the built environment design.
Proposed Research Approach

We will apply six DOF identification methodologies, including the interview method, the three information flow methods (CPA, SDMA, and ESM), and the two screening methods (the optimization based and the approximation based) on our building case studies. Each method is separately applied to each case study in order to identify the most crucial building systems that should be targeted for incorporating flexible design. These building systems have critical roles in the design of flexible green-convertible buildings since they facilitate future smooth transition to low-energy buildings with minimal expense and intervention. An example of a flexible building system is an over-designed structural system to support future installation of PV electricity generation systems on the top of the building roof. The research processes to achieve the objective of identifying critical building systems are:

1) Apply each DOF identification method to each building case study
2) For each method, determine a prioritized list of building systems as appropriate candidates for incorporating flexibility in building design
3) Summarize the findings of various DOF identification methods and prepare a collective list of building systems critical in flexible green-convertible buildings
4) Characterize portability, robustness, and simplicity of various DOF identification methods

Each building project is unique; building stakeholders and their expectations also vary from a project to another. Therefore, it is very difficult to generalize our findings beyond our limited number of projects. However, if a building system is identified as a major component to incorporate flexibility under each DOF identification method across our case studies, we can safely conclude that building designers should give particular attention to this system as an appropriate candidate for incorporating flexibility. Preparing a list of building systems, which are critical in flexible green-convertible buildings, is an important outcome of this research activity.

Develop a Model for Evaluating Green-Convertible Buildings

Research Background

Economic analysis of flexible building systems in a green-convertible building is as important as identifying and characterizing these flexible features. Design decision-makers and developers of building projects need to compare the financial performance of traditional, green, and green-convertible alternatives to assess sustainability from the economic standpoint. The major economic objective of sustainable building design and development is to avoid both under and overinvestment and ensure that scarce resources are efficiently allocated to building projects (Ellingham and Fawcett 2006). Life Cycle Cost Analysis (LCCA) is designed to determine the right balance between life cycle costs and benefits of a building or a building system. The current standard practice for measuring the LCCA of a building and a building system is ASTM E917–05 that was developed to calculate the Net Present Value (NPV) of mutually exclusive design alternatives for a given functional requirement on the basis of all costs and benefits arising from their implementation, consisting of both future and present costs/benefits.

Buildings, however, evolve and change over time. To address the issue of uncertainty about cash flow elements in LCCA, the deterministic NPV approach is enhanced with several uncertainty analysis techniques, such as sensitivity analysis, probability analysis, and Monte Carlo simulation. Despite major improvements in the traditional NPV analysis to incorporate uncertainty in LCCA, many managers think that the assumptions of the NPV analysis under uncertainty do not properly represent real world design decision-making and its findings do not seem to match their own experience (Ellingham and Fawcett 2006). One of the most important reasons is that the current LCCA standard assumes that all decisions related to a building must be
made at the beginning of the project and all of them are irrevocable; this assumption is not consistent with the real-world decision-making process.

Future building owners can and will make decisions about a building or a building system that impact the values of its future cost and benefit cash flows. Adaptable design or flexible building systems can also effectively reduce LCCA and let a building remain useful when situations change. Flexible design features are valuable since they avoid or limit undesirable outcomes of an investment by revising initial decisions or by deferring decisions to the future when updated information becomes available. An example is a dual flexible heating system that can be switched with no extra cost from gas to electricity when the price of gas becomes substantially more expensive than electricity. This would be the case if a GSHP co-exists with its gas fired tandem HVAC system. This added value, however, comes at a cost that should be weighed against the strategic flexibility value in LCCA for alternative design selection. The standard NPV approach is inadequate to support such LCCA. The financial assessment of green-convertible design alternatives should be performed considering the great uncertainty about whether, when, and how existing buildings will be transformed to low-energy green buildings. The real option methodology is useful for this purpose. The term ‘real option’ was first introduced by (Myers 1977). It referred to the application of financial option pricing in finance and banking, such as (Black and Scholes 1973) formula to the assessment of non-financial or “real” investments with strategic management flexibility like multi-stage development or modular plant expansion. The real option methodology is an emerging state-of-the-art capital budgeting paradigm that addresses managerial flexibility and strategic behaviors of decision-makers under dynamic uncertainty (Amram and Kulatilaka 1999; Dixit and Pindyck 1994; Smit and Trigeorgis 2004).

The field of real option analysis has gone through a massive transition from a topic of modest academic interest in 1980s and 90s to considerable, active academic and industry attention (Borison 2005). The application of real options in architecture and design of building systems is not numerous (Greden and Glicksman 2005; Greden et al. 2006). No standard has yet been developed for design decision-makers in buildings or building systems to apply real option approach in their investment valuation process. Thus, an appropriate combination of real option methods, which are rooted in independent disciplines of management science/decision analysis and finance (Borison 2005), should be utilized to assess flexibility in green-convertible buildings.

Proposed Research Approach
A comprehensive life cycle cost and benefit analysis under uncertainty will be conducted to evaluate the economic performance of various building systems, which were identified as candidates to incorporate flexibility. The research methodology is the real option approach, which is a state-of-the-art analysis technique for evaluating flexible alternatives under evolving environmental uncertainty and future management options. The research processes are:

1) Investigate the broad market of innovative renewable building energy technologies to characterize uncertainty associated with future technology forecasting and define several future scenarios along with their likelihood.

2) Study the broad government sustainability initiatives related to energy-efficiency in the built environment, such as the energy-neutral Federal Buildings 2030 (GSA Commissioner Winstead testimony on the greening of federal buildings (April 17, 2008), available from http://www.gsa.gov/Portal/gsa/ep/contentView.do?contentType=GSA_BASIC&contentId=2
4402\textsuperscript{noc=T}) to determine the critical milestones for building transformation, along with the specified building life cycle.

3) Characterize the evolving uncertainty of energy price in the utility market with an appropriate stochastic model.

4) Determine the initial design, construction, and operation (if any) costs of a flexible building system.

5) Estimate the cost of changing a flexible building system (i.e., exercise cost) at the optimal building conversion time.

6) Estimate the benefit of a flexible building system in terms of its cost-savings for when it becomes optimal to transform into a low-energy green building.

7) Use Monte Carlo simulation to generate (a) several future paths for energy price in the utility market; and (b) several scenarios for future renewable energy technologies.

8) For each scenario, determine when it is optimal (if at all) to exercise the flexibility option and transform into a low-energy green building.

9) For each scenario, conduct life cycle cost/benefit analyses for the flexible building system.

10) Use the real option approach to determine the option premium of a flexible building system.

11) Measure the environmental performance of a building using the life cycle energy consumption calculation, based on whole building simulation, incorporating uncertainties in building parameters and usage scenarios overtime and under changing climate conditions. The end result is translated into CO2 emission data over the life span of the building, leading to an impact score in the GHG impact category.

12) Prioritize flexible building systems in terms of their expected overall economic and environmental benefits; consideration of environmental benefits, i.e. reduction of environmental impacts, is in the scope of this proposal limited to the calculation of depletion of fossil fuel and additions to greenhouse gas emissions.

13) Recommend an ordered list of flexible building systems (if any) which together form a green-convertible building that is more valuable than a conventional building in terms of meeting mid- to long-term building energy-efficiency.

The economic and environmental evaluation of a green-convertible building is critical since it attempts to make a business case for upfront investments in flexible building systems, which make transforming to low-energy green buildings less expensive and more convenient. Economic assessment will also be conducted on a regular building – which is designed based upon the idea of “wait and see” when it comes to cope with future possible interventions for energy-efficiency requirements in buildings; the results will be compared to the green-convertible building.

CONCLUSION

First and foremost, this research is promising for its potential contributions to extensively identify, model, and analyze flexibility in sustainable building design. Development of a flexibility identification framework will provide a novel approach for building designers and retrofitters to enhance the future utilization of renewable energy technologies, such as PV Systems, and facilitate the conversion of existing buildings to energy-efficient buildings. The new design is an innovative green-convertible building with less environmental impacts in terms of energy consumption and CO2 emissions. Development of a novel financial evaluation framework based on real option theory will enlighten decision-makers about the
economic/environmental inefficiencies that a conventional design produces and provide a methodology to mitigate such inefficiencies.

The true benefits of this novel assessment approach come not only from our innovative analytical model or our sophisticated financial analysis method but also from real option thinking that helps building design professionals in identification and understanding the significance of strategic flexibility in design. Building designers can use the information resulting from our valuation approach to decide on which flexible design features are worth investments over the building life cycle, modify design alternatives, and develop more cost-effective strategies. This research impacts various stakeholders that are involved in building planning and design. Identifying and evaluating flexibilities on/in building projects are potential sources of the competitive advantage for American Architecture/Engineering/Construction + Facility Management (AEC+FM) firms in the global market. The new approach for building design LCCA will assist these businesses to develop more cost-efficient and effective design systems and development practices for projects around the world.

REFERENCES


