A FRAMEWORK FOR APPLICATION OF SYSTEM ENGINEERING PROCESS MODELS TO SUSTAINABLE DESIGN OF HIGH PERFORMANCE BUILDINGS

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ABSTRACT

Building owners, designers and constructors are seeing a rapid increase in the number of sustainably designed high performance buildings. These buildings provide numerous benefits to the owners and occupants to include improved indoor air quality, energy efficiency, and environmental site standards; and ultimately enhance productivity for the building occupants. As the demand increases for higher building energy efficiency and environmental standards, application of a set of process models will support consistency and optimization during the design process. Systems engineering process models have proven effective in taking an integrated and comprehensive view of a system while allowing for clear stakeholder engagement, requirements definition, life cycle analysis, technology insertion, validation and verification. This paper overlays systems engineering on the sustainable design process by providing a framework for application of the Waterfall, Vee, and Spiral process models to high performance buildings. Each process model is mapped to the sustainable design process and is evaluated for its applicability to projects and building types. Adaptations of the models are provided as Green Building Process Models.

KEYWORDS

Sustainable Design, High Performance Buildings, Systems Engineering, Process Models, Waterfall Model, Vee Model, Spiral Model, Integrated Design Process

INTRODUCTION

The increase in green buildings is moving sustainable design practice to the mainstream of the design industry. The number of buildings certified under the LEED green building rating system now exceeds 10,000 (USGBC 2011). Architect-Engineer design firms are rated in Green Design by Engineering News Record (ENR). Building owners such as the federal,

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state and local governments and industry are requiring green buildings. This swift growth in demand for high performance buildings has brought on a need for a consistent approach to the sustainable design process that is effective and replicable. Systems Engineering's inter-disciplinary approach dovetails with the multi-disciplinary skills needed for a full scale green building design. One attribute of systems engineering is the use of process models to support improvement and enhance process management (CURTIS 1992). Process models have been developed and put into operation within systems engineering, business management, and the software industry to ensure the key stakeholders are engaged and that the needed stages are implemented for proper requirements definition and ultimately verification and validation. Use of process models provides a comprehensive approach that accounts for the broad collaboration required for the complexities of green building design (Klotz 2007).

This paper overlays three systems engineering process models on sustainable design for high performance buildings and provides a framework for application. This is accomplished by mapping the integrated design process to the process models. The models analyzed for applicability are the Waterfall Model, Vee Model, and Spiral Model. The models are explained in depth with an analysis of the advantages and disadvantages. The approach for application of these models is to view the building as a system with subsystems, components and elements. Considering the building as the system optimizes the performance of the building as a whole and allows for an integrated set of subsystems. A Green Building Process Model is developed for each model.

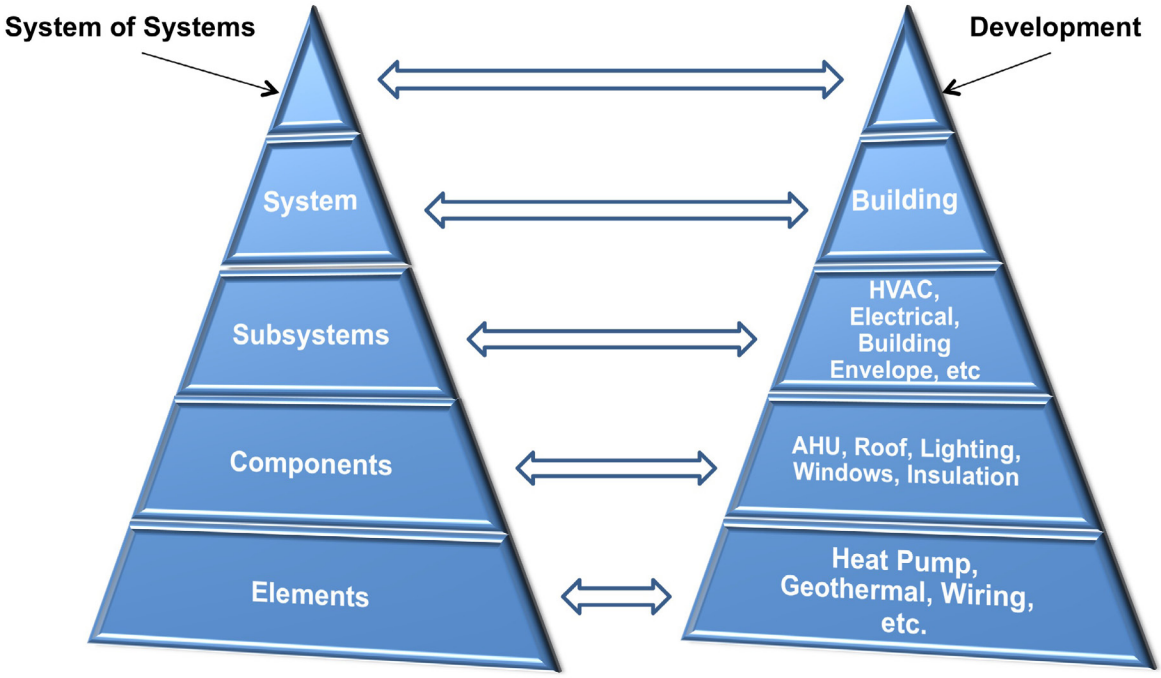
OVERVIEW OF SYSTEMS ENGINEERING AND PROCESS MODELS

Systems engineering is an inter-disciplinary approach to complex systems that ensures that the user's needs are satisfied through the entire life cycle of the project. It provides a structured approach that focuses on the need for upfront definition of requirements to enable the realization of successful systems (INCOSE 2011). A systems approach includes these key elements:

- "Focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.
- Integrates all the disciplines and specialty groups into a team effort forming a structured development process.
- Proceeds from concept to production to operation.
- Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs (INCOSE 2011)."

Traditionally, within the Architect Engineer Construction (AEC) industry, the system could be the HVAC, electrical, building envelope, site work, or several other portions which are aligned with the specialty trades. These can be viewed as subsystems with the building as the system. This optimized approach allows integration of all aspects of green design that lead to a high performance building. The view of a building as a system is shown in Figure 1. Recognition of this approach was made in 2003 when The Natural Edge Project was launched in Australia that developed a program of study for "Whole System Design: An Integrated Approach to Sustainable Engineering" (TNEP 2003-11).

FIGURE 1. The view of the building as the system.



Whereas this paper is focused on a building as a system there may be times when it is necessary to take a system of systems approach. A systems of systems label is used when five characteristics are met; Operational Independence of the Individual Systems, Managerial Independence of the Systems, Geographic Distribution, Emergent Behavior, and Evolutionary Development (Sage and Cuppan 2001). Examples of application of a system of systems approach in the built environment include a development, a complex (industrial, medical, university, commercial, military installation, etc) or a planned community.

Process models were developed and refined over time to allow for a consistent approach to systems engineering, business management, and software development. Process models differ from other modeling in that they typically involve the engagement and interaction by humans (CURTIS 1992). A process model provides the order for phases, steps and activities necessary to take a systems approach to a project. They are prescriptive in nature in that they provide a systematic approach with guidelines (Scacchi 2002). Within the model the actions and steps are sequenced. Model selection is a factor of the complexity of the effort and experience of the project team.

Use of a process model provides several advantages to a project team. Employing a model provides the team with a common template that sequences the steps needed to complete the project, thereby ensuring that needed actions are accomplished with an understanding of the succession. By using an accepted and proven process model, the team can replicate the process for multiple or sequential projects as well as having a common understanding of the actions to be completed. The use of a process model allows for the identification of non-value added steps and removal of waste from the process (Klotz 2007). This is central to learning

the process. Assigning time and resources to each item of the process model can be a basis for budgeting and resource allocation (Boehm 1986). The process models are not tied to a particular industry, process or application. Given that they are "context free" (Scacchi 2002) they can be adopted for sustainable design through mapping while accounting for the benefits of the Integrated Design Process. The mapping provides adaptation for the sustainable design activities to a process model. This paper also takes the process models and modifies them for use with green building design. The non-operational aspects of these process models allow for conceptual understanding and detailed process mapping without a requirement to alter the actions needed for a successful integration of sustainable design, while allowing the flexibility to tailor for specific types of high performance buildings. An empirical study by the University of Adger in Norway confirmed positive correlation exists between modeling processes and project outcome (Eikebrokk 2008). Benefits of using a process model are shown in Table 1.

TABLE 1. Process Model Benefits.

Process Model Benefits
• Allow for new technology insertion
• Consistent approach
• Identify cost drivers
• Measurable
• Understandable
• Adaptable
• Baseline for improvement
• Distance collaboration
• Subcontractor coordination and alignment
• Transparency
• Improve understanding of the process
• Add new steps
• Visualization
• Decomposable
• Extendable
• Collaboration identification, coordination and communication

This paper reviews three process models at the meta-model stage. Using the meta model level allows tailoring for specific projects and needs while allowing a consistent, effective and repeatable approach. The three process models that are analyzed and applied to sustainable design are the Waterfall Model, Vee Model and Spiral Model (Boehm 1986; Royce 1987; Forsberg and Mooz 1992). These three were selected as they are considered "well known process models" for systems engineering (Blanchard 2006). Guidelines are established for model use thereby providing a process model approach that can be implemented by an organization at different sites and by individuals of varying skill levels. The common ontology and taxonomy allows for a consistent application across the Architect Engineer Construction (AEC) industry. This shared and common approach provides a baseline for refinements, enhancements and technology leaps.

METHODOLOGY

The methodology for this research was mixed-method with primarily a qualitative emphasis and included an intense literature review, semi-structured discussions with domain experts, narrowing of the applicable Systems Engineering Process Models, review and analysis of systems engineering process models and the Integrated Design Process, mapping of integrated design to the Waterfall, Vee and Spiral models), a synthesis of the key factors that lead to selection of the most appropriate Systems Engineering Process Model, and development of a framework. The research was converged through the mapping of the systems engineering process models to the integrated design process as applied to sustainable design. The mapping was accomplished using published information on the Integrated Design Process with accepted process models for the Waterfall, Vee, and Spiral. The research was centered on providing a framework with a mapped process that sustainable design practitioners could employ in a value added manner on a consistent and repeatable basis for high performance buildings.

Domain Expert Discussions

Discussion questions and requests for feedback were posed in a semi-structured manner to a select cross section of domain experts, from the Architect Engineer Construction Industry, who are engaged with sustainable design for the built environment. The cross section included representatives from government, academia, and industry. These discussions were held to get a perspective from domain experts on their knowledge of systems engineering process models and their use of them for sustainable design of high performance buildings. The majority of these domain experts are directly engaged with green buildings as owners, designers, constructors, and maintainers.

The vast majority of the domain experts work with green building design with 94% of the respondents directly involved in sustainable design. Of those engaged in sustainable design, 50% are involved with greater than 5 projects per year and 13% are involved with greater than 100 projects per year. A significant majority (87%) stated that they use the LEED green building rating system for sustainable design and the remainder indicated that they do not use a sustainable design rating system.

When asked if they find the current rating system fragmented or restrictive, 85% replied in the affirmative. They found the continuous rating criteria changes difficult to keep up. Use of process model will support this concern as it provides a common structure that can be applied independently as a framework to accommodate changes to a sustainable design rating system.

For sustainable design of high performance buildings, the respondents indicated that they used the Integrated Design Process, the LEED rating process and in some cases a process that is customized to meet the clients expected involvement and technical understanding. Only 29% indicated that they are familiar with Systems Engineering Process Models. Of those, none were familiar with all three models considered in this paper—the Waterfall Model, Vee Model and Spiral Model. One of the respondents indicated that they use a modified Waterfall model for sustainable design. The familiarity and increasing use of the Integrated Design Process within industry provides a rational baseline for mapping to process models.

The discussions with domain experts for sustainable design confirmed that a repeatable, consistent and effective process model could add positive value. Whereas, many of the domain experts regard that each sustainable design project stands on its own and requires a customized approach; the use of process models allow for a tailored customized approach and can be valuable for discrete project efforts.

Waterfall Model

The Waterfall Model is a phased linear and sequential development method with extensive documentation at each phase. The project is divided into phases and as each is completed the project proceeds directly to the next phase in a systematic fashion. Using feedback loops accounts for the likelihood of overlap during a project. Figure 2 shows a widespread approach to the Waterfall Model that includes feedback loops.

This phased approach model began with use in industry and was later adapted for software development. A sequential phasing is a natural approach and is therefore commonly used on many projects. Project managers continue to a subsequent phase upon completion of existing phases. Phases of the Waterfall model include: feasibility, analysis, design, implement, test and maintain. The Waterfall Model was first described in detail by Royce in his paper "Managing the Development of Large Software Systems (Royce 1987). Though, Royce did not use the term Waterfall. An early concern with the Waterfall model was the lack of feedback loops;

FIGURE 2. Waterfall Model.

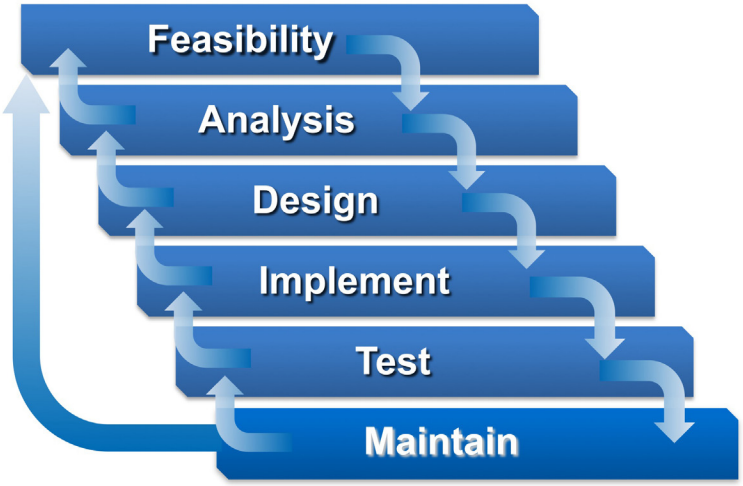


TABLE 2. Waterfall Model Advantages and Disadvantages.

Advantages	Disadvantages
• Disciplined approach • Sequential phases can prevent wasted time • Focus on documentation at each phase • Source for reference certification • Simplicity • Natural approach • Project familiarity by new team members • Phases function as milestones • Early problem detection/resolution • Ease of understanding/implementation • Ease of project management • Early requirements identification	• Assumes static requirements • Large phases • Changing requirements/difficult to go back and change • Difficult to time and cost • Does not always reflect reality • Less collaboration emphasis • Limited backtracking • Limited client engagement • Rigidity • Ripple effect of small changes/errors

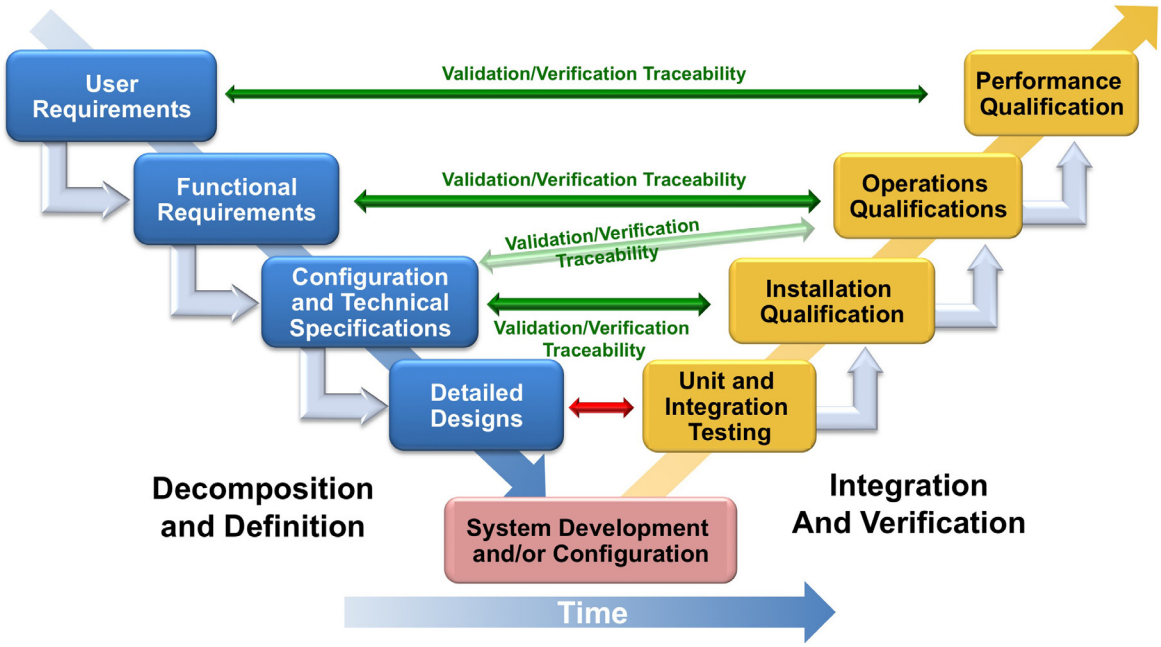
however that has been alleviated with future versions that modified the Waterfall model to include feedback loops. The simplicity of the Waterfall Model has led to unwarranted criticism as the model has applicability for non-complex endeavors and can bring to those efforts the requisite consistency, repeatability, structure and effectiveness. Royce has five steps that are needed for waterfall effectiveness. They are; Program Design Comes First, Document the Process, Do it Twice, Plan Control and Monitor Testing, and Involve the Customer (Royce 1987). Advantages and Disadvantages of the Waterfall model are in Table 2.

Vee Model

The Vee model (at times referred to as the V Model) is a graphical representation of the project life cycle phases and the associated testing stage as in Figure 3.

The name is derived from the letter "V" shape of the model. This model is also called a Verification and Validation model. The Vee model represents the systems development life cycle and begins in the upper left and proceeds down with Decomposition and Definition, it then goes up the right side of the V with Integration and Verification. The Vee Model was presented in the United States by Forsberg and Mooz at the National Council on Systems Engineering and American Society for Engineering Management conference in 1991 (Forsberg and

FIGURE 3. Vee Model.



Mooz 1992). It was developed at the same time in Germany for use by the Federal Ministry of Defence (Klaus 1996). Forsberg contended that many models at the time had a common deficiency in that work downstream could not begin until upstream review and control gates were satisfied (Forsberg). He asserts that the Vee model allows detailed work to begin early in the project cycle (Forsberg and Mooz 1992). The Vee model has applicability to complex projects that may require technology insertion, concurrent engineering, and incremental development. The steps flowing down the Vee are User Requirements, Functional requirements, Configuration and Technical Specification, and Detailed Design. The bottom of the Vee is System Development and / or Configuration. Flowing up the right side of the Vee are Unit and Integration Testing, Installation Qualification, Operations Qualification, and Performance Qualification. Verification is applied to ensure that the developed product meets the design and specification requirements. Additionally, the product development undergoes a validation traceability to ensure that it meets the users' requirements.

Advantages and Disadvantages of the Vee model are in Table 3.

TABLE 3. Vee Model Advantages and Disadvantages.

Advantages	Disadvantages
• Deliverables for each phase • User engagement and participation • Simplicity and straightforwardness, easy to use • Early on testing, verification and validation • Allows for tailoring • Quality assurance and testing throughout project lifecycle • Includes top down and bottom up approach • Design is mapped to development • Maintained by a change control board • User engagement and participation	• Project versus organization focus • Can be labor resource intensive • Can be viewed as rigid / inflexible • No early prototypes • O&M not directly addressed plus disposal • Customer see design late in the process • No early prototypes • Only survive the life of a project, not institutionalized

Spiral Model

The Spiral Model is a cyclical approach that has built in risk management as in Figure 4.

It combines design and iterative development through prototyping. The Spiral Model was developed by Barry Boehm in his 1986 article, "A Spiral Model of Software Development and Enhancement." Each cycle begins with design requirements and ends with the user. The Spiral Model starts at the center and develops clockwise. Each cycle has the following actions: identify design and development objectives, evaluate alternatives, develop strategies to mitigate or eliminate risk and planning for the next cycle. Each cycle results in a deliverable. These deliverables are referred to as prototypes within the Spiral Model. Boehm designed the Spiral Model in that the, "radial dimension . . . represents the cumulative cost incurred in accomplishing the steps to date; the angular dimension represents the progress made in completing each cycle of the spiral"(Boehm 1986). In essence, each spiral is a Waterfall model. The Spiral Model is best applied in complicated, high risk and large projects or programs with multiple products. The early focus on reuse of existing designs ties directly to site adapt high performance building projects. Advantages and disadvantages of the Spiral Model are shown in Table 4.

FIGURE 4. Spiral Model (Boehm 1986).

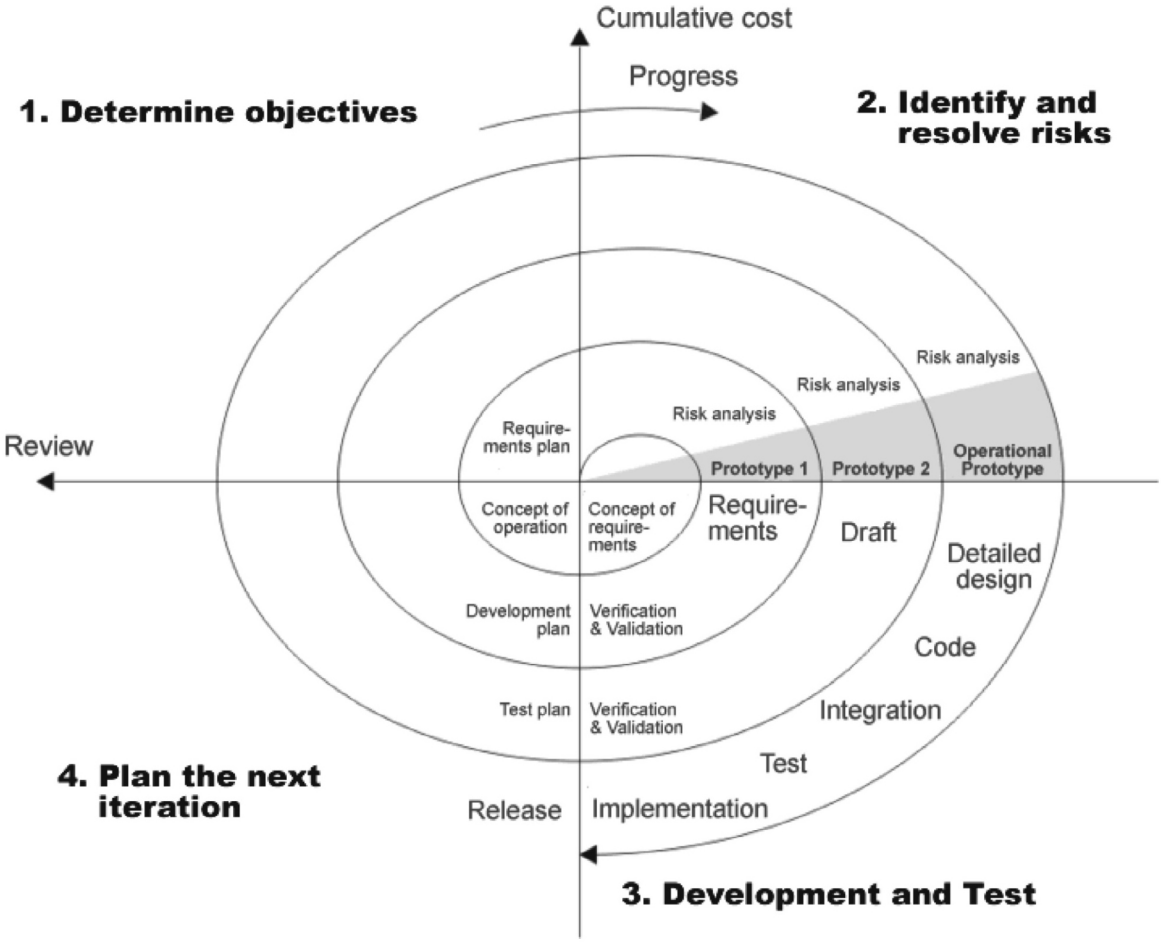


TABLE 4. Spiral Model Advantages and Disadvantages.

Advantages	Disadvantages
• Incorporates prototyping • Accommodates rework or go-back (Boehm, 1988) • Focuses early attention on reuse of existing designs • Early focus on eliminating errors and unattractive alternatives • Accommodates design / requirements changes and technology insertion • Multiple deliveries / evolutionary development • Mitigates / reduces risk • Design flexibility • Users' knowledge grows as project develops • Early risk detection • User approval prior to next cycle (validation)	• Can be difficult to cost out and schedule • Risk of not meeting budget / schedule • Highly customized difficult to reuse • Lack of milestones • Not good for small projects • Models requires certain level of expertise • Challenging for new team members • Lack of risk management expertise • Deliverables are not necessarily well defined • Spiral could continue indefinitely • Each spiral is a waterfall model

Additional Process Models

While the research presented in this paper is concentrated on the application of the Waterfall, V and Spiral models to sustainable design, there are other process models that may well be of interest. They are described briefly in Table 5 with references to allow for further study. A limited review indicates that these process models could be applied in as a sub model or in conjunction with the models presented in this paper. Though, the models in Table 5 would have restricted applicability as a standalone process model for design and construction.

TABLE 5. Additional Process Models.

Process Model	Description	Reference
Agile Model	Early and continuous delivery	(AgileAlliance 2012)
Incremental Model	Application of the waterfall model in an iterative manner	(Larman and Basili 2003)
Evolutionary Model	Early delivery of high value products	(Johansen 2005)
Prototyping Model	Early simplified version of proposed system	(Government 1998)
Rapid Application Development	Early reduced functionality system	(Scacchi 2002)

INTEGRATED DESIGN PROCESS AND GREEN BUILDING

The conventional design process is not optimal for sustainable design as these projects are more challenging necessitated by a need for inter-disciplinary collaboration and intense performance requirements (Klotz 2007) .The conventional (or traditional) design process for buildings begins with the client and architect determining the buildings core features, architecture and layout. Then the various disciplines are engaged to provide their division of the design (mechanical, civil, electrical, fire protection, etc). This work is either performed in parallel or isolation and in some cases both. While it would be an oversimplification to state that conventional design does not integrate the design features of the various disciplines, it is fair to say that they are coordinated by the project management and not by a structured process.

The Integrated Design Process (IDP) improves on conventional design by providing a collaborative effort that is multi-disciplinary and includes client and stakeholder engagement throughout the process. These stakeholders with the addition of the constructors and maintainers are continuously engaged in the process and take an active role. Natural Resources Canada initiated the C-2000 Program effort in 1993 to demonstrate energy and environmental performance in Advanced Commercial Buildings (CANMET 1993). The C-2000 Program initiative led to what is now referred to as the Integrated Design Process and served as the baseline model for the IDP efforts by the International Energy Association. (Larsson 2000). The International Energy Association emphasized in their Integrated Design procedure (with a Design Process Development Model) a whole building system optimization and delivery of high level subsystem performance (IEA 2003). "The best buildings result from active, consistent, organized collaboration among all players," (WBDG 2011). IDP accounts for the building as a system across the entire building lifecycle (IEA 2003). Sanvido modeled the Integrated Design Process to better integrate the activities needed for building design and to minimize liability by the design firm (Sanvido and Norton 1994). This included five primary sub functions, each of which has inputs and outputs. They are Acquire Design Project/Work, Plan and Control Design, Acquire Resources and Services, Perform Design, and Communicate Design to Others. Benefits of his model include allowing the designer to see current and futures steps as well a providing a tool that can be used to define project expectations (Sanvido and Norton 1994). His model is not directly included in this research, though it could without difficulty be a sub-model within the design events. IDP is a collaborative team process that actively and continuously engages the key stakeholders to ensure a transparent process that result in a building design solution that optimizes the needs of the owner and occupants and the performance of the building. Keeler and Burke in their book, *Fundamentals of Integrated Design for Sustainable Building,* equate integrated design with sustainable (green) design (Keeler 2009). The DOE's Greening Federal Facilities guide states, "Integrated design is the key to the most cost-effective green procurement strategy," (Energy 2001). The USGBC has recognized the Integrated Design Process in Pilot Credit number 42 Integrated Process, which states, "Develop an early understanding of the relationships between technical systems, natural systems and occupants within a building project, its site, its context, and its intended use. Engage all key project team members for the purpose of making cost- and environmentally-effective integrated decisions throughout the design and construction process." (USGBC 2011). The framework put forth in this paper for applying systems engineering process models to sustainable design presents a tool for implementing this pilot credit. Given the relevance of the integrated design process to sustainable design this paper maps integrated design to each of the three aforementioned systems engineering process models.

Ultimately a sustainable design, within the context of this paper, results in the construction and delivery of a High Performance building. Within the Architect Engineer Construction (AEC) industry the three prevalent means of building delivery are Design-Bid-Build, Design Build, and CM (Construction Management) At-Risk. In Design-Bid-Build the design contract is separate from the construction or build contract. They are separated by an acquisition or bid process that is based on the design performed by the Architect Engineer. Design-Bid-Build is the conventional method of building delivery. Over the past 10 years Design-Build has seen significant growth in the industry (Cox, Molenaar et al. 2002). In Design-Build the

design and construction are combined into one contract. CM At-Risk is an alternative building delivery method wherein the design and construction are contracted separately with the construction manager providing a guaranteed maximum price and functioning as the general contractor during the construction phase. The Integrated Design Process is independent of the project delivery method and as such can be employed with these three building delivery methods. Furthermore, use of process models is autonomous of the project delivery method and can be applied with these building delivery techniques, though to gain full benefit the owner can prescribe the use thereby ensuring that the full building lifecycle is addressed.

Mapping of IDP to SEPM

The actions needed for integrated design vary with source document and there does not appear to be an industry accepted standard, though most source documents on integrated designs have a similar suite of actions. Korkmaz's research of models of the design process found that no universally accepted model had emerged which in turn can lead to sub-optimization and waste leading to higher costs and lower performing buildings (Korkmaz, Messner et al. 2010). This paper takes design events from multiple sources (Keeler, Sanvido, 7group and Whole Building Design Guide) and complements these with activities needed for sustainable design (Keeler 2009), (Sanvido and Norton 1994), (7group and Reed 2009), (WBDG 2011) . Additional clarity is brought to the process models by emphasizing the systems engineering focus on requirements identification and gathering.

The sustainable design and green building events outlined in this paper and mapped to the systems engineering process models are: Requirements Gathering, Sustainable Strategy, First Charette, Performance Criteria, Systems Integration, Conceptual Design, LEED Criteria, Second Charette, Schematic Design, Design Development, Energy Modeling, Construction Documents, Construction, Commissioning, Acceptance, Data Collection, Real Time Commissioning and Occupant Survey. Though not mapped to the process models, End of Life, is included in the below event list as it is a significant part of the full building life cycle.

A concise description of each event, incorporating some of the foremost artifacts, used for the mapping follows:

Requirements Gathering. Involves determining the requirements for the facility from a mission, code, features, flow, layout and architectural perspective. The determination and agreement of the requirements for the building sets the stage for all further work. These requirements become the design challenge and can be divided into those items the user must have and those the user would like to have.

Sustainable Strategy. Early on the project team, to include the key stakeholders, must collaborate and determine the sustainable objectives for the building. Elements considered at this stage include energy (electricity and water) efficiency, material selection, indoor air quality, waste minimization, historic aspects, green house gas emissions and life cycle analysis. These will impact siting and drive the rating certification level to be achieved.

First Charette. This is a collaborative effort in a workshop setting to establish the vision for the project. It ties the requirements and sustainable strategy into a direction for the facility. The public can be included as charette participants, as appropriate.

Performance Criteria. This is derived from the requirements. It is focused on energy usage for the building and the integration of renewable energy sources. There are several other aspects of the design for which performance criteria might need to be established to include, indoor air quality, structural, material usage, medical applications, manufacturing applications, etc. Performance criteria are established to meet the targeted level of green building certification.

Systems Integration. Bringing together all of the subsystems, components and elements for the building in a way that they function together and optimize the performance of the building as a system.

Conceptual Design. "In the Conceptual Design phase, the project team is starting to design the building with real requirements and consideration of details. Steps include building design modeling, architecture planning, identifying potential barriers, evaluating detailed cost and performance goals, and collecting a list of building materials necessary to meet the project goals.", ((DOE) 2011). In this phase alternatives can be provided to the owner.

LEED Criteria. Leadership in Energy and Environmental Design (LEED) is the prevailing green building certification standard within the United States. In some cases the LEED certification level is established by mandate, such as the Navy requires LEED Gold certification and the City of Seattle requires a standard of LEED Silver. Substitution of other green building certifications (such as Green Globes and BREEAM) can be used within this step and applied with the process models.

Second Charette. A second workshop is held that gathers the key stakeholders. This ensures that as performance criteria are established, systems integration is underway, the conceptual design is underway the key stakeholders are engaged in a collaborative manner to review the progress and desired outcome. Both validation and verification occur in this second charette. An operational definition for validation and verification is that verification is meeting the specification, "building it right" and validation is meeting the user requirements, "building the right thing."

Schematic Design. During this phase the conceptual design is translated into graphical and written solutions that can be modeled and costed as necessary. The schematic design has limited detail, yet must provide enough information for analysis of alternatives, user concurrence and regulatory approvals as required.

Energy Modeling. Computer based programs are used to analyze the energy performance of the building and its components. For the greatest impact energy modeling should begin early in the design process where it can influence the design and then be advanced as the design matures.

Design Development. The detailed design drawings, specifications and documents are prepared to include all disciplines (civil, mechanical, electrical, structural, fire protection, etc.).

Construction Documents. This includes the drawings, specifications and documents with the addition of the contract administration procedure, contract terms and bidding papers. This is the set of information is used for bidding and proposal purposes.

Construction. The building to include site work and utilities is erected and assembled.

Commissioning. Building commissioning is a process to verify that the subsystems operate and perform according to the design and specification. Additionally it validates the performance of the building to meet the user / owners requirements.

Acceptance. This is the final stage wherein the project team has completed the high performance building to include documentation, testing, verification and validation and provides the facility to the user / owner for occupancy.

Data Collection. The ongoing collection, measurement and reporting of information is required to ensure that the building continues to provide high performance and energy efficiency.

Real Time Commissioning. This is an ongoing methodology for analyzing a building and its subsystems performance to ensure peak performance by evaluating the subsystems and correcting any inefficiencies.

Occupant Survey. A post occupancy survey of the building occupants is done to assess the usability, comfort and air quality of the building. The occupant survey can be conducted periodically to establish that the building is meeting the needs of the users.

End of Life. The total building lifecycle considers end of life decisions such as renovation, retrofit for reuse or demolition and disposal. A decision to consider retrofit or renovation begins the process anew and the selected process model is employed from the first phase (Salsbury 1999). This event is not mapped to the process models.

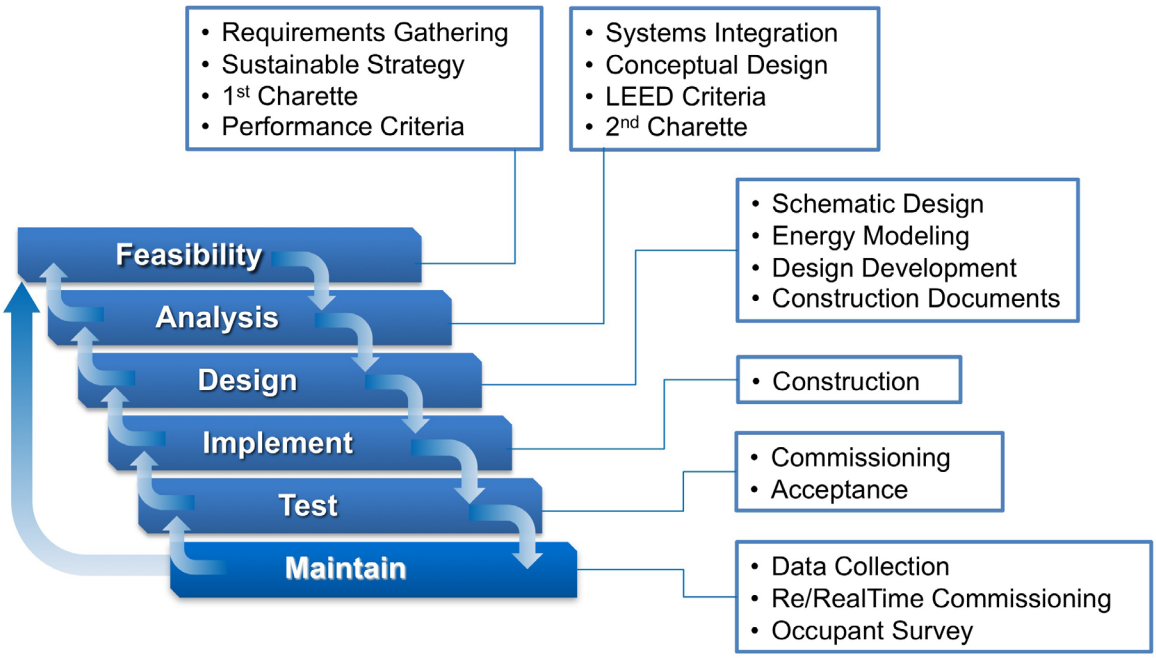
The first eighteen events defined above and listed in Table 6 are mapped to the Waterfall, Vee, and Spiral process models. End of life is not mapped to the process models, though its vital consideration as part of the overall building lifecycle. For consistency purposes the event sequencing is continued for each model in a similar fashion. This consistent event sequencing approach allows for ease of understanding and application of the systems engineering process models to sustainable design. The process models cover the whole systems development life cycle, which takes the design to a built facility and therefore includes the mapping for construction, acceptance and post occupancy events. Table 7 should not be read that the activities are all to be processed linearly without the ability to transcend activities or implement feedback loops. Feedback loops are inherent in process models to support verification and validation. Additionally, some activities, such as energy modeling, are started early in the process and continued throughout the design effort.

The Waterfall Model's straightforward phased linear approach is modeled with the sustainable design events connecting to each phase as it proceeds from feasibility through design to occupancy and then maintenance. Figure 5 shows the mapping of the sustainable design activities to the Waterfall model, the mapping shows the entire systems development lifecycle for a high performance building. The uncomplicated attributes of the Waterfall model bode well for use with non-complex facilities as well as for use by junior engineers and architects. Extensive documentation is completed with the end of each phase of the Waterfall model. The Feasibility phase includes the gathering and definition of requirements. All key stakeholders have an opportunity to participate collaboratively via the process and openly via the first Charette. After the requirements are set to include the sustainable strategy with performance criteria the

TABLE 6. Sustainable Design Green Building Events.

Sustainable Design High Performance Buildings	Waterfall Model	Vee Model	Spiral Model
Requirements gathering		User Requirements	
Sustainable Strategy	Feasibility		Concept of Requirements
First Charette			
Performance Criteria			
Systems Integration	Analysis	Functional Requirements	Concept of Operation
Conceptual Design			
LEED Criteria			
Second Charette		Configuration and Technical Specifications	Requirements Plan
Schematic Design			
Design Development	Design	Detailed Design	Detailed Design
Energy Modeling			
Construction Documents		System Development and/or Configuration	
Construction	Implement	Unit &Integration Testing	Code and Integration
Commissioning	Test	Installation Qualification	Test
Acceptance		Operations Qualification	Implementation
Data Collection	Maintain	Performance Qualification	Release
Real Time Commissioning			
Occupant Survey			

FIGURE 5. Mapping of Sustainable Design to the Waterfall Model.



next phase occurs for the integration of the systems with the green building criteria that lead to a conceptual design which is validated during the second Charette. During this phase the team looks at synergistic measures considered necessary for a high performance building—such as the natural day lighting, color palette and heating/cooling load. The waterfall design phase takes the conceptual design and proceeds on to detailed design development and construction documents. Verification with the specifications and validation with the user's requirements takes place at this phase and at each phase. The Implement phase equates to the construction of the high performance building. To ensure that the building meets sustainable criteria and meets energy efficiency requirements a formal commissioning of the facility takes place.

The Vee model's other name which is the Verification and Validation model is a natural fit for the complexities and collaboration required for challenging green design projects. Figure 6 shows the mapping of the Vee Model to sustainable design. The left side of the Vee is designed for decomposition and definition. Here the team establishes and refines their requirements and sustainable strategy. New technology insertion can take place anywhere on the left side of the Vee, though as one proceeds through the steps it becomes more resource intensive. The right side of the Vee is the integration and verification wherein the team builds, commissions and maintains the building. At each phase the Vee Model requires validation and verification traceability, which ensures that the design and construction proceed per the specifications and meet the user's requirements. At the first phase "user requirements" the project team gathers the building requirements, establish performance criteria and develop their sustainable strategy. Proceeding down the Vee the team next accomplishes their conceptual design to include the integration of the systems and establishes their plan for meeting the planned green building criteria. If LEED criteria are used the team goes over the sections of LEED and determines which credits they will try to attain and ultimately the level of certification desired for

the building. During the step for Configuration and Technical Specifications the team holds a second Charette and takes the conceptual design. This sets the stage for the final design and energy modeling. Though as noted with the Waterfall model, energy modeling can and should be accomplished throughout the design process. The base of the Vee is the aggregation of the design process combined with the construction documents to provide a detailed design that can be built to meet the sustainable strategy and performance criteria. Deliverables are produced at each phase. Once the construction documents are prepared the construction of the building is initiated, in the Vee this is the Unit and Integration phase. The bidirectional arrows across the Vee point to the need to perform verification and validation. This is to ensure the building under construction meets the specifications and user requirements. After construction the next three phases are for qualification, installation, operation and performance. These phases consist of accepting, commissioning, testing and maintaining the building and constitute full life cycle analysis for a high performance building. A commonly stated disadvantage of the Vee model that it does not directly address operations and maintenance is alleviated via this mapping by including data collection and real time commissioning in the performance qualification phase. The operations phase has a long duration and is costly compared with design and construction (Hodges 2005). A sustainable design that focuses on a suitable lifecycle and total cost of ownership analysis during the requirements generation and design will extend the service life of the building (Hodges 2005).

The Spiral Model appears more complicated than the Waterfall or the Vee and to some extent it can be characterized in that manner. Yet, using the spiral model with the mapping for sustainable design is a relatively straightforward process. Figure 7. Starting at the center of the model in the phase Concept of Requirements the team sets forth the fundamentals for the high performance building. These begin with requirements gathering and move forward with a sustainable strategy, performance criteria and a collaborative effort to ratify these in

FIGURE 6. Mapping of Sustainable Design to the Vee Model.

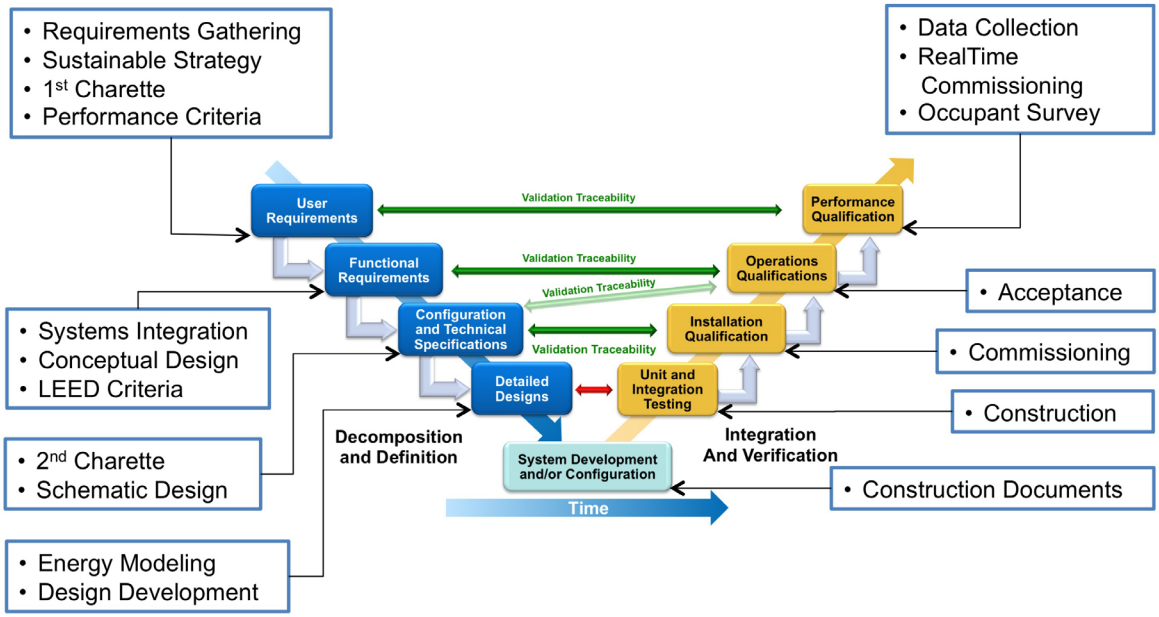
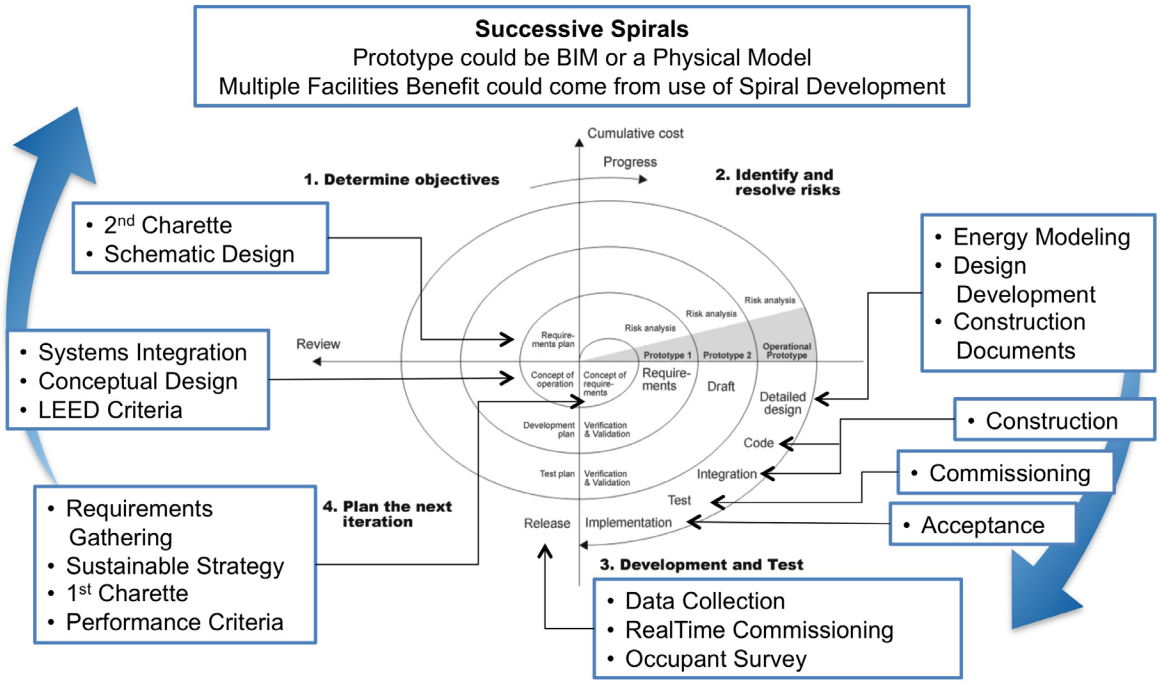


FIGURE 7. Mapping of Sustainable Design to the Spiral Model.



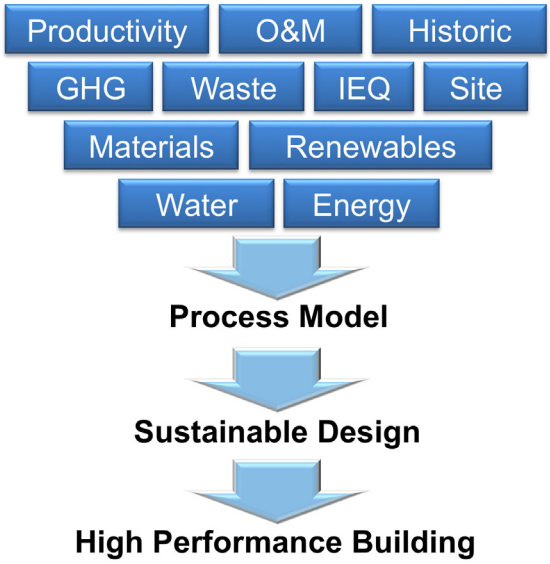
the first Charette. The process then flows clockwise around the spiral in a similar manner to the Waterfall and Vee model. The delivery of prototypes with each spiral for the buildings can take the form of a physical model, a BIM deliverable or even the first of successive buildings for a development of facilities. The spiral is able to be used for follow on projects that are similar to prior facilities. This allows the use of the model for site adapt building projects.

FRAMEWORK AND PRACTICAL APPLICATIONS

The complexity of sustainable design requires that the designer account for additional aspects beyond conventional design for buildings. Figure 8. These factors are reviewed from the onset with the gathering of the requirements and development of the sustainable strategy. They include: site selection, energy efficiency, water usage, gray water recovery, storm water runoff, indoor environmental quality, use of recycled and local materials, waste minimization, renewable power integration, historic aspects, green house gas emissions and life cycle analysis. These sustainability factors are balanced with requirements, team experience, project complexity and any constraints to determine the appropriate process model for use by the project team. The advantages and disadvantages of each process model are weighed and used for selection. Less complex projects with lower sustainable goals and a less experienced team might opt for the Waterfall model, as it is uncomplicated and straightforward. Whereas more complex projects with higher sustainable goals and a more experienced team could opt for use of the Vee or Spiral Model. The Vee and Spiral Model contain the steps necessary for complex systems. Multiple facilities or site adapt of existing facilities benefit from the spiral model wherein the team can consider the earlier buildings as prototypes and cycle the spiral accordingly. The models are presented for use by the entire project team, though with modifications they could be applied by a subset of the team for a particular aspect or subsystem of the green building.

The mapping of sustainable design events to systems engineering process models can be used by green building practitioners without revision as displayed in Figures 5, 6 and 7. Based on the discussions with domain experts there is limited familiarity within the AEC industry with systems engineering process models and therefore the terminology of the Waterfall, Vee and Spiral models could become an unnecessary obstacle to effective use for the design of high performance buildings. Therefore in this section the sustainable design activities are used as inputs to the activities of the three analyzed process models. An output is derived that is consistent with prevalent terminology within the AEC Industry. Examples of context diagrams used to determine outputs are shown in figures 9 and 10. These two figures are shown to illustrate that for some of the sustainable design events the activity varies but the output is the same for each Green Building Process Model, while for others the inputs lead to two different outputs.

FIGURE 8. Considerations for Framework Application.



Utilizing the mapping in Figures 5, 6 and 7 along with the context diagram approach the process models are redrawn as Green Building Process Models. Figures 11, 12 and 13 are the Green Building Process Models.

FIGURE 9. Context Diagram with Consistent Output.

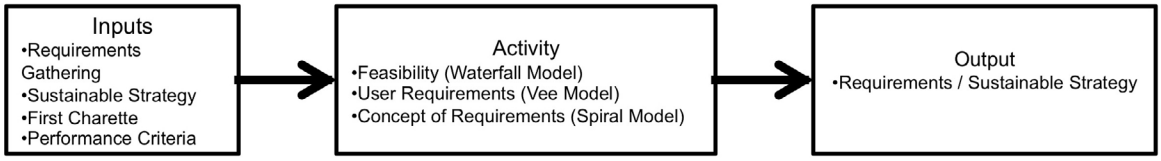


FIGURE 10. Context Diagram with Varied Output.

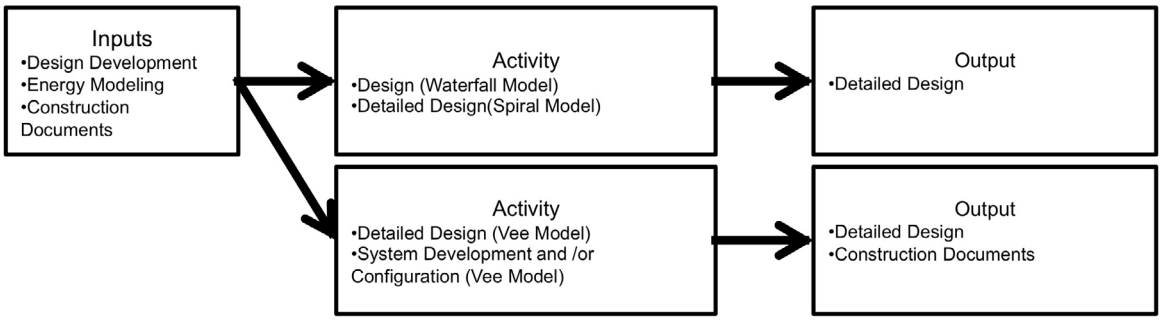


FIGURE 11. The Waterfall Green Building Process Model.

FIGURE 12. The Vee Green Building Process Model.

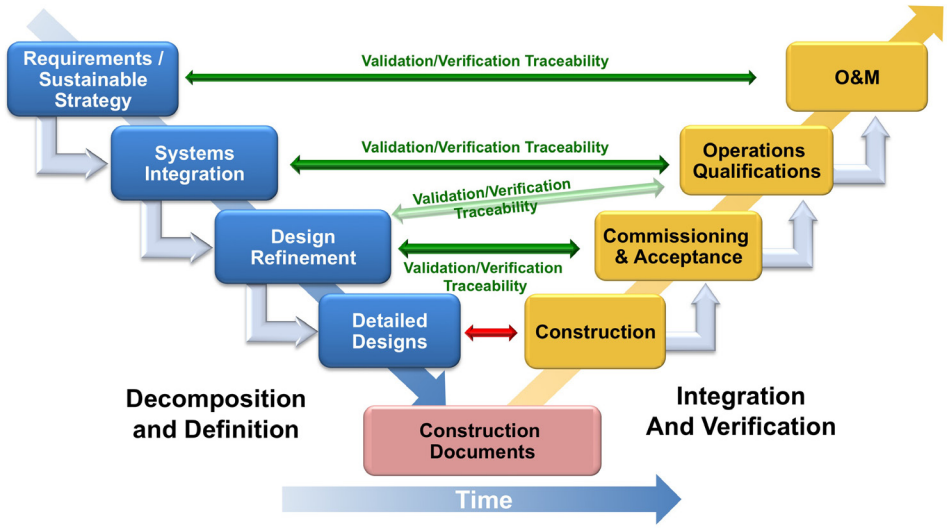


FIGURE 13. The Spiral Green Building Process Model.

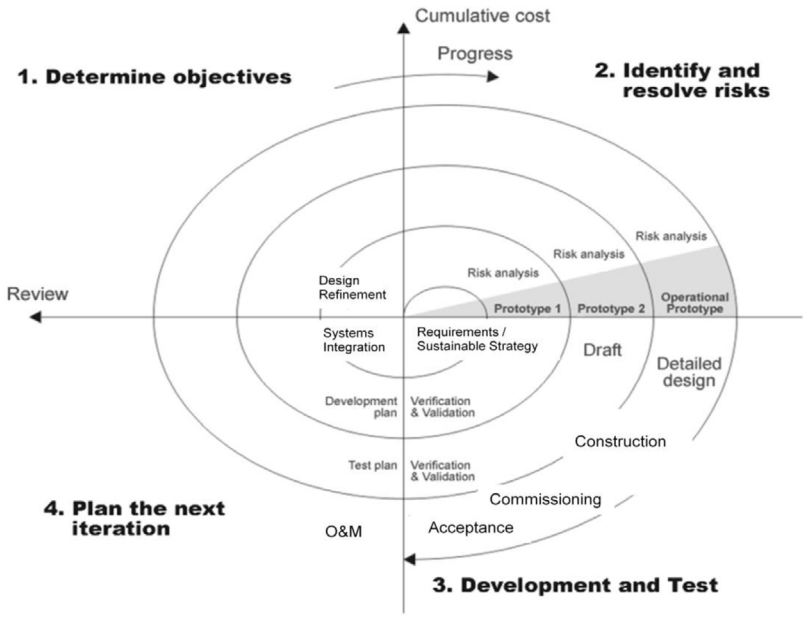
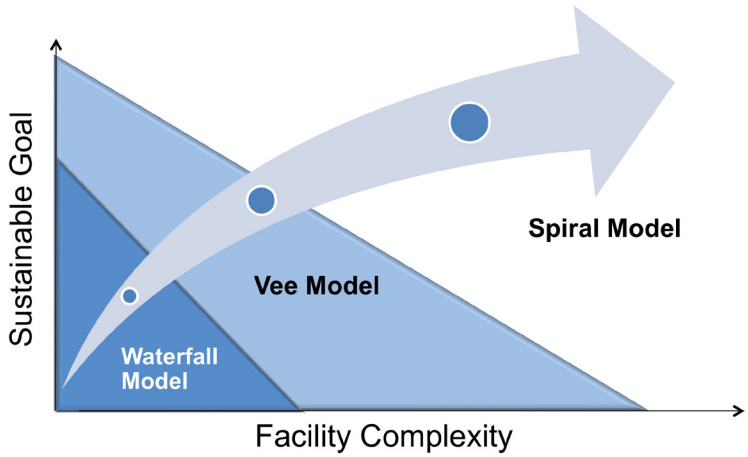


FIGURE 14. Framework Application.



The application of the systems engineering process models is structured to be independent of the sustainable design and construction approach. As such it can be applied to DB, DBB, CM At-Risk and other project delivery methodologies. The selection of the systems engineering process model to use for sustainable design is a factor of the desired sustainable goal and the complexity of the building. An increase in the sustainable goal drives the model selection proceeds from the Waterfall Model to the Vee Model to the Spiral Model. A similar approach is taken on the x axis as the complexity of the facility increases. See Figure 14.

CONCLUSIONS

Green buildings are rapidly becoming the mainstream standard for new facilities. Engineers and architects are increasingly called upon to bring the highest possible energy savings and sustainability to new buildings. The increased use and demand for sustainable design calls for a replicable method that can take advantage of demonstrated processes while accounting for changes in criteria and technology. Utilization of a proven systems engineering process model with mapping to the requirements of a high performance building provides practitioners with a method for ensuring a consistent approach that accounts for the many elements that must be incorporated to result in a green building. The mapped models provided in this research account for the complexities of high performance buildings and provide a framework for consistency, technology insertion and optimization of the building lifecycle. The framework provided can be used by practitioners of sustainable design for high performance buildings, as well as serving as a baseline for high performance building initiatives and research. The necessity for enhanced collaboration on green designs is accounted for in the process models and when employed will provide stakeholder engagement for a project that can be verified and validated as conforming to the specified sustainable strategy.

Whereas the process for integrated design is well documented there is less documentation on the sustainable design process and limited use of process models for the building design. The list of events associated with high performance buildings that are mapped to the models is comprehensive. The models present a methodology and process that can be used as part of the overall framework to enhance the design effort.

Green buildings provide benefits to the building occupants, are better for the environment and more energy efficient. Use of a process model allows for early requirements generation and

enhancing the effectiveness and efficiency of the sustainable design process. They have proven effective in taking an integrated and comprehensive view of a system while allowing for clear stakeholder engagement, requirements definition, life cycle cost analysis, technology insertion, validation and verification. The framework provided can be used in conjunction with Design Build, Design Bid Build CM At-Risk, and Integrated sustainable design. The model is developed to be agnostic to green building ratings systems and as such can be employed with any of the existing ratings systems as well as emerging rating ratings systems. These enhancements to the research on sustainable design process modeling would support the pathway to greener more efficient buildings.

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