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An Intelligent Virtual Design Studio (vds) For Integrative Design Of Green Buildings

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Abstract

The overall goal of the study was to develop a “Virtual Design Studio (VDS)”: a software platform for integrated, coordinated and optimized design of green building systems with low energy consumption, high indoor environmental quality (IEQ), and high level of sustainability. My dissertation research was focused on the development of a key VDS component -- an integrated design process and a near-real time performance simulation approach for fast feedbacks at the early stage of the integrated design process.

A design process module “Magic Cube” (MC) was developed for the VDS as the core for the design integration and coordination. It sets up the whole design framework in 3 dimensions: design stages (assess, define, design, apply, and monitor), design factors (site and climate, form and massing, external enclosure, internal configuration, environmental systems, energy systems, water systems, material use and embodied energy, and system interdependencies), and involved teams (architectural design, systems design, and project management). Within this 3D framework, “Task” is proposed as the unit to represent the whole design process with attributes of the design stage, actor, factor, and interdependencies (process and information flow interdependencies). Each individual task is represented in “Input-Process-Output” pattern, composing of: necessary input (quantitative, qualitative, reference, and user-defined information) to support its execution; clearly stated actions need to be performed in order to complete the task; output information will be generated, which be used by next linked tasks (interdependencies). To further facilitate the easy process navigation and management, tasks can also be decomposed and aggregated using the built-in parent and child relationships. Multiple types of views also have been incorporated for better design process visualizations.

Comparing with the traditional design process (often a linear process, teams are involved only when necessary, building systems are designed in isolation with limited optimization among others), the developed MC intended support seamless design transition among stages, enhance multi-disciplinary coordination of (architects, engineers, and project management) team members, and design factors integration through whole building performance analysis.

A Leadership in Energy & Environmental Design (LEED) platinum rated medium-size office building was used as a hypothetical case study to illustrate how the MC method could be applied to achieve a high-performance office building design. From early to the detailed design stage, the building design process and associated design parameters with heavy impacts on the building's performance were investigated, respectively. The design alternatives with optimal performance were recommended.

As the early stage design decisions have the most and fundamental impact on building performance, a simplified and scalable heat-flow based approach for the form, massing and orientation optimization was developed. A reference building model (RBM) was first defined with pre-selected building materials and heating, ventilation, and air conditioning (HVAC) systems for the intended climate and site conditions. The energy performance of this RBM was estimated by the whole building energy simulation using the detailed EnergyPlus model. Heat fluxes from the enclosure to the indoor air were extracted from the RBM simulation. A simplified physics-based correlation model was developed to predict how these fluxes would be affected by the shape of the building geometry, window-to-wall ratio (WWR), and orientation of a proposed building design. Based on building indoor air space heat balance, the predicted heat fluxes were then used to predict the energy consumption of the proposed building. Compared with conventional detailed energy simulation, this simplified scalable heat-flow prediction method was demonstrated to be 2,500+

times faster (depending on the complexity of the proposed design) with good accuracy. It hence enables effective design evaluations and fast iterations for the early stage HPB design optimization.

An Intelligent Virtual Design Studio (VDS) for Integrative Design of Green Buildings

by

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A very special thanks to my family. Your unconditional love and support were what sustained me thus far. I would thank my parents Guanghua Meng and Fengxian Ma, my wife Jing Wang, and two lovely boys Daniel (Xianze) and Nathan (Xianen). You are the love of my life. Having you by my side is the reason for my success and I love you so much.

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List of Acronyms

ANSI: American National Standards Institute

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

DOE: Department of energy

EPA: Environmental Protection Agency

GUI: Graphical user interface

HPB: High-performance building

HVAC: heating, ventilation, and air conditioning

IECC: International Energy Conservation Code

IEQ: Indoor environmental quality

LBNL: Lawrence Berkeley National Laboratory

LEED: Leadership in Energy & Environmental Design

NREL: National Renewable Energy Laboratory

PNNL: Pacific Northwest National Laboratory

RBM: Reference building model

SHGC: Solar Heat Gain Coefficient

WWR: Window-to-wall ratio

CHAPTER 1.INTRODUCTION

1.1. Background and problem definition

Buildings are responsible for approximately 39% of energy consumption (residential and commercial, Figure 1.1) in the United States (U.S. Energy Information Administration, 2020), 40% in the European Union (Friedrich, 2013), and 20% in China (Building Energy Research Center of Tsinghua University, 2018). In 2018, total U.S. energy consumption reached a record high of about 101 quadrillion British thermal units (Btu) (U.S. Energy Information Administration, 2020). The buildings sector[1] and people's activities in buildings are responsible for approximately one-third of global energy-related CO_2 emissions, approximately two-thirds of halocarbon, and approximately 25~33% of black carbon emission (USA and the International Institute for Applied Systems Analysis, 2012). Therefore, the high-performance building design, construction, operation, and retrofitting are the key to a sustainable future.

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[1] The GEA refers to energy use in the buildings sector as all direct energy use in buildings, including appliances and other plug loads, and accounting for all electricity consumption for which activities in buildings are responsible. Embodied energy use, emissions of the production of building materials, and their transport to the construction site, and other equipment are not included.

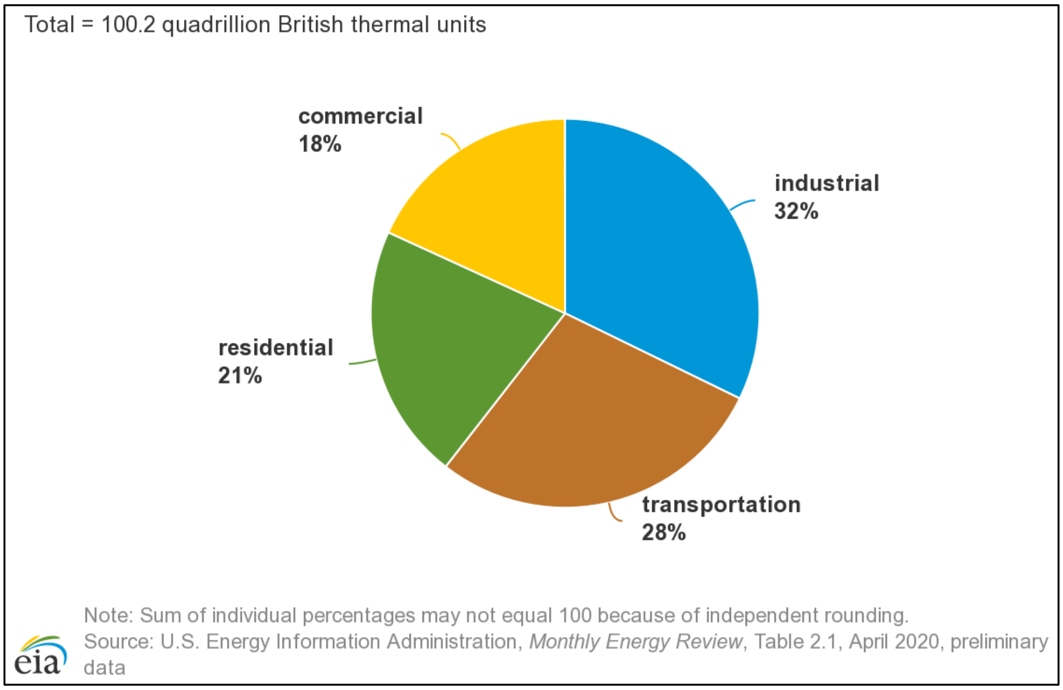


Figure 1.1 Share of total U.S. energy consumption by end-use sectors, 2019 (U.S. Energy Information Administration, 2020)

As the materials and technologies in modern buildings continue to evolve, buildings become more complex. Buildings consist of multiple interactive systems (which often have multiple sub-systems), for instance: enclosure (roof, wall, windows etc.), mechanical environmental control, and lighting systems. In addition, buildings need to meet stricter energy (Figure 1.2), IEQ, and other project requirements which often have competing goals. The predominant energy codes International Energy Conservation Code (IECC) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 90.1 standards increase the performance requirements with each new release. IECC 2030 and ASHRAE 90.1-2031 are anticipated to require net zero performance (Figure 1.3). High-performance building (HPB) design calls for integration, especially for early stage design which has fundamental impact on building performance.

	Title 24	CalGreen	Other State Energy Goals	ZNE Goals
2010	2008 Title 24 part 6 Standards in Effect (R/NR)			
2011		2010 CA Green Building Standards in Effect (R)		
2012	2013 Title 24 part 6 Standards Adopted (R/NR)			
2013		2013 CALGreen Adopted (R/NR)		
2014	2013 Title 24 part 6 in Effect (R)	2013 CALGreen in Effect (R)		
2015				
2016	2016 Title 24 part 6 Standards Adopted (R/NR)	2016 CALGreen Adopted (R/NR)		
2017	2016 Title 24 part 6 in Effect (R)	2016 CALGreen in Effect (R)	CA Solar Initiative 2,550 MW capacity by 2017 -- 1,940 from IOUs	
2018	2019 Title 24 part 6 Standards Adopted (R/NR)	2019 CALGreen Adopted (NR)		
2019				
2020	2019 Title 24 part 6 in Effect (R)		AB 32 - CO2 emissions reduced to 1990 levels; Renwable Portfolio Standard to 33%	All new residential construction is zero net energy by 2020
2021				
2022	2022 Title 24 part 6 Standards Adopted (NR)	CALGreen Adopted (NR) - ZNE for some new buildings		
2023				
2011				
2024				
2025	2025 Title 24 part 6 Standards Adopted (NR) - ZNE for some new buildings	2025 CALGreen Adopted (NR) - ZNE for all new buildings		
2026				
2027				
2028	2028 Title 24 part 6 Standards Adopted (NR) - ZNE for all new buildings			
2029				All new commercial construction is zero net energy by 2030
2030				

* R= Residential, NR= NonResidential

Figure 1.2 Building Energy Efficiency Standards Update Schedule (Sioshansi, 2013)

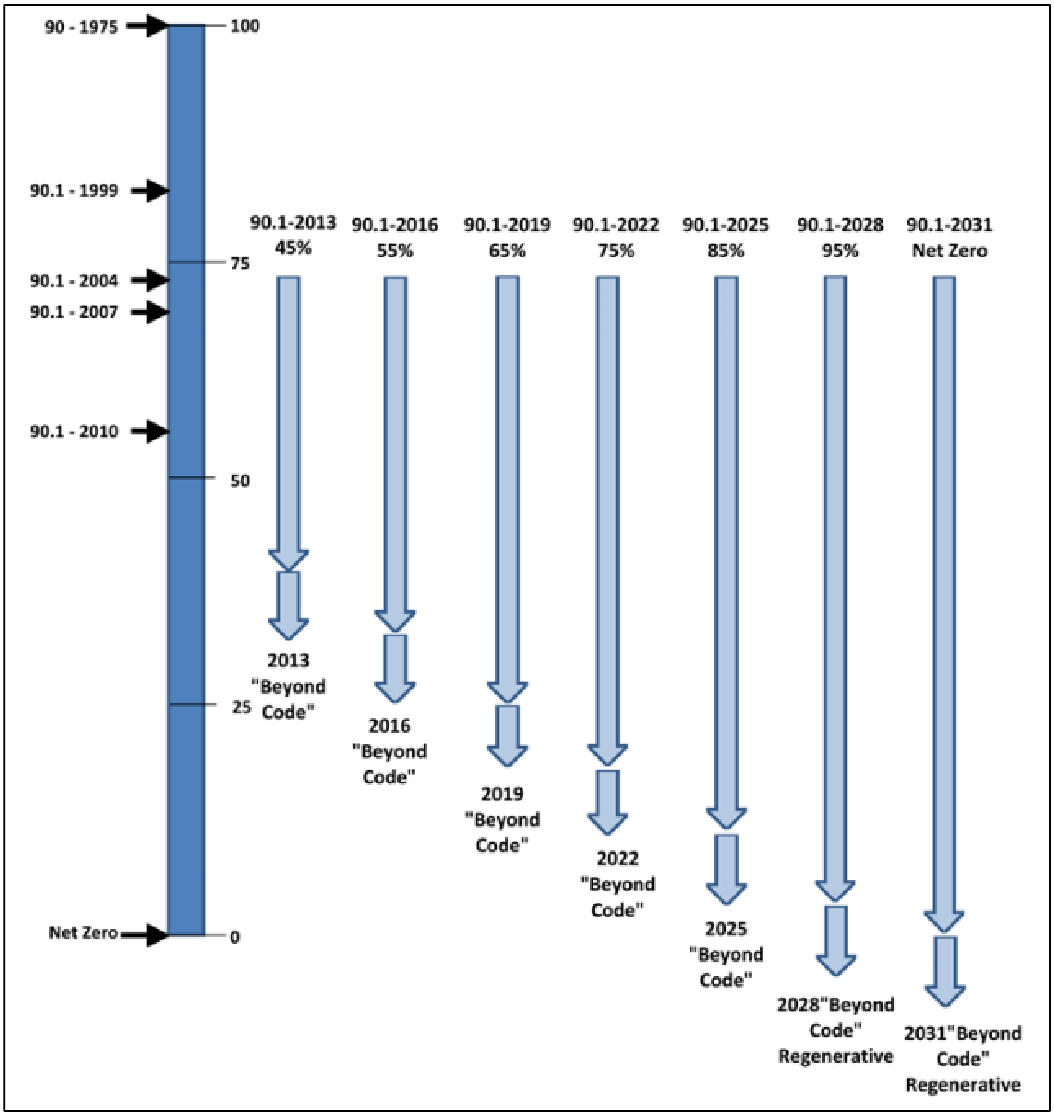


Figure 1.3 Example of a path forward for ASHRAE Standard 90.1 toward and even beyond net zero energy buildings (Pacific Northwest National Laboratory, 2015)

Building design is a multi-disciplinary process requiring coordination among all participating disciplines such as architectural, engineering and management team members. Teams from different areas have very specialized expertise and working fashions. “Hundreds of linear processes must be completed in concert so that foundations can be poured, walls can rise, interiors can be fitted out, and occupancy can occur” (7group & Reed, 2009). It is hence critical to be able to define the critical tasks and required information, effectively organize the workflow, and facilitate the integration among them.

Building simulation is a very powerful technologies which can assist the performance evaluations and system optimizations for HPB design. There are many existing simulation programs have been developed, such as: EnergyPlus**,** eQuest, DesignBuilder, OpenStudio, Ladybugs Tools. These simulation programs do not integrate with practice related design processes as part of their framework. Although they could achieve relative high accuracy, these sophisticated programs require detailed input parameters throughout the design processes. Although early design stages decisions have significant impact on building performance, the design information is very limited. These simulation tools are predominantly suitable for the detailed design stage in which various design parameters have been specified.

1.2. Objectives

The objective of this dissertation is to develop an intelligent design platform for integrative design of green buildings from conceptual to detailed design stages. It intended to overcome the disciplinary boundaries by using the same tool, more coherent and integrated design flow and associated information, and support the early stage performance evaluation and design decision making by the simplified performance evaluation model.

Specific objectives of the project include:

1) Develop an integrated and coordinated process for performance-based building design. It can provide seamless transition among design stages (from conceptual to detailed

design), enhance multi-disciplinary coordination, and assist design factors integration and optimization through whole building performance analysis.

2) Develop a simplified and scalable heat-flow based approach for form, massing and orientation which has heavy impact for HPBs in early design stage. The simplified and physics-based correlation model was based on building space heat balance. The predicted heat fluxes were then used to predict the energy consumption of the proposed building.

1.3. Scope

Through this study, a prototype of the VDS software has been developed. There are 4 modules (process, input, result, performance) that have been completed for the full building design circle. As VDS is a large project, the development work was divided into different modules. This study was focused on the following components:

1) A process module named “Magic Cube” (MC) for planning and defining the design tasks for various design stages and teams. It includes input (both quantitative and qualitative) and output variables for each task and the relationship among tasks. Task decomposition and aggregation methodologies were incorporated. Multiple levels of dependency inferred graphical design process presentations have been developed to facilitate the design process management and navigation. Design flow and information were streamlined through the MC module.
2) A holistic and representative office building design template that covers major design and analysis tasks have been developed. These tasks have heavy impact on building

performance. They include design factors like site and climate, form and massing, internal configurations, external enclosure, environmental systems, and their optimizations. A LEED Platinum rated medium-size office building was used as the case study to illustrate how the coordinated and integrated MC method could be applied to achieve a high-performance green office building design.

3) A simplified and physics-based correlation model was developed to support the early stage design performance evaluation and decision making.

1.4. Organization of the dissertation

Chapter 1 introduces the background and problem definition, research objectives, research scope, and the organization of the dissertation.

Chapter 2 provides the literature review, which consists of the following: (1) performance-based design methodologies; (2) building design process; (3) Building performance and evaluation systems; and (4) existing leading building design and simulation tools. Finally, the knowledge gap identified in this study is presented.

Chapter 3 first introduces the overall framework of VDS. Then it focusses on its core module named “Magic Cube” (MC) -- an integrated and coordinated process for performance-based building design. The software framework is introduced, including methodology, software architecture, data model, and viewer/GUI (graphical user interface). A LEED Platinum rated, the Syracuse Center of Excellence (CoE) Headquarters building is used for a hypothetical case study. The case study demonstrated how the developed MC could effectively guide all interdisciplinary teams navigate through the whole project, align their design intent therefore facilitate collaborations. Design factor integration analyses were performed by process coupled performance simulations for multiple systems design and optimization.

Chapter 4 shows the method and procedure for a simplified and scalable heat-flow based performance prediction approach for form, massing and orientation early stage design of HPBs. Reference building model (RBM) is first defined. The energy performance of this RBM is estimated by whole building energy simulation. Heat fluxes from the enclosure are extracted from RBM simulation for simplified and physics-based correlation model. Based on building space heat balance, the predicted heat fluxes were then used to predict the energy consumption of the proposed building. Finally, the simplified model is tested via a case study and its performance were discussed.

Chapter 5 summarizes the conclusions from this study and suggests areas for further research and development on the subject and platform development.

CHAPTER 2. LITERATURE REVIEW

2.1. Performance-based design methodologies

For high-performance building design, it is critical to understand which performance criteria can be achieved and to what degree, through what strategies and the implementation of available and appropriate (active, passive, and hybrid) building system components. A review of the state of art and established approaches have shown various ways of combining design and performance-based working methodologies.

The "Ecological Circle of Buildings" (Daniels, 2003) demonstrates the methodology to correlate design considerations with performance criteria and system interactions. The graphical principle of the "Ecological Circle of Buildings" depicts a way of systematically organizing and correlating the expected or demonstrated performance relationships between exterior space, building fabric, and technical installations.

The ongoing development of the "Ratcliff Green Matrix" (Ratcliff, 2007) elaborates on the relationships between areas of design consideration and standard US project stages. The "Green Matrix" shown in Figure 2.1 is designed to cross-reference topics of sustainability with standard phases of the project design, thereby illuminating appropriate strategies for a particular phase of work. Within the "Green Matrix" there is a horizontal heading for the five introduced sustainable topics: site, water, energy, materials, and indoor environment. Vertically listed are seven design phases: pro-forma, master planning, pre-design, schematic design, design development, construction documents, and construction/post occupancy. At the intersection of topics and phases are listed design strategies particular to that condition. The user "clicks" the intersection under consideration and is led to more specific information about the strategies and further resource links – some of which may reside on the website itself or may be linked to independent web sources. The "Green Matrix" therefore correlates four relevant areas: design stage, design consideration and suggested procedures, as well as internal and external references. However, there are not quantitative simulation capacities for the "Green Matrix".

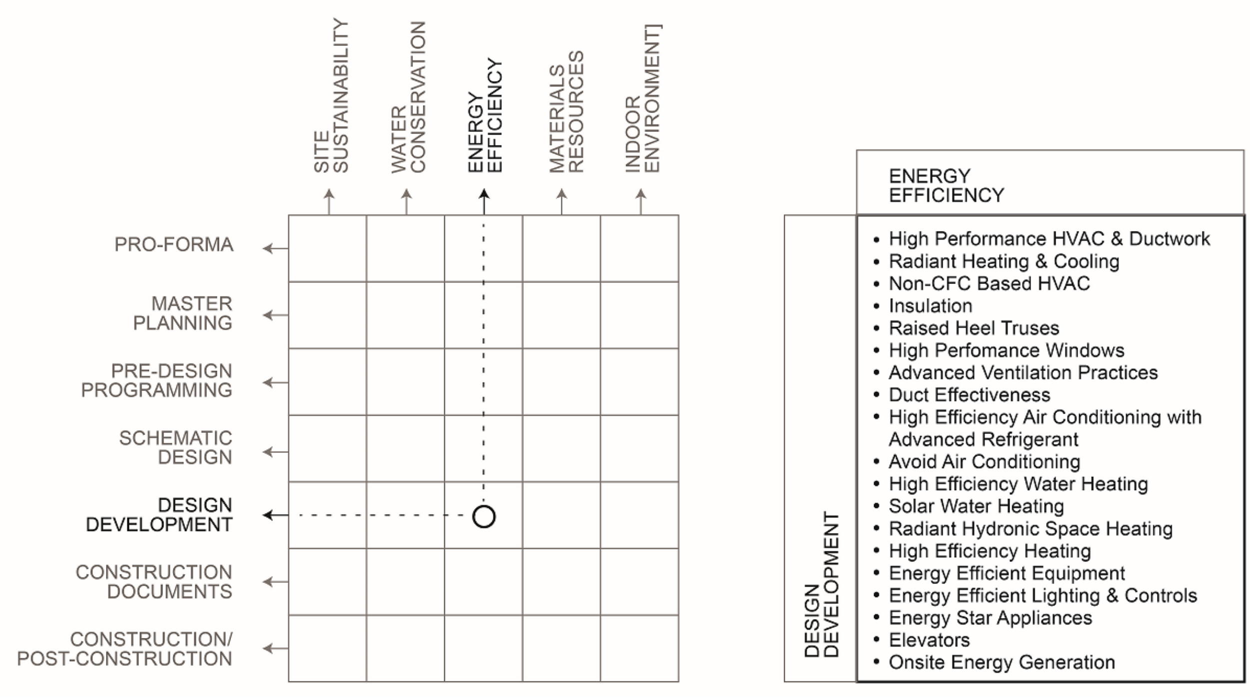


Figure 2.1 Green Matrix (Ratcliff, 2007)

Harputlugil and Hensen (Harputlugil & Hensen, 2006) discuss a similar approach that adds another dimension to the described organization of a two-dimensional matrix. As in previous examples, the proposed methodology relates design criteria (in form of performance rating systems like LEED, BREEAM, and BG-tool) to Building Process Phases and Design Stages in a project matrix. The structure correlates Pre-Design, Design, Construction, Operation and Renovation stages, and sub-stages to respective assessment stages (Pre-design assessment, design assessment, construction assessment, and operation assessment). The authors argue that “Since buildings are so diverse, serving many different types of occupancies or functions, any attempt to develop a single system to define and rate the performance of these buildings will not be perfect and will even be unsatisfactory for many potential users (MacDonald 2000). Hence, it might be one strategy to at least define a flexible system that can have many possible configurations for dealing with the issues created by the diversity. MacDonald emphasized that major issues were related to: who will be the users of such a rating system; how any rating results will impact actions of building owners, operators, and other building industry actors; how such abilities will be deployed and maintained; and how quality will be assured.”

In addition to the relationship of performance criteria and an appropriate assessment during all design stages, user diversity should also be considered as a third important aspect. In relation to the list of typical “standard” design team services, various specialists from different fields need to be involved depending on the complexity and building program, required planning input, as well as the expected building performance and environmental quality according to established industry and rating standards. As a result, all three categories (design stage, design factor, and involved actor) need to be correlated and facilitated by an integrated platform.

An example of such an attempt is the “Sustainable Toolkit” (Parsons Brinckerhoff, 2013) that Parsons Brinckerhoff, a global consulting firm, has developed for different project types like Buildings, Highways, Transit and Ports. Also organized in a “Buildings Matrix” format, the “Sustainable Toolkit” structure provides guidance throughout the design stages by asking “What to do if you are… (a member of the project team working on a particular area)”. The actors are hereby categorized by client/project management, various architectural team members, and a range of consulting engineering parties. In addition to the way all participating parties can now find their way through the process, a detailed overview of sustainability measures for all areas is provided. Next to this project-specific and task-related guidance, multiple links to external resources and references are provided in the different sections of the toolkit.

The design methodologies reviewed in this section organized the knowledge (design strategies, design guidance, and/or associated resources and references) for high-performance building design by performance criteria, design teams, design factors, design stages, and/ or project types. However, there are not quantitative simulation capacities for these design methodologies.

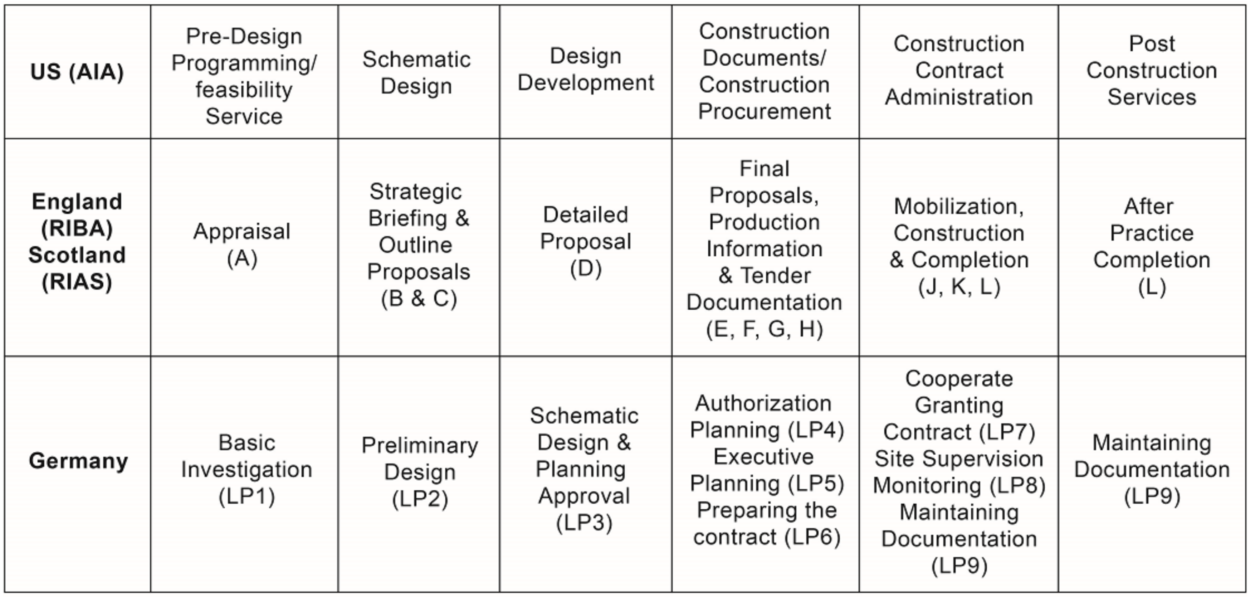
For the assistance of an integrated and coordinated multi-disciplinary building design process of a given project type, VDS needs to also include three dimensions in representing respective steps: design team, design factors, and design stages. For each task performed by a specific design team, at a specific design stage, and for a specific design factor, all aspects of the building performance need to be assessed both qualitatively and quantitatively. There are five aspects of the building performance in VDS, including Site Sustainability, Water Efficiency, Energy & Atmosphere, Materials & Resources, and Indoor Environmental Quality (Table 2-3). This outcome constitutes a basic requirement and structure for the VDS platform development.

2.2. Building design process

2.2.1. Design stages

In order to develop methodologies for a coordinated and fully integrated workflow, the architectural design process itself, as well as its planning parameters need to be understood. In general, the building process can be categorized into four overarching stages: 1) pre-design, 2) design and systems coordination, 3) construction and systems implementation, and 4) occupation, operation and maintenance. Industry standards cover all in-between steps and respective requirements in greater depth. As examples, professional working stages from the US, UK, and Germany were analyzed and compared (Table 2-1).

Table 2-1: Professional architectural working stages in the US, UK, and Germany (Pelken, et al., 2013)

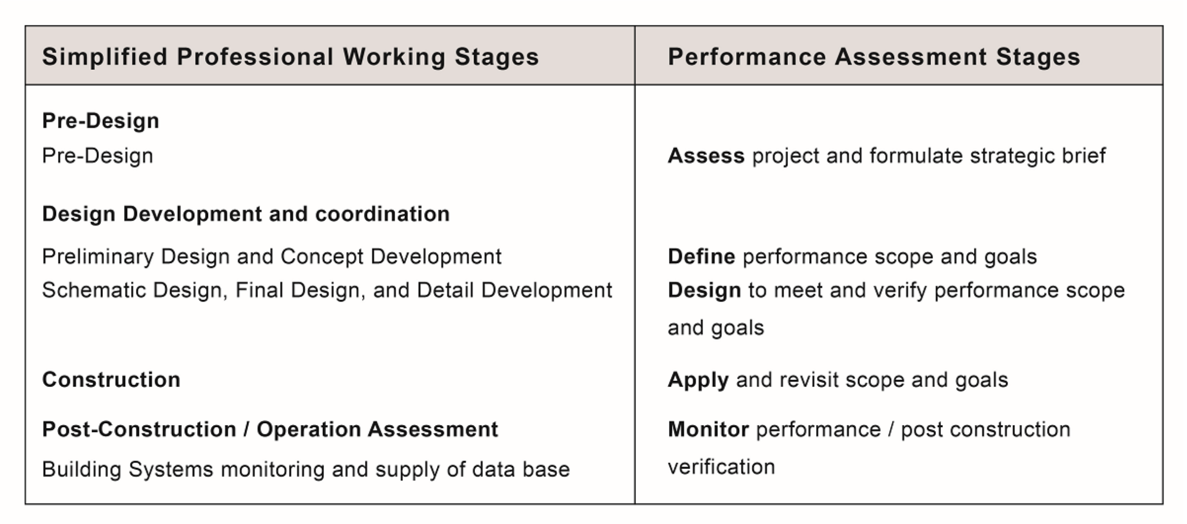


US (AIA)	Pre-Design Programming/ feasibility Service	Schematic Design	Design Development	Construction Documents/ Construction Procurement	Construction Contract Administration	Post Construction Services
England (RIBA) Scotland (RIAS)	Appraisal (A)	Strategic Briefing & Outline Proposals (B & C)	Detailed Proposal (D)	Final Proposals, Production Information & Tender Documentation (E, F, G, H)	Mobilization, Construction & Completion (J, K, L)	After Practice Completion (L)
Germany	Basic Investigation (LP1)	Preliminary Design (LP2)	Schematic Design & Planning Approval (LP3)	Authorization Planning (LP4) Executive Planning (LP5) Preparing the contract (LP6)	Cooperate Granting Contract (LP7) Site Supervision Monitoring (LP8) Maintaining Documentation (LP9)	Maintaining Documentation (LP9)

Although the mentioned planning stages are considered universal in nature, they can be further informed by the client structure and participating parties. US American Contract Documents are hereby divided into eight categories based on project type and/or the chosen delivery method, and suggest a wide range of possibilities for the project procurement (AIA, 2012). As another example, next to the nine prescribed planning stages, the German chamber's regulations prescribe a series of drawing scales that are aligned with the increased complexity and achieved project resolution (HOAI, 2009). Respectively, in the British system, planning stages foresee work on buildings and fit out projects carried out in eleven planning steps (RIBA, 2007).

The typical working stages discussed above can be simplified and further translated into performance evaluation stages that can now be seen as universal steps for a performance evaluation and implementation in VDS (Table 2-2).

Table 2-2 Professional project working stages simplified to the VDS ADDAM design stages (Pelken, et al., 2013)



Simplified Professional Working Stages	Performance Assessment Stages
Pre-Design	
Pre-Design	**Assess** project and formulate strategic brief
Design Development and coordination	
Preliminary Design and Concept Development	**Define** performance scope and goals
Schematic Design, Final Design, and Detail Development	**Design** to meet and verify performance scope and goals
Construction	**Apply** and revisit scope and goals
Post-Construction / Operation Assessment	**Monitor** performance / post construction verification
Building Systems monitoring and supply of data base	

2.2.2. “Traditional” vs. “Integrated” design process

The building design process is a very important for achieving energy-efficient buildings. Many of the current practices are still following the traditional design process which is one of the most significant obstructions to improve the design performance. Comparing to the traditional design process, the integrated design process has many advantages. The comparison between traditional and integrated design processes is shown in Figure 2.2. Design stages from conceptual to construction are listed from left to right in the figure. Dashed arrow lines represent the scope refinement path. Color-coded piles of rectangles within the dashed arrows indicate aspects of the key sub-systems. Rounded rectangles between design stages are workshops and charrettes.

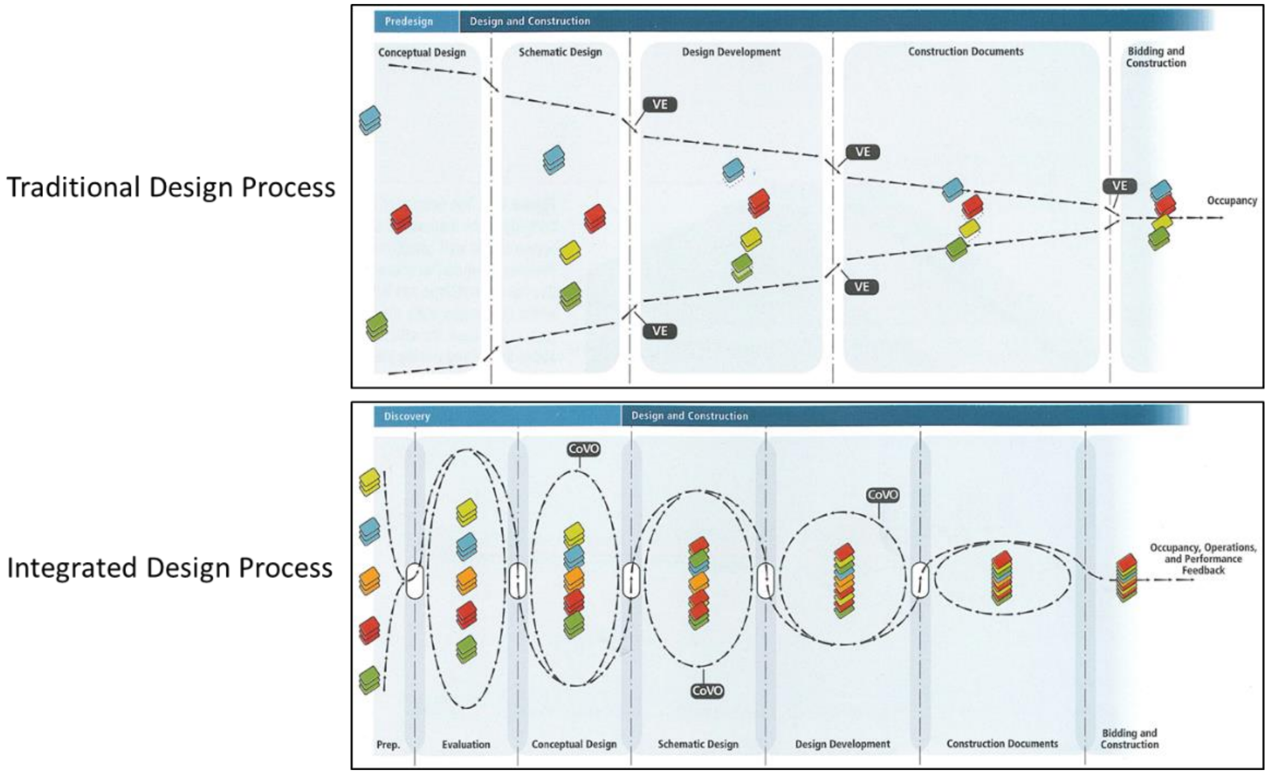


Figure 2.2 traditional & integrated design process comparison (7group & Reed, 2009)

2.2.2.1. Traditional design process

The traditional design process is a forward "single thread" process. The workstream of the traditional design process has very limited local or even no feedbacks. The downstream design is very much based on given conditions from the previous stage(s). For example, early-stage form and massing design can heavily impact daylight accesses. A form and massing design without considerations of daylight accesses could result in difficulties of optimal fenestration allocations on the facades. In this case, it is very possible to lose the chance for optimizing the form and massing (geometries) which may result in higher lighting energy consumptions.

In the traditional design process, design actors work on a fragmented basis at the same time, shown as the separated piles of little rectangles in Figure 2.2. So, the success of the high-performance design is more based on individual systems rather than overall success. This may also lead to creating barriers for whole building systems integration.

Last but not least, design actors from different parties involved in the project at different design stages. The overall design goals may be lost along the long designing period which harms the final performance. It also rises the chance of one system putting significant limitations to other systems.

2.2.2.2. Integrated design process

Comparing to the traditional design process, the integrated process has many advantages. Firstly, the integrated process is an iterative design refinement of a system with frequent feedbacks (within and across design stages). This helps the design synchronization of systems with impacts on dependent systems.

Secondly, the integrated process not only enhances the same upstream and downstream design alignment, it also helps to achieve better overall performance by concurrently considering the multi-design factors. For example: in the early stage, architects often lead the form and massing design. If engineers can collaborate with architects, the form and massing design could be guided by the energy performance analysis which is provided by the engineering team. It can effectively help form and massing design to avoid excessive energy exchanges on the building's external enclosures which result in lower environmental system loads, which may even further reduce the project cost by downsizing the environmental equipment. The concurrent design factors integration between form and massing and environmental systems increases the chance to achieve better overall performance.

Thirdly, the integrated design process strongly encourages (or even requires) all stakeholders and designers to participate in the project from the very beginning. For instance, all stakeholders and designers attend charrettes to assess the available resources of the project or set the performance goals. Therefore, all involved parties and members understand and share the same design goals. It significantly reduces the chances of design deviations from the shared common goals along the long time period of design.

2.3. Building performance criteria and assessment systems

In addition to the working stages (Table 2-2) and their respective deliverables, national and regional building codes form a highly specific planning framework and inform all aspects of the individual design agenda. Code compliance is hereby mandatory to successfully design and construct the building. Among many others, they can regulate site related and civic planning aspects, building program related concerns, building massing, the use of materials, accessibility, and environmental control issues. Recent changes to building codes internationally consider energy and environmental performance evaluations and certification as an additional area of consideration.

The US Environmental Protection Agency (EPA) provides a broad and holistic overview of recommendations in their Science & Technology: Sustainable Practices section. The EPA states that “Agency researchers and their partners from across a wide spectrum of investigative fields are working together to form a deeper understanding of the balance between the three pillars of sustainability—environment, society, and economy.” Various sustainability guidelines hereby address two categories: Urban and Local Sustainability and Industrial Sustainability (U.S. Environmental Protection Agency, 2012). Among others in the US, evaluation systems that more clearly address the building sector such as ASHRAE 189.1 (ASHRAE, 2018) and LEED (USGBC, 2019) standards are predominant in structuring environmental performance assessment methods for the built environment.

The National Institute of Building Sciences (NIBS, authorized by the U.S. Congress in the Housing and Community Development Act of 1974) provides guidance in various areas of construction. “The Institute's mission to serve the public interest is accomplished by supporting advances in building sciences and technologies for the purpose of improving the performance of our nation's buildings while reducing waste and conserving energy and resources” (NIBS, 2021). NIBS is organized by councils and committees that address a wide range of building performance related topics (Advanced Materials Council, Building Enclosure Council, Building Enclosure Technology and Environment Council, High Performance Building Council, etc.). NIBS’s publications by various divisions support the dissemination of specific knowledge from individual areas of investigation. For instance, the “*Journal of Building Enclosure Design”* is an official publication of the Building Enclosure Technology and Environment Council (BETEC) of the NIBS. Further monthly E-Newsletters include the Journal of Advanced High-Performance Materials, Journal of Building Information Modeling, and the Journal of Hazard Mitigation and Risk Assessment.

Additionally, NIBS also offers United States National CAD and BIM Standards. The latest edition of “United States National CAD Standards” is currently available in Version 6. The “National BIM Standard - United States Version 3”, by the NIBS building SMART alliance, “provides consensus-based standards through referencing existing standards, documenting information exchanges and delivering best business practices for the entire built environment.” (NIBS, 2015)

The Building Seismic Safety Council (BSSC) and Multihazard Mitigation Council (MMC) are examples of nationally applicable, highly specific design provisions. Among others, the Building Enclosure Technology and Environment Council (BETEC) and the High-Performance Buildings Council (HPBC) represent the “Facility Performance and Sustainability Program”. The HPBC states that the “Council’s overall goal is to put standards in place to define the performance goals of a high-performance building in order to facilitate the design, construction, financing, and operating buildings with an emphasis on life cycle issues rather than initial costs”. The HPBC identifies the metrics and level of required performance for specific design objectives (energy, security, durability, moisture, acoustics, etc.) for building products, systems and subsystems, and references industry standards for validating these performance requirements (NIBS, 2019).

Furthermore, the National Institute of Standards and Technology (NIST) governs national industry standards for environmental performance, energy, and sustainable practice with standards for the smart grid, energy-efficient lighting, photovoltaics, net-zero-energy buildings, software for smart buildings.

Various standards are defined by the German Energy Agency and other legislative agencies. Amongst others, the Energy Conservation Legislation (Energieeinsparungsgesetz EnEG and Energieeinsparverordnung EnEV) provide guidelines for the efficiencies of buildings, as much as many national standards described in the German Industry Norms (Deutsches Institut für Normung e. V., 2020)

BREEAM (Building Research Establishment Environmental Assessment Method), first launched in 1990, forms a predominant and comprehensive framework for the performance planning and evaluation in the United Kingdom. The evaluation criteria have typically been differentiated by building program and type and have been extended for an international application. BREEAM is used in a range of formats from country-specific schemes, adapted for local conditions, to international schemes intended for the certification of individual projects anywhere in the world (BREEAM, 2020). Amongst other information, case studies are available online for categories such as communities, datacenters, industrial, educational, offices, and mixed-use developments (BREEAM, 2020).

All the reviewed environmental assessment methodologies are based on the following three areas of consideration: the economy of resources (including energy conservation, water conservation, and material conservation), Life Cycle Design (throughout the Pre-Building Phase, the Building Phase, and the Post-Building Phase), and Humane Design considerations which are further defined as the Preservation of Natural Conditions, Urban and Site Planning Strategies, and the Design for Human Comfort (Kim, 1998).

For a comprehensive understanding of all design-related issues, complex investigations on various scales are required. Planning considerations range from general sustainability aspects to a large number of highly specific sites and building-related topics.

Six fundamental principles have been identified for a “Whole Building Design Guide (WBDG)” by the US National Institute for Building Science (WBDG Sustainable Committee, 2018): 1) Optimize site potentials, 2) Optimize energy use, 3) Protect and conserve water, 4) Optimize building space and material use, 5) Enhance indoor environmental quality (IEQ), and 6) Optimize operational and maintenance practices.

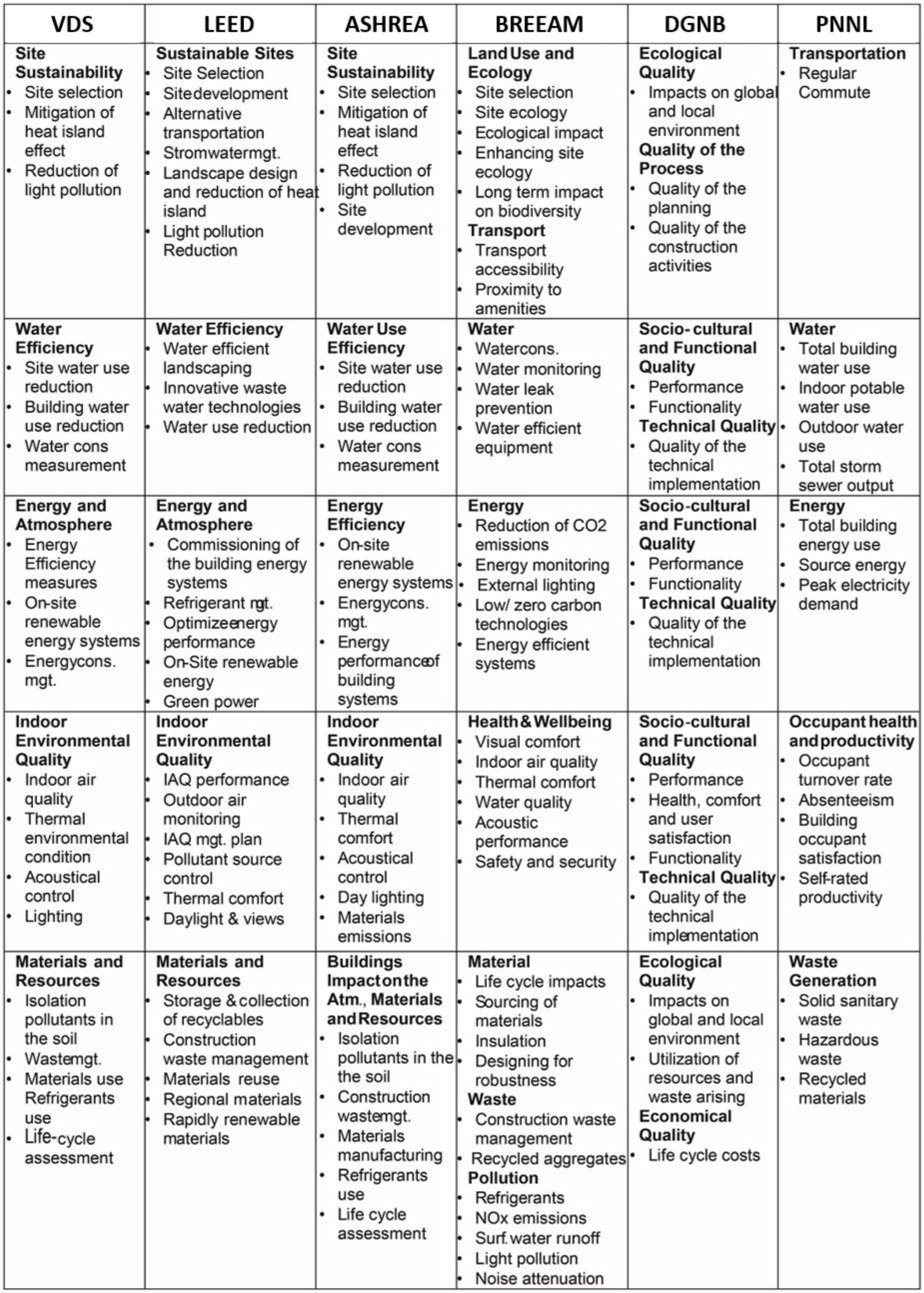
Similarly, the US Green Building Council’s (USGBC’s) LEED (Leadership in Energy and Environmental Design) certification program differentiates among various focus areas that include sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, location and linkages, awareness and education, innovation in design and regional priority (USGBC, 2021). The LEED Rating System is further categorized for the evaluation of new construction, existing buildings, commercial interiors, healthcare, homes, and neighborhood developments, amongst others (USGBC, 2021).

Another example of a well-adopted evaluation system is ASHRAE's (American Society of Heating, Refrigerating and Air Conditioning Engineers) Standard 189.1 (ASHRAE, 2018) for the Design of High-Performance, Green Buildings. "Standard 189.1 provides a total building sustainability package for those who strive to design, build and operate green buildings. From site location to energy use to recycling, this standard sets the foundation for green buildings by addressing site sustainability, water use efficiency, energy efficiency, indoor environmental quality, and the building's impact on the atmosphere, materials and resources. Standard 189.1 serves as a compliance option in the 2018 International Green Construction Code™ (IgCC) published by the International Code Council. The IgCC regulates construction of new and remodeled commercial buildings." (ASHRAE, 2018).

Compare to other standards/guides, the WELL Building Standard is the first building standard to focus exclusively on the health and wellness of the people in buildings. It is a performance-based system for measuring, certifying, and monitoring features of the built environment that impact human health and wellbeing (International WELL Building Institute, 2020). Its latest version WELL Building Standard™ version 2 covers 10 concepts: air, water, nourishment, light, movement, thermal comfort, sound, materials, mind, and community. Determined primarily by ownership type, the applicability and scoring may vary (International WELL Building Institute, 2021).

Table 2-3 shows the five performance aspects considered by VDS and their relationship with those included in the various performance assessment systems reviewed (Pelken, et al., 2013). All aspects should be considered throughout the service life of the building from design to construction to operation.

Table 2-3 Performance aspects considered by VDS and existing assessment systems (Pelken, et al., 2013)



VDS	LEED	ASHREA	BREEAM	DGNB	PNNL
Site Sustainability • Site selection • Mitigation of heat island effect • Reduction of light pollution	**Sustainable Sites** • Site Selection • Sitedevelopment • Alternative transportation • Stromwatermgt. • Landscape design and reduction of heat island • Light pollution Reduction	**Site Sustainability** • Site selection • Mitigation of heat island effect • Reduction of light pollution • Site development	**Land Use and Ecology** • Site selection • Site ecology • Ecological impact • Enhancing site ecology • Long term impact on biodiversity **Transport** • Transport accessibility • Proximity to amenities	**Ecological Quality** • Impacts on global and local environment **Quality of the Process** • Quality of the planning • Quality of the construction activities	**Transportation** • Regular Commute
Water Efficiency • Site water use reduction • Building water use reduction • Water cons measurement	**Water Efficiency** • Water efficient landscaping • Innovative waste water technologies • Water use reduction	**Water Use Efficiency** • Site water use reduction • Building water use reduction • Water cons measurement	**Water** • Watercons. • Water monitoring • Water leak prevention • Water efficient equipment	**Socio-cultural and Functional Quality** • Performance • Functionality **Technical Quality** • Quality of the technical implementation	**Water** • Total building water use • Indoor potable water use • Outdoor water use • Total storm sewer output
Energy and Atmosphere • Energy Efficiency measures • On-site renewable energy systems • Energycons. mgt.	**Energy and Atmosphere** • Commissioning of the building energy systems • Refrigerant mgt. • Optimizeenergy performance • On-Site renewable energy • Green power	**Energy Efficiency** • On-site renewable energy systems • Energycons. mgt. • Energy performanceof building systems	**Energy** • Reduction of CO2 emissions • Energy monitoring • External lighting • Low/ zero carbon technologies • Energy efficient systems	**Socio-cultural and Functional Quality** • Performance • Functionality **Technical Quality** • Quality of the technical implementation	**Energy** • Total building energy use • Source energy • Peak electricity demand
Indoor Environmental Quality • Indoor air quality • Thermal environmental condition • Acoustical control • Lighting	**Indoor Environmental Quality** • IAQ performance • Outdoor air monitoring • IAQ mgt. plan • Pollutant source control • Thermal comfort • Daylight & views	**Indoor Environmental Quality** • Indoor air quality • Thermal comfort • Acoustical control • Day lighting • Materials emissions	**Health & Wellbeing** • Visual comfort • Indoor air quality • Thermal comfort • Water quality • Acoustic performance • Safety and security	**Socio-cultural and Functional Quality** • Performance • Health, comfort and user satisfaction • Functionality **Technical Quality** • Quality of the technical implementation	**Occupant health and productivity** • Occupant turnover rate • Absenteeism • Building occupant satisfaction • Self-rated productivity
Materials and Resources • Isolation pollutants in the soil • Wastemgt. • Materials use Refrigerants use • Life-cycle assessment	**Materials and Resources** • Storage & collection of recyclables • Construction waste management • Materials reuse • Regional materials • Rapidly renewable materials	**Buildings Impact on the Atm., Materials and Resources** • Isolation pollutants in the soil • Construction wastemgt. • Materials manufacturing • Refrigerants use • Life cycle assessment	**Material** • Life cycle impacts • Sourcing of materials • Insulation • Designing for robustness **Waste** • Construction waste management • Recycled aggregates **Pollution** • Refrigerants • NOx emissions • Surf. water runoff • Light pollution • Noise attenuation	**Ecological Quality** • Impacts on global and local environment • Utilization of resources and waste arising **Economical Quality** • Life cycle costs	**Waste Generation** • Solid sanitary waste • Hazardous waste • Recycled materials

2.4. Existing building design and simulation tools

Originated from 1960s, people started to use building simulations to assist the design. The International Building Performance Simulation Association (IBPSA-USA) comprehensively listed the evolution of building energy modeling (BEM) as shown in Figure 2.3 (IBPSA-USA, 2019). The evolution flow chart highlights the development and release of many BEM software programs. In addition, the key market drivers along the timeline are indicated, for example: ASHRAE 90.1 Appendix G, Title 24 standards (California Energy Commission, 2019) for the state of California, and the Leadership in Energy & Environmental Design (LEED) program from the U.S. Green Building Council (USGBC).

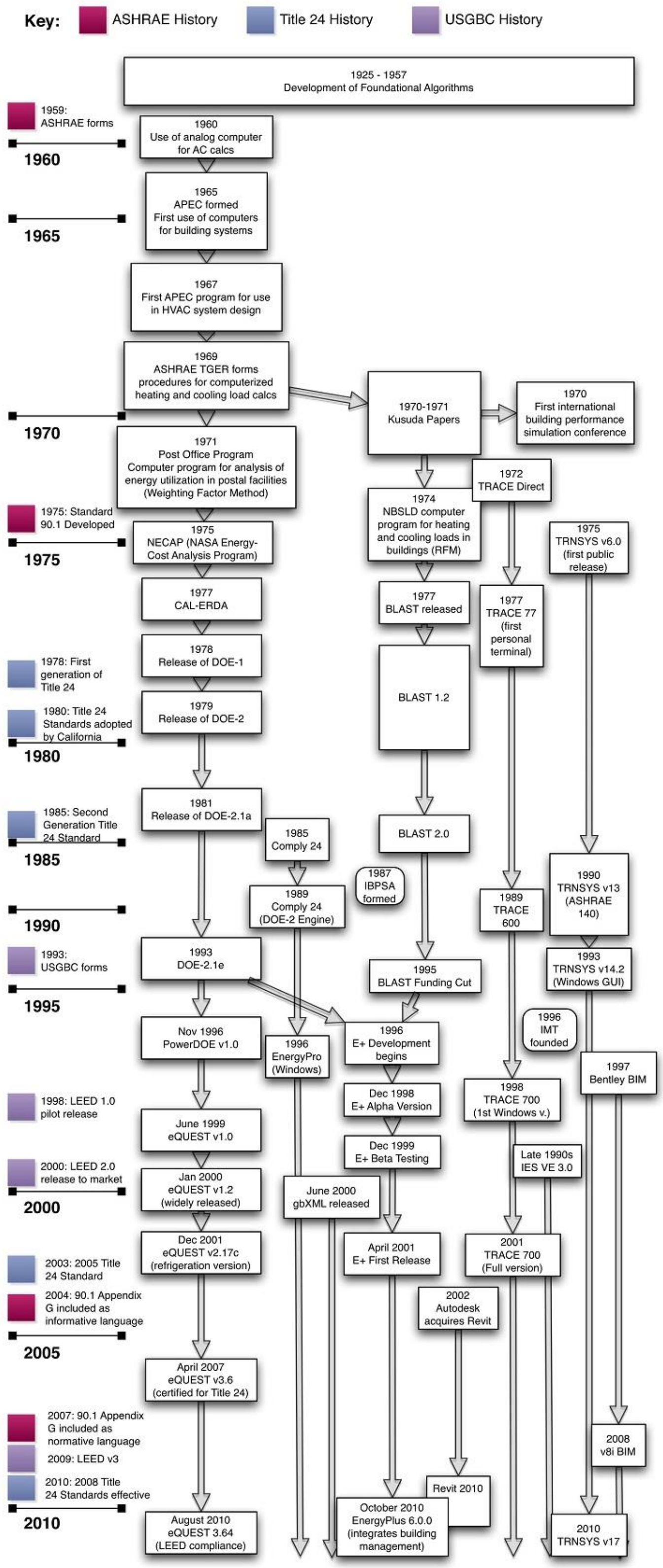


Figure 2.3 History of building energy modeling (IBPSA-USA, 2019)

After years of developments, a wide range and a large number of building simulation tools were developed with various capabilities (IBPSA-USA, 2021). The capability categories include whole-building energy simulation, load calculations, building energy benchmarking, lighting simulation, indoor air quality simulation, life-cycle analysis, detailed envelope simulation, etc. Several whole-building design and simulation tools are widely adopted in current professional practices, such as: EnergyPlus**,** eQuest, Green Building Studio, DesignBuilder, OpenStudio, Ladybugs Tools.

EnergyPlus is a whole building energy simulation program that engineers, architects, and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and water use in buildings (U.S. Department of Energy Building Technologies Office, 2020). It has very comprehensive analysis capabilities, but its textural based user interface limits its applications, especially for non-technical designers. So many other tools developed their own GUI and use it as the simulation engine to fully take the analysis advantages of EnergyPlus. For instance: DesignBuilder, OpenStudio. Another EnergyPlus GUI worth noticing is Simergy which was developed by Lawrence Berkeley National Laboratory (LBNL). It includes a 'drag and drop' component-level schematic editor for HVAC systems (Digital Alchemy, 2020).

eQuest is a “quick energy simulation tool” which developed upon DOE-2 (James J. Hirsch & Associates, 2020). It intended to be comprehensive and intuitive enough that all design teams can use it in any design phase (EnerLogic, James J. Hirsch & Associates, 2020). Although the building modeling input is mainly textual based, the implemented wizards of building model creation, detailed systems design, and energy efficiency measure (EEM) in eQuest made the process easier than pure textual based programs. In the meantime, the pre-designed wizards may have limited flexibility to reflect the actual design. In addition to tabular results representation, the high-level performance results can be graphically reported.

Green Building Studio (GBS) is Autodesk’s core whole building energy simulation engine and powers the analysis in other products from Autodesk. GBS is a cloud-based service that allows users to run building performance simulations to optimize energy efficiency and to work toward carbon neutrality in the early conceptual phase of the design process. GBS uses the DOE-2.2 simulation engine to calculate energy performance and creates geometrically input files for EnergyPlus (IBPSA-USA, 2020). It also can work with other tools via standard file format Green Building XML (gbXML).

DesignBuilder is a whole building energy use analysis simulation tool. It is the oldest, easiest to use graphical user interface to EnergyPlus. It also includes ASHRAE 90.1 Appendix G Baseline HVAC System templates, materials, and construction libraries. Building models created in DesignBuilder can be exported out as EnergyPlus files for further manipulation and advanced analysis (IBPSA-USA, 2020).

OpenStudio is a collection of software tools to support whole building energy modeling. The graphical applications include the SketchUp Plug-in (Trimble Navigation Limited, 2020), Application, ResultsViewer and the Parametric Analysis Tool. The Plug-in is an extension to a 3D modeling tool named SketchUp, favored by architects, that allows users to quickly create geometry needed for EnergyPlus. It supports the import of gbXML and IFC for geometry creation. The OpenStudio Application is a fully featured graphical interface to OpenStudio models including envelope, loads, schedules, and HVAC. ResultsViewer enables browsing, plotting, and comparing simulation output data, especially time series. The Parametric Analysis Tool enables studying the impact of applying multiple combinations of OpenStudio Measures to a base model (Alliance for Sustainable Energy, LLC., 2020).

Ladybug Tools is a collection of free computer applications that support designers create an environmentally-conscious architectural design (Ladybug Tools LLC, 2021). Its Ladybug module uses standard EnergyPlus weather files for designers to test their initial design options for implications from radiation and sunlight-hours analyses results. Its Honeybee module connects the visual programming environment of Grasshopper to four validated simulation engines (EnergyPlus, Radiance, Daysim and OpenStudi). These plugins enable a dynamic coupling between the flexible, component-based, visual programming interface of Grasshopper and validated environmental data sets and simulation engines (IBPSA-USA, 2021).

Although there are many simulation programs developed to simulate building energy and IEQ performance, they are not integrated with design processes as part of their operational framework. These simulation tools require detailed input parameters throughout all design phases. As the design information is very limited in the early design stages, most of these simulation tools are suitable only for detailed design stages.

2.5. Knowledge gap

The building design is a multi-disciplinary process requiring coordination among all participating disciplines such as architectural, engineering, and management team members. Teams from different areas have very specialized expertise and working fashions. “Hundreds of linear processes must be completed in concert so that foundations can be poured, walls can rise, interiors can be fitted out, and occupancy can occur” (7group & Reed, 2009). It is hence critical to be able to define the critical tasks and required information, effectively organize the workflow, and facilitate the integration among them. As mentioned in section 2.4, while the simulation programs have made it easier for designers to use existing energy simulation tools, they do not provide sufficient support for design coordination and integrated analysis of energy and IEQ performance from early to final design stage. Most of the simulation tools are not integrated with interdisciplinary design process requirements and respective collaborative practices. The crucial process management (information input, categorization, and filtering, critical working path) and information transfer are missing.

In addition, although these sophisticated programs could achieve relative high simulation accuracy, they require detailed input parameters throughout the design processes. The early design stages decisions have significant impact on building performance, but the design information is very limited. These simulation tools are predominantly suitable for the detailed design stage in which various design parameters have been specified.

The goal of this study to develop an intelligent design platform for integrative design of green buildings from conceptual to detail design stages. It intended to overcome the disciplinary boundaries by using the same tool, more coherent and integrated design flow and associated information, and support the early stage performance evaluation and design decision making by the simplified performance evaluation model.

CHAPTER 3. VDS FRAMEWORK AND "MAGIC CUBE" (MC)- AN INTEGRATED AND COORDINATED PROCESS FOR PERFORMANCE-BASED BUILDING DESIGN

This chapter first introduces the VDS framework, features, and implementations. It is a software platform developed in support of high-performance building design and system integrations. The following sections illustrate the methodology, representation, and implementation of the VDS core components MC. The MC was developed to provide seamless transition among design stages, enhance multi-disciplinary coordination, and assist design factors integration through whole building performance analysis. Finally, a LEED Platinum rated medium-size office building was used as the case study to demonstrate how the coordinated and integrated MC method would be applied to achieve a high-performance green office building design.

3.1. VDS framework introduction

The building design is a multi-dimensional process involving multi-disciplinary design teams, multi-design stages, multi-design factors, and multi-performance objectives. Designing a building is like solving a "magic cube" puzzle in which every step should be coordinated to reach the final solution efficiently. The designers at a given project stage need to consider the primary parameters for the current stage, but also the parameters that are further considered in the more detailed subsequent design stages. These parameters represent multi-design factors including Site & Climate, Form & Massing, Internal Configuration, External Enclosure, Environmental System (HVAC), Energy Supply-System, Water Supply-System, Materials, and their Interdependences.

The impact of these design parameters on the building performance needs to be evaluated and analyzed throughout the design process to optimize the design. Sufficient and timely iterations are necessary among the different design factors in different design stages for component trade-offs and whole building optimization (Figure 3.1).

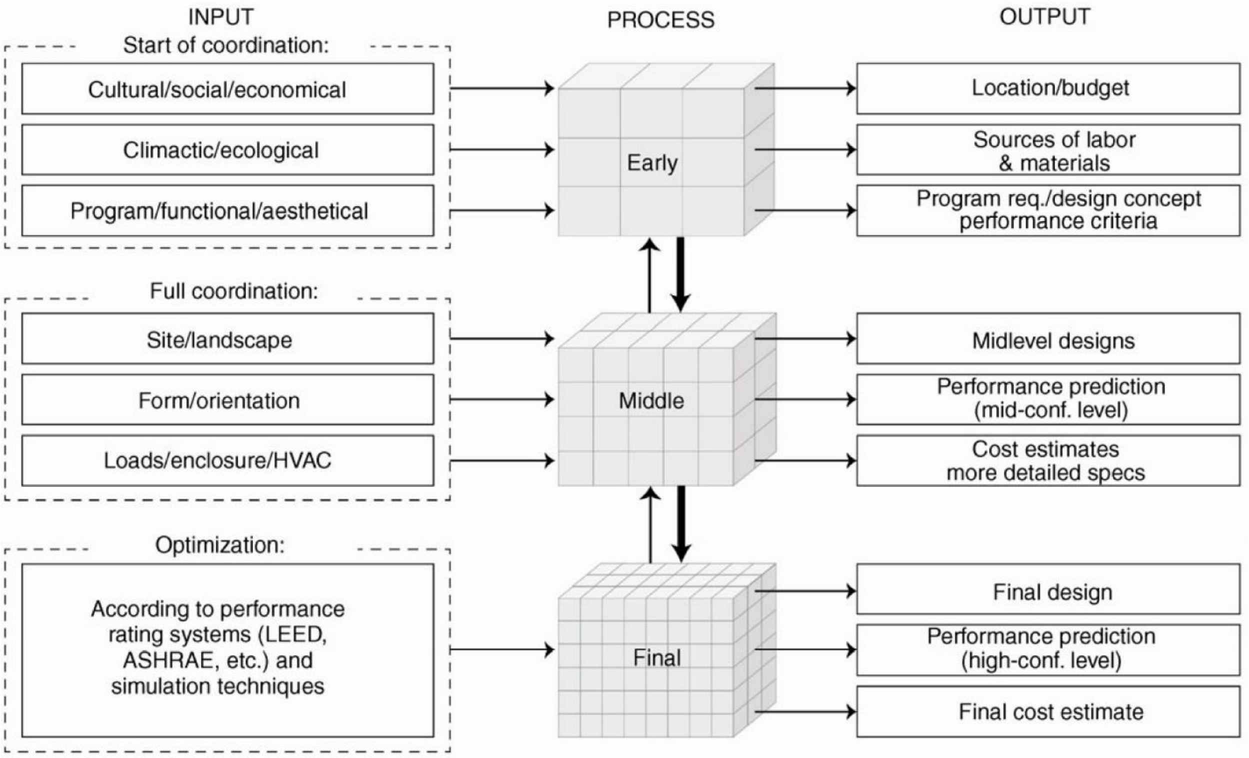


Figure 3.1 Increased complexity of staged design process in VDS structure (Pelken, et al., 2013)

In order to realize the above goals, the software platform VDS was developed for supporting an integrated, coordinated and optimized design of high-performance buildings from early to advanced design stages. It has the following major features:

1) Estimations of whole building performance at each design stage;

2) Event-driven simulations and iteration within and between design stages -- i.e., the provision of feedback loops and the confirmation of consistency and optimized results;

3) Information/data flow cascades with evolving default settings to simplify the data entry and assisting the users in considering design options;

4) Comparison of design options and visualization of design and performance.

3.1.1. Graphical user interface (GUI)

The VDS GUI features four interactive windows with a counterclockwise layout (Figure 3.2). Tab pages are used to present different categories of information in each quad, from a high to a detailed level. Within each tab page, further details regarding the information category are presented in forms that are most adequate for the category while consistency is sought whenever possible within the same quad.

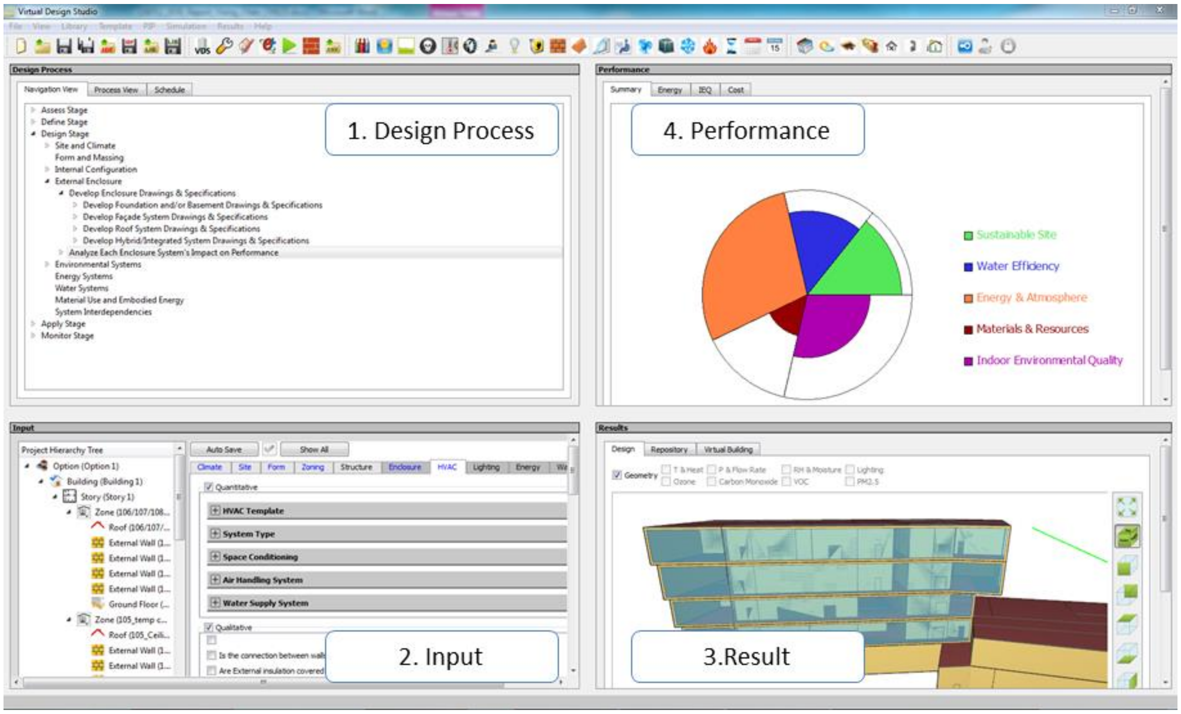
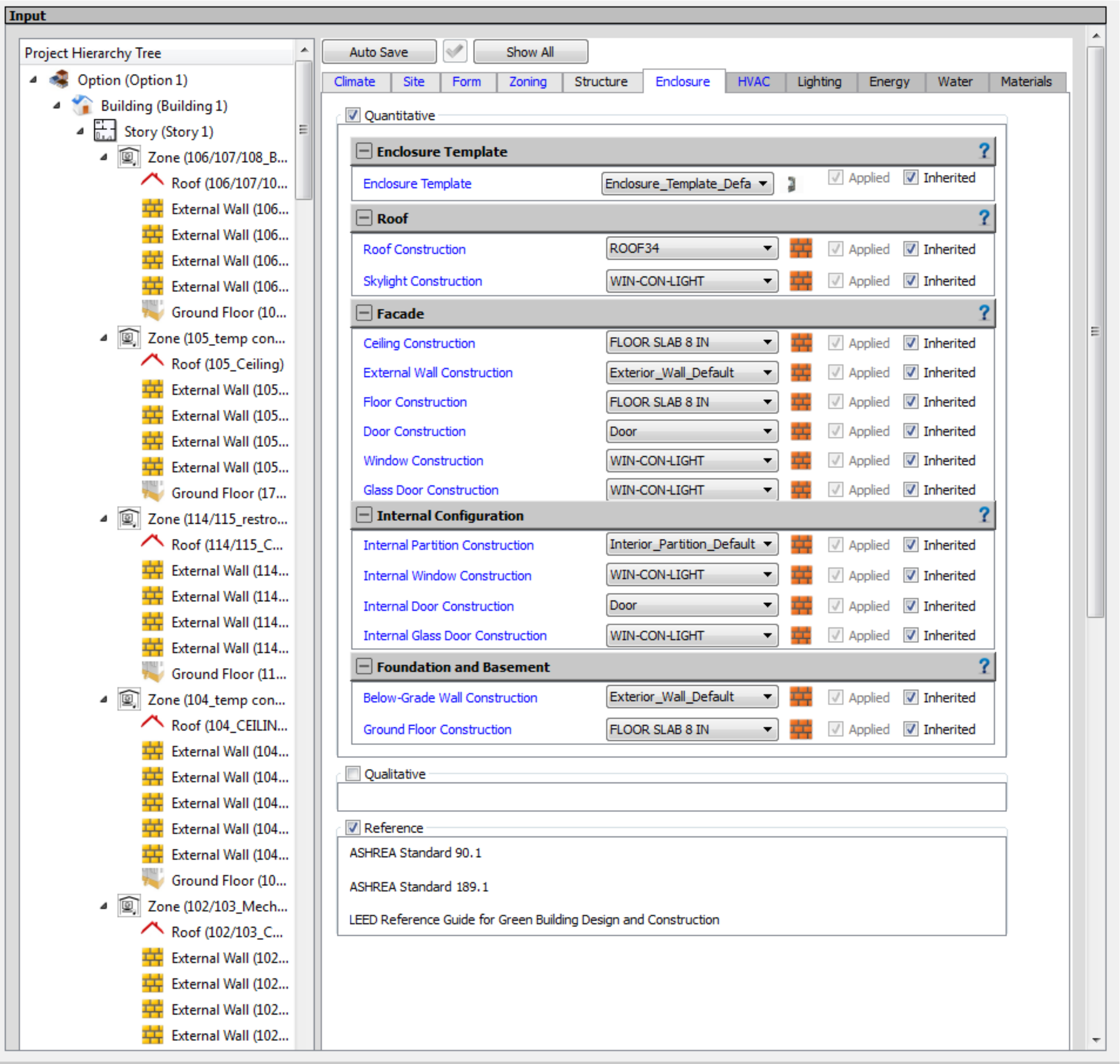


Figure 3.2 Four quads form (viewer) of VDS (Zhang, et al., 2013)

Design Process window: presents the design stages, actors, design factors, associated tasks and schedule, and the input-process-output relationships among tasks, which also enables fast navigation through a complex design process. It includes a “navigation” tree for task management (creation, deletion, and revision) as well as ease of navigation, a “process” page for representing the relationships between tasks and the input and output of each task, and a “schedule” page for tracking the task progress and completion. MC was developed as the core of providing all functionalities and support for this window. Details of MC is elaborated in section 3.2.

Input window: presents the opportunity to input all required design parameters (both quantitative and qualitative) and view supporting reference information. It includes a browsing tree on the left and tab pages on the right (Figure 3.3). The tree allows users to focus on a specific level in the building’s hierarchical structure. Each tab page represents a category of input parameters of a specific design factor. They are Climate, Site, Form, Zoning, Structure, Enclosure, HVAC, Lighting, Energy, Water, and Materials (embedded energy or carbon emission analysis). The quantitative design parameters in each category are further organized into groups. The value of a design parameter at a higher level can be “applied” to all its children; while the value at a lower level can obtain the value from its parent by clicking the “inherited” box.



☑ Quantitative

Enclosure Template

Enclosure Template: Enclosure_Template_Defa ☑ Applied ☑ Inherited

Roof

Roof Construction: ROOF34 ☑ Applied ☑ Inherited

Skylight Construction: WIN-CON-LIGHT ☑ Applied ☑ Inherited

Facade

Ceiling Construction: FLOOR SLAB 8 IN ☑ Applied ☑ Inherited

External Wall Construction: Exterior_Wall_Default ☑ Applied ☑ Inherited

Floor Construction: FLOOR SLAB 8 IN ☑ Applied ☑ Inherited

Door Construction: Door ☑ Applied ☑ Inherited

Window Construction: WIN-CON-LIGHT ☑ Applied ☑ Inherited

Glass Door Construction: WIN-CON-LIGHT ☑ Applied ☑ Inherited

Internal Configuration

Internal Partition Construction: Interior_Partition_Default ☑ Applied ☑ Inherited

Internal Window Construction: WIN-CON-LIGHT ☑ Applied ☑ Inherited

Internal Door Construction: Door ☑ Applied ☑ Inherited

Internal Glass Door Construction: WIN-CON-LIGHT ☑ Applied ☑ Inherited

Foundation and Basement

Below-Grade Wall Construction: Exterior_Wall_Default ☑ Applied ☑ Inherited

Ground Floor Construction: FLOOR SLAB 8 IN ☑ Applied ☑ Inherited

☐ Qualitative

☑ Reference

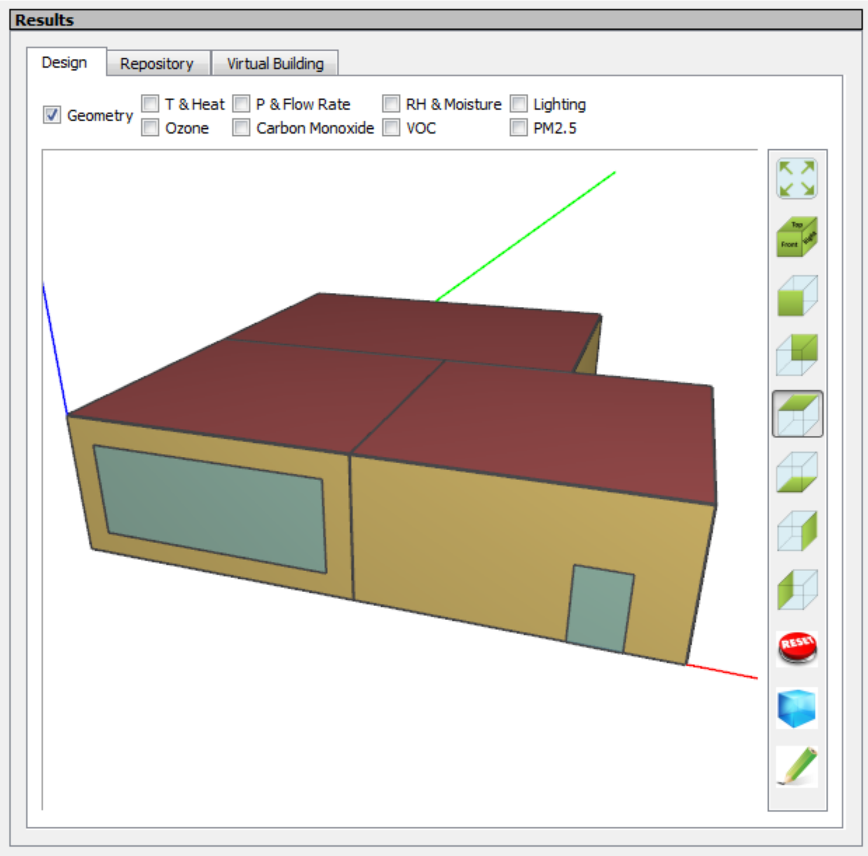
ASHREA Standard 90.1

ASHREA Standard 189.1

LEED Reference Guide for Green Building Design and Construction

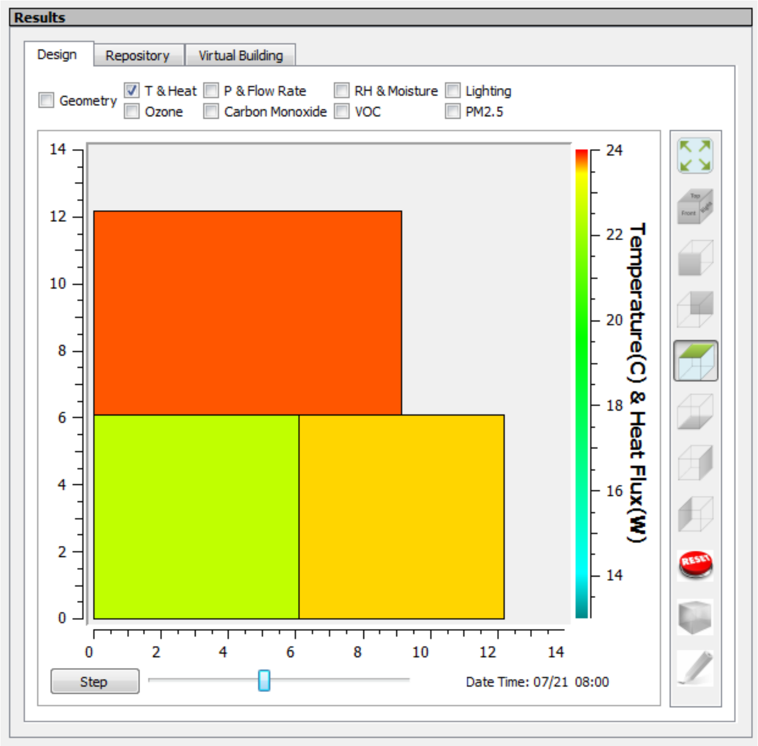
Figure 3.3 VDS design parameters organized by design factors (right) with displays filtered by design tasks and position in the hierarchical tree (left)

Result window: presents the "Design" of the building in a 3-D view (Figure 3.4), the simulation results of heat (Figure 3.5), air, moisture, daylighting (Figure 3.6), and pollutants in the building, and a "Repository". The "Heat", "Air", "Moisture" "Daylighting" and Pollutant" distributions are represented in the forms of contour maps and flux maps with architectural design overlay (Figure 3.5 and Figure 3.6). The “Repository” page links directly to the document sharing interface.



☑ Geometry ☐ T & Heat ☐ P & Flow Rate ☐ RH & Moisture ☐ Lighting
☐ Ozone ☐ Carbon Monoxide ☐ VOC ☐ PM2.5

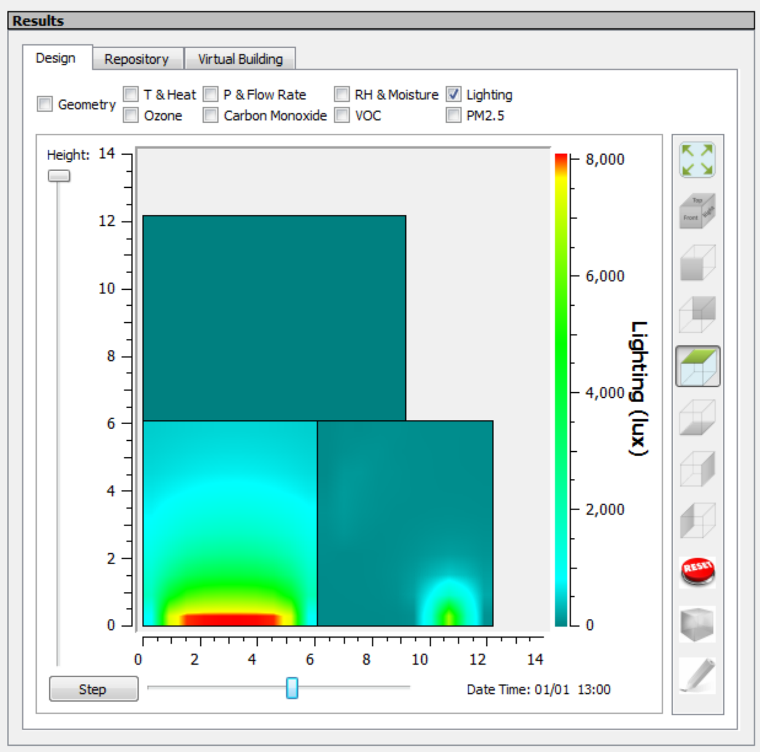
Figure 3.4 The “Design” of a 3-zone building



☐ Geometry ☑ T & Heat ☐ P & Flow Rate ☐ RH & Moisture ☐ Lighting
☐ Ozone ☐ Carbon Monoxide ☐ VOC ☐ PM2.5

Date Time: 07/21 08:00

Figure 3.5 Temperature field of the 3-zone building



☐ Geometry ☐ T & Heat ☐ P & Flow Rate ☐ RH & Moisture ☑ Lighting
☐ Ozone ☐ Carbon Monoxide ☐ VOC ☐ PM2.5

Date Time: 01/01 13:00

Figure 3.6 Lighting map of the 3-zone building

Performance window: represents the overall building performance (Figure 3.7), individual aspects of building performance (Energy-related, Figure 3.11), and cost information. By clicking on an aspect of the building performance in the summary view, the sub-performance aspects of the selected performance aspect will be shown (Figure 3.8). Furthermore, by clicking on a sub-performance aspect, the contributions of each design factor to the improvement of the sub-performance aspect are shown (Figure 3.9). Finally, by clicking on a design factor, the relationship map of the selected design factor with the other factors is shown (Figure 3.10). Future program extensions will include the confidence intervals for the predicted performance.

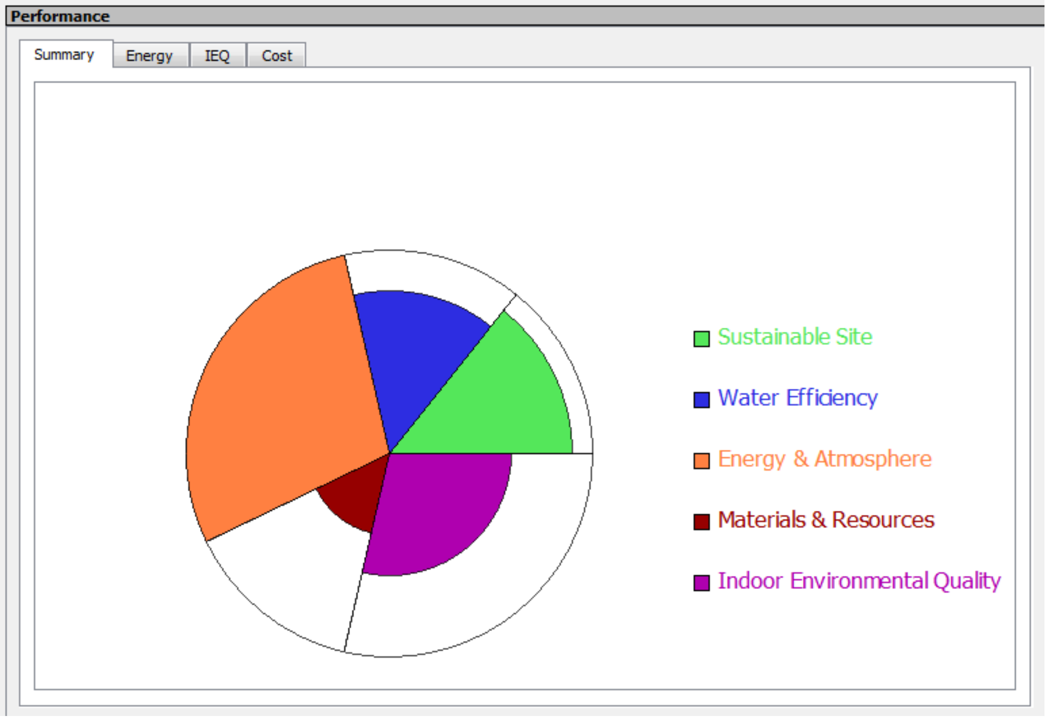


Figure 3.7 Proposed overall building performance summary view

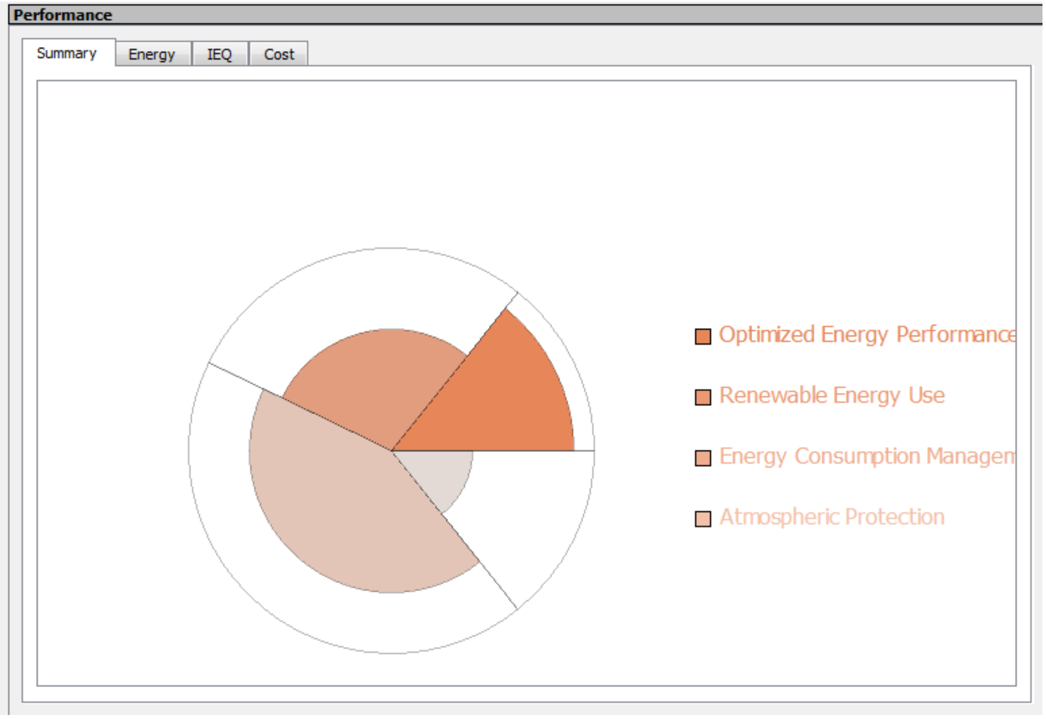


Figure 3.8 Energy & Atmosphere detail

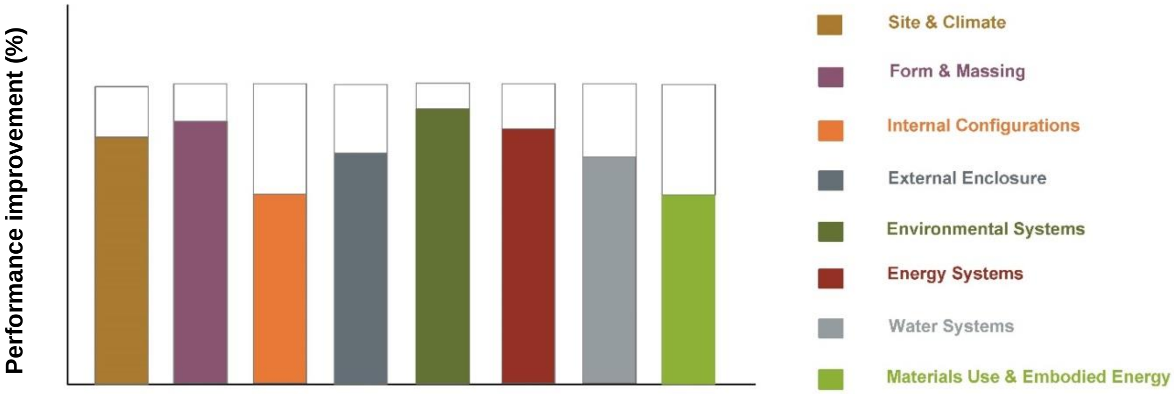


Figure 3.9 Performance improvement relative to reference building by design factor

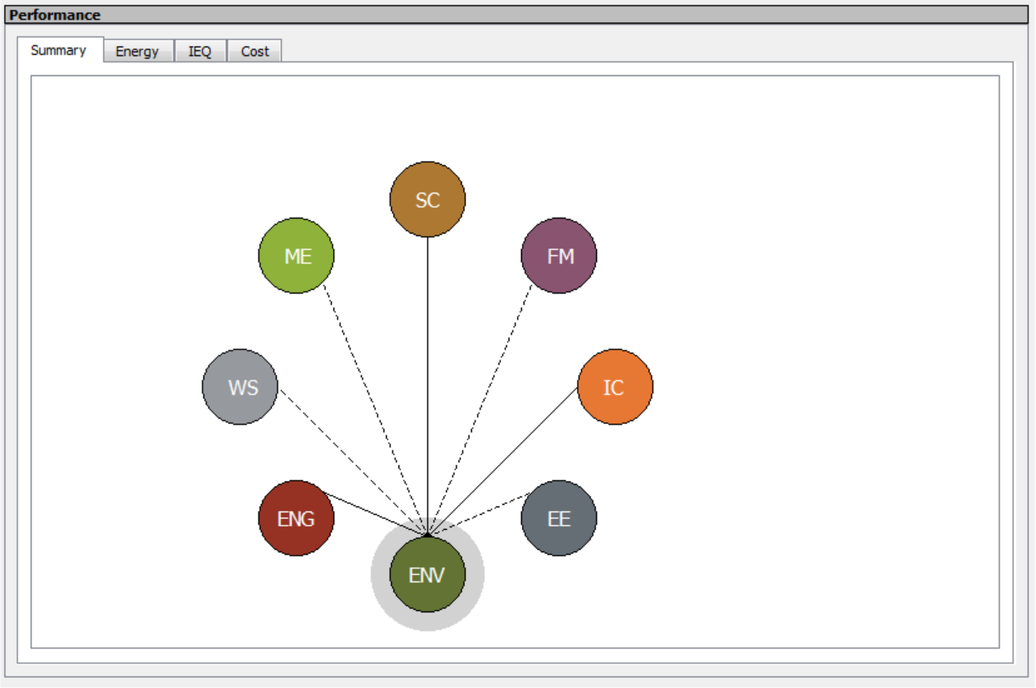


Figure 3.10 Design factor relationship map for the IAQ sub-performance aspect

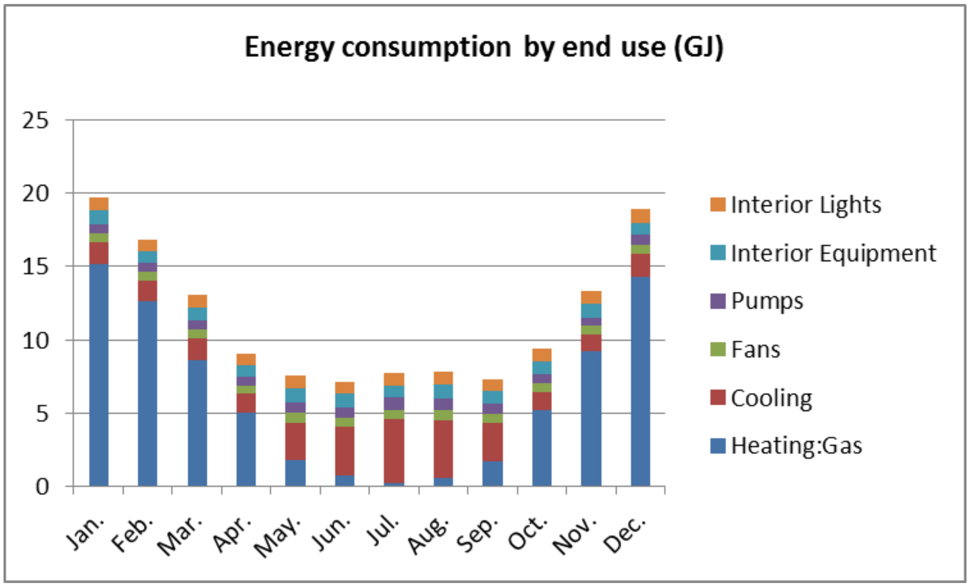


Figure 3.11 Sample of energy end use distribution in Performance Window

3.1.2. Reference building model (RBM)

Building energy codes and standards establish the minimum level of energy efficiency for residential and commercial buildings. They improve efficiency by mandating performance, achievable through careful construction and proper selection of building components, including insulation for both opaque elements and fenestration, SHGC (Solar Heat Gain Coefficient) for fenestration, HVAC equipment, and lighting power density and controls. Standards and guidelines like: “ANSI/ASHRAE Standard 55 (ASHRAE, 2017) - Thermal Environmental Conditions for Human Occupancy”, “ANSI/ASHRAE Standard 62.1-2019 (ASHRAE, 2019) - Ventilation for Acceptable Indoor Air Quality”, “ANSI/ASHRAE Standard 90.1-2019 (ASHRAE, 2019) - Energy Standard for Buildings except Low-Rise Residential Buildings” were used to develop the RBM.

NREL (NREL, 2011) also detailed the development of standard or reference energy buildings for the most common commercial buildings to serve as starting points for energy efficiency research. The models represented realistic typical building characteristics and construction practices. Fifteen commercial building types and one multifamily residential building were determined by consensus between DOE, NREL, PNNL, and LBNL, and represent approximately two-thirds of the commercial building stock.

The RBMs provided a common starting point to measure the progress of DOE energy efficiency goals for commercial buildings. The models of the reference buildings are used for DOE commercial buildings research to assess new technologies; optimize designs; analyze advanced controls; develop energy codes and standards; and conduct lighting, daylighting, ventilation, and indoor air quality studies.

In VDS, the RBM is a simplified version of the proposed design which is easy to draft yet can represent the performance of the proposed design. Based on this RBM, a simplified and scalable heat-flow based approach for optimizing the form, massing and orientation for HPB was developed (Chapter 4). It is defined as a building with a rectangular footprint, 0° orientation, and a 1.5 aspect ratio. Fenestrations are evenly distributed on all facades with an equal window-to-wall ratio (WWR) at 33%. It also shared the same total floor area, enclosure materials and assemblies, and HVAC systems with the proposed design. The zone settings of RBM are also the same as the proposed design. Table 3-1 shows the data sources for the design parameters in each group of the VDS RBM.

Table 3-1 Data sources for the design parameters in each group of the VDS RBM

Category	**Group**	**Data sources**
	Building type	Proposed design
Climate	Climate zone	Proposed design
	Heating and cooling design conditions	Proposed design
	Detailed climate conditions	Proposed design
	Atmosphere pollution	Proposed design
Site	Site location	Proposed design
	Building position	Proposed design
	Landscape and surrounding environment	Proposed design
Form		Proposed design and NREL reference building
Zoning	Program type	NREL reference building
	IEQ requirements	ASHRAE 62.1 and 55 and NREL reference building
	Occupancy	ASHRAE 62.1 and 55 and NREL reference building
	Lighting	ASHRAE 90.1 and NREL reference building
	Equipment	NREL reference building
	Pollutant source and sink	ASHRAE 62.1
	Initial pollution conditions	ASHRAE 62.1
Enclosure	Roof	ASHRAE 90.1 and NREL reference building
	Façade	ASHRAE 90.1 and NREL reference building
	Internal Assembly	ASHRAE 90.1 and NREL reference building

	Foundation and Basement	ASHRAE 90.1 and NREL reference building
HVAC	System type	ASHRAE 90.1
	Space conditioning	ASHRAE 90.1, and 62.1
	Air handling system	ASHRAE 90.1, and 62.1
	Water supply system	ASHRAE 90.1

3.2. MC - an integrated and coordinated process for performance-based building design

MC was developed as the core process module of VDS for supporting an integrated, coordinated, and optimized design of high-performance buildings from early to advanced design stages. As mentioned in section 3.1, the design process window in VDS presents the design stages, actors, design factors, associated tasks and schedule, and the input-process-output relationships among tasks. MC provides all functionalities and support for it to realize seamless transition among design stages, enhance multi-disciplinary coordination, and assist design factors integration through whole building performance analysis.

3.2.1. Introduction

Buildings consume a large share, approximately 39% of energy consumption in the United States, 40% in the European Union, and 20% in China. Today and future building designers face more challenges in practices, not only because of the stricter requirements and higher level of sustainable goals, but also from the complexity of the building design process itself:

- **Building design process covers multi-design stages**. As introduced in 2.2.1, it includes conception, planning, design, construction, operation, retrofitting, reuse or demolition and dis-assembly. The design considerations and goals need to be applied throughout the full life cycle of buildings.

- **Multi-disciplinary teams are involved in building design process**. Because green building design results from continuous, organized collaboration among multi-disciplinary design teams, it is quite important to allow all teams to realize their highest potentials while coordinating and integrating their contributions to the whole project.

- **Multi-design factors (systems) need to be integrated**. Very often factors are competing. For example, larger windows on the building envelope may improve the visual quality but may result in higher energy cost because of the air conditioning. Therefore, green building design calls for integration among all design factors. Their interactions and interdependencies need to be understood, evaluated, and appropriately applied.

Institutions, such as the American Institute of Architects (AIA), the National Institute of Building Science, have developed guidance on integrative design (American Institute of Architects, 2007). However, there is no systematic methodology to implement it. Software exit for either performance simulation or planning, none integrate both functions to support multi-disciplinary design team coordination and integrated energy and IEQ analysis throughout all design stages. MC was developed to overcome these hurdles.

3.2.2. Methodologies

3.2.2.1. 3D MC framework

The 3D MC (Figure 3.12) was developed to provide seamless transition among design stages, enhance multi-disciplinary coordination, and assist design factors integration through whole building performance analysis (Pelken, et al., 2013). The professional working stages can be translated into the five universal performance assessment stages as the first dimension of MC: assess, define, design, apply, and monitor. To provide flexibility in customizing each project set up, three core team categories have been identified as the second dimension of MC: architect design team, systems design team, and project management team. Nine design factors have been identified as key focus areas which constitute the third dimension of MC. The first eight factors target individual design consideration while the last manages the whole building system, they are site and climate, form and massing, external enclosure, internal configuration, environmental systems, energy systems, water systems, material use and embodied energy, and system interdependencies.

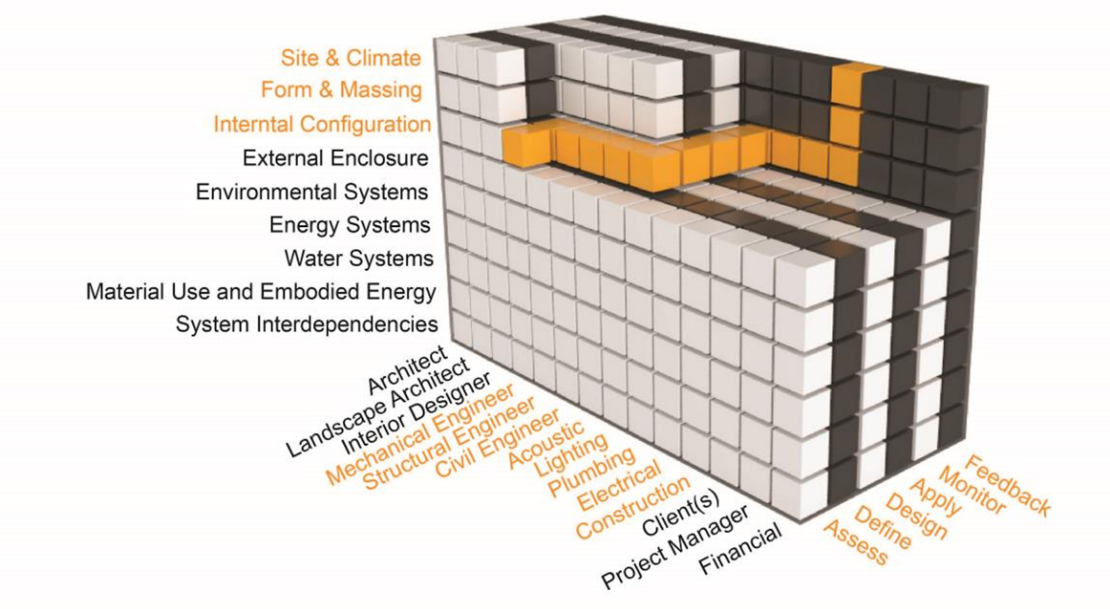


Figure 3.12 Three-dimensional “Magic Cube” matrix for VDS structure (Pelken, et al., 2013)

3.2.2.2. Design process representation

Task Definition - Within the 3D framework of MC, “Task” is proposed as the unit to represent the whole design process with attributes of the design stage, actor, factor, and interdependencies (process and information flow interdependencies). Each individual task is represented in “Input-Process-Output” pattern (Figure 3.13), composing of: necessary input (quantitative, qualitative, reference, and user-defined information) to support its execution; clearly stated actions need to be performed in order to complete the task; output information will be generated, which be used by next linked tasks (interdependencies). It is not yet realistic to quantify all the design factors (parameters) and simulate their impact on building performance. It is assumed that designers would consider both quantitative and qualitative factors (parameters) in green building design. Quantitative factors are accounted for by input parameters to the simulation models, while qualitative design factors can be used as guidance in design to estimate the possible whole building performance. In addition, for flexibility/customization considerations, references, and user-defined input are also considered in MC. References consist of any design helpful information that may be beneficial to share with all participated design members, like documentations, websites, etc. User-defined input serves as complementary parameters which are not processed by simulations, but useful to communicate among team members or consolidate all design information in one place.

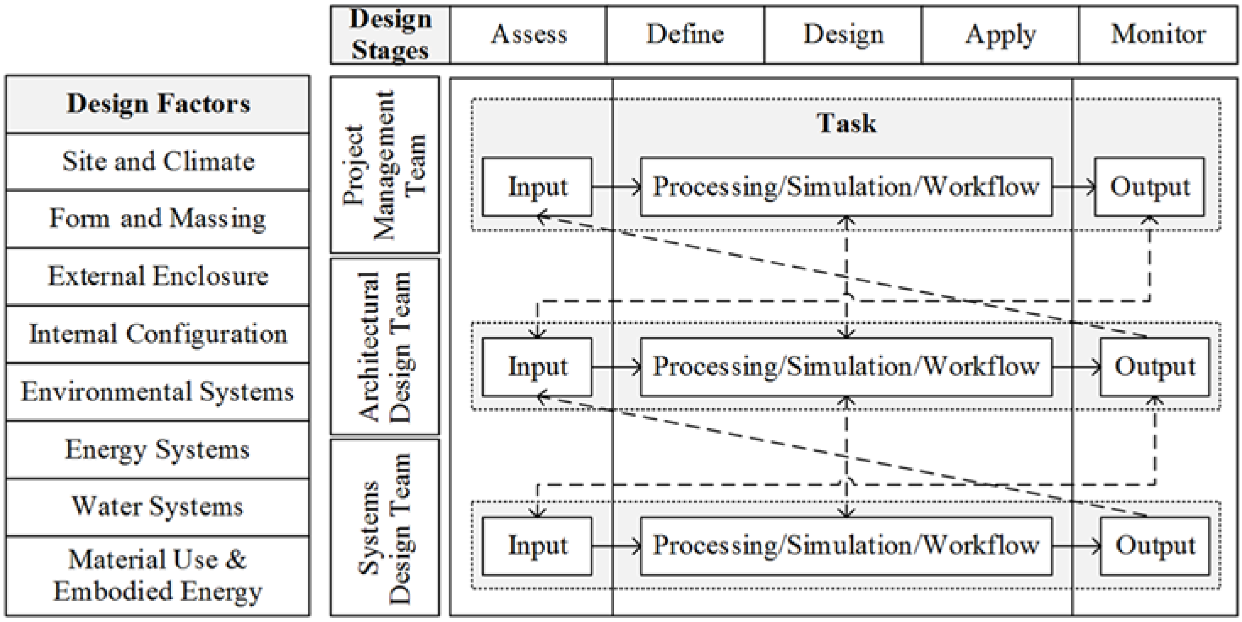


Figure 3.13 Input-Processing-Output methodology and feedback loops (Pelken, et al., 2013)

Easier Process Navigation and Management - composition and aggregation. In order to effectively organize the complex design process (besides the stage, actor, and factor attributes of each task), large scale tasks are systematically decomposed into several levels of smaller scale tasks from top to bottom, take external enclosure design as an example, it could be decomposed into smaller scale subtasks such as roof, façade, foundation, and hybrid enclosure design tasks. This hierarchical decomposition among all tasks help process navigation (high-level quick overview or focus on local detail) and management (divide the overwhelming amount of design inputs to tasks for involved actors at a given stage, filtering the unrelated/indirect information for execution of specific tasks). The same principle in reversed direction is used to aggregate the tasks as well as input/output from the bottom up to the top level. MC categorizes tasks into three levels according to scale and the decomposition and aggregation structure is shown in Figure 3.14:

- Root Task -- the largest scale task at the top/highest level. It is an aggregation of all "Tasks" or "Process Activities" that are associated with it.

- Task -- breaks down "Root Task" and performs a part of the "Root Task". It can be extended to as many levels as desired. It is an aggregation of lower level "Tasks" or "Process Activities" as well.

- Process Activity -- is the lowest level of the task and encapsulates the work level actions to be performed and connects to associate input/output variables. A well-defined "Process Activity" is a process step that has clear and tangible inputs generally described by physical or virtual documents, or data elements.

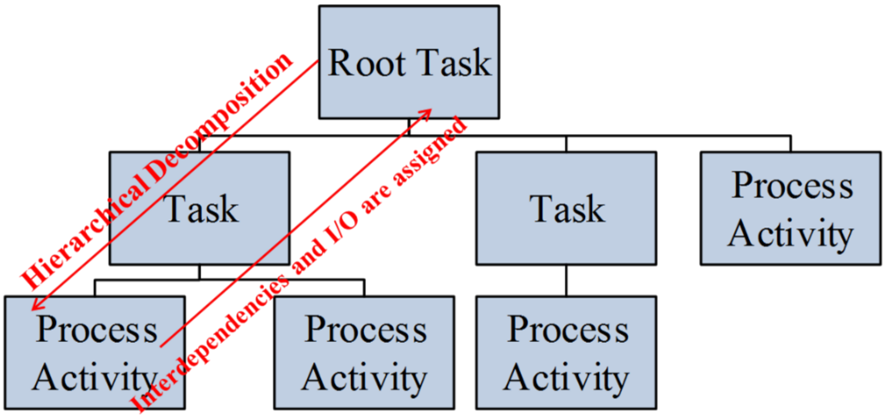


Figure 3.14 Task decomposition and aggregation principles (Meng, et al., 2014)

Seamless Transaction and Integration – interdependencies. In addition to the hierarchical decomposition of the design process, the task interdependencies are also built in the design process in terms of input and output. They are defined at the bottom level and all upper-level interdependencies are inferred from these base-level definitions.

As the example shown in Figure 3.15, there are totally three levels of process decomposition and two defined dependencies at the bottom level: process activity (PA221) depends on process activity (PA121) at level 2, and process activity (PA21) depends on process activity (PA122) (crosses level 1 and 2), respectively.

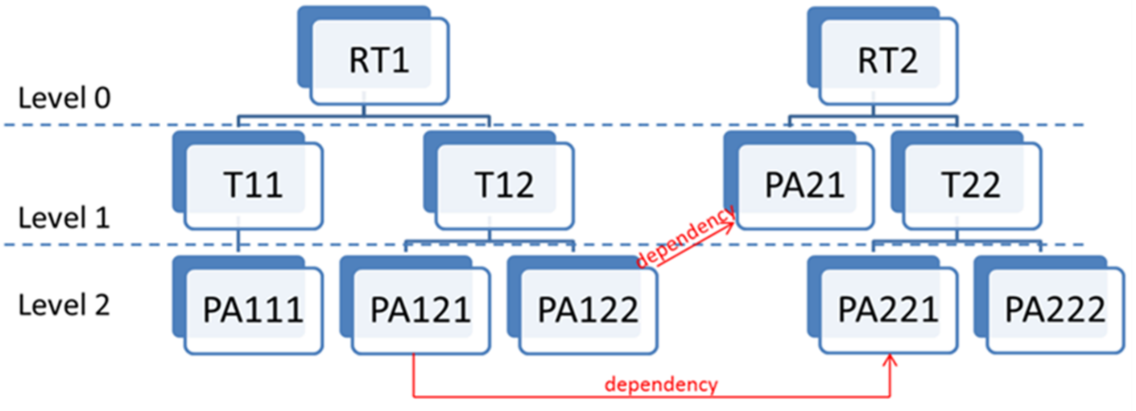


Figure 3.15 Task interdependencies definition and inferring methodology (Meng, et al., 2014)

In Figure 3.16, the process flows are grouped at different levels using the dependencies. In the level 0 process diagram, dependencies inferred from the lowest level showing that root task (RT2) depends on root task (RT1) because children of RT2 depends on children of RT1. Similarly, in the level 1 process diagram, task (T22) and process activity (PA21) depend on task (T12) because they depend on children of the task (T12).

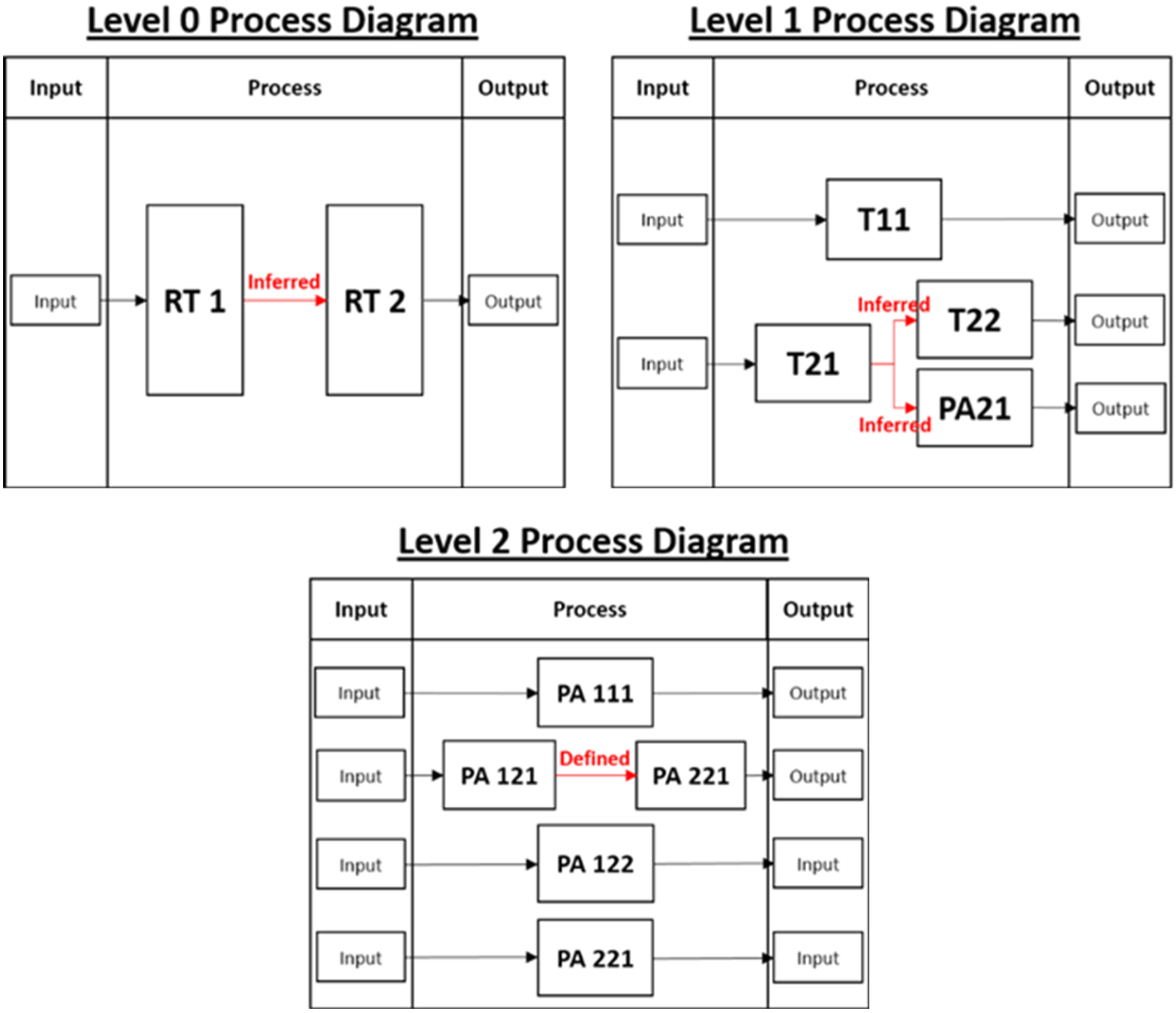


Figure 3.16 Multi-level task dependency diagrams/views (Meng, et al., 2014)

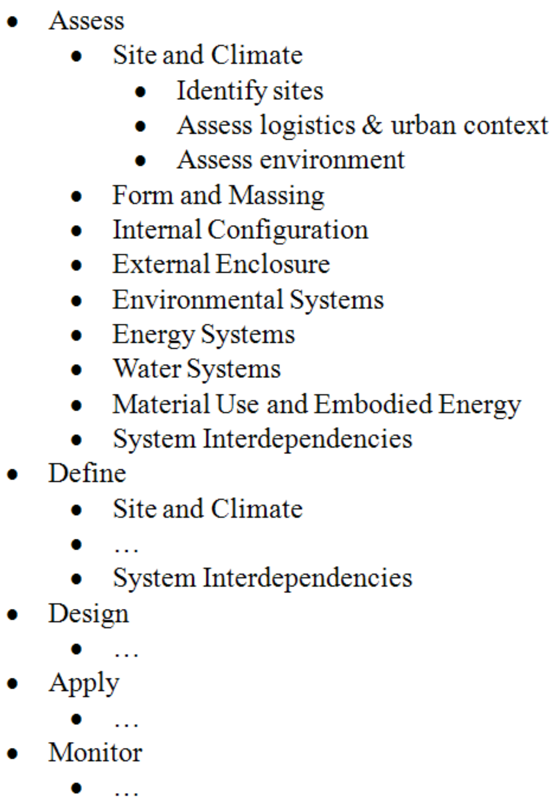
Built-in interdependencies of tasks facilitate not only the transaction among design stages in terms of data reuse, but also design intent and objective alignment. Firstly, the interdependencies connect the information flows. As the building design process is an evolving process, process activities performed within and among each stage provide ever-increasing data/information as it iterates over the design process. MC enables passing this kind of intrinsic inheritance of design data/information through all the design stages. It helps the users timely reuse the data/information generated by previously performed task(s) to complete the current design task. Secondly, the interdependencies serialize the workflow, so all involved teams have a holistic understanding of workflow. It greatly helps the alignments of design intents and objectives through the design stages. Design teams also have the option to either quickly scan through the high-level workflow diagram/view (level 0 in Figure 3.16) or dive into lower-level diagram/view with related work demands (level 2 Figure 3.16).

3.2.2.3. Design process visualization

The visualized design process template can help users understand and further utilize the information. Therefore, MC employed three formats of views to visualize the whole building design process from different angles. Each format has its own properties that directly help to achieve associated functionalities.

3.2.2.3.1. Navigation view

The tree structure is widely used to effectively represent a large set of hierarchical information. The MC design process which includes task decompositions and input/output aggregations also shares this hierarchical similarity with the tree structure. Therefore, tree view becomes the natural choice to represent the whole building design process. The tree view not only supports quick process navigation by hierarchically sorting tasks/process activities by design stages and factors, but also enables process management by task modification (Figure 3.17)



- Assess
    - Site and Climate
        - Identify sites
        - Assess logistics & urban context
        - Assess environment
    - Form and Massing
    - Internal Configuration
    - External Enclosure
    - Environmental Systems
    - Energy Systems
    - Water Systems
    - Material Use and Embodied Energy
    - System Interdependencies
- Define
    - Site and Climate
    - …
    - System Interdependencies
- Design
    - …
- Apply
    - …
- Monitor
    - …

Figure 3.17 Navigation view example

3.2.2.3.2. Process view

The process view represents the MC design process by process flow diagrams at multiple levels so users can visualize the design process in a very intuitive way. The process flow diagrams also indicate relationships between tasks and the input and output of each task. The starting point for this tab is the root level MC design flow diagram (Figure 3.18).

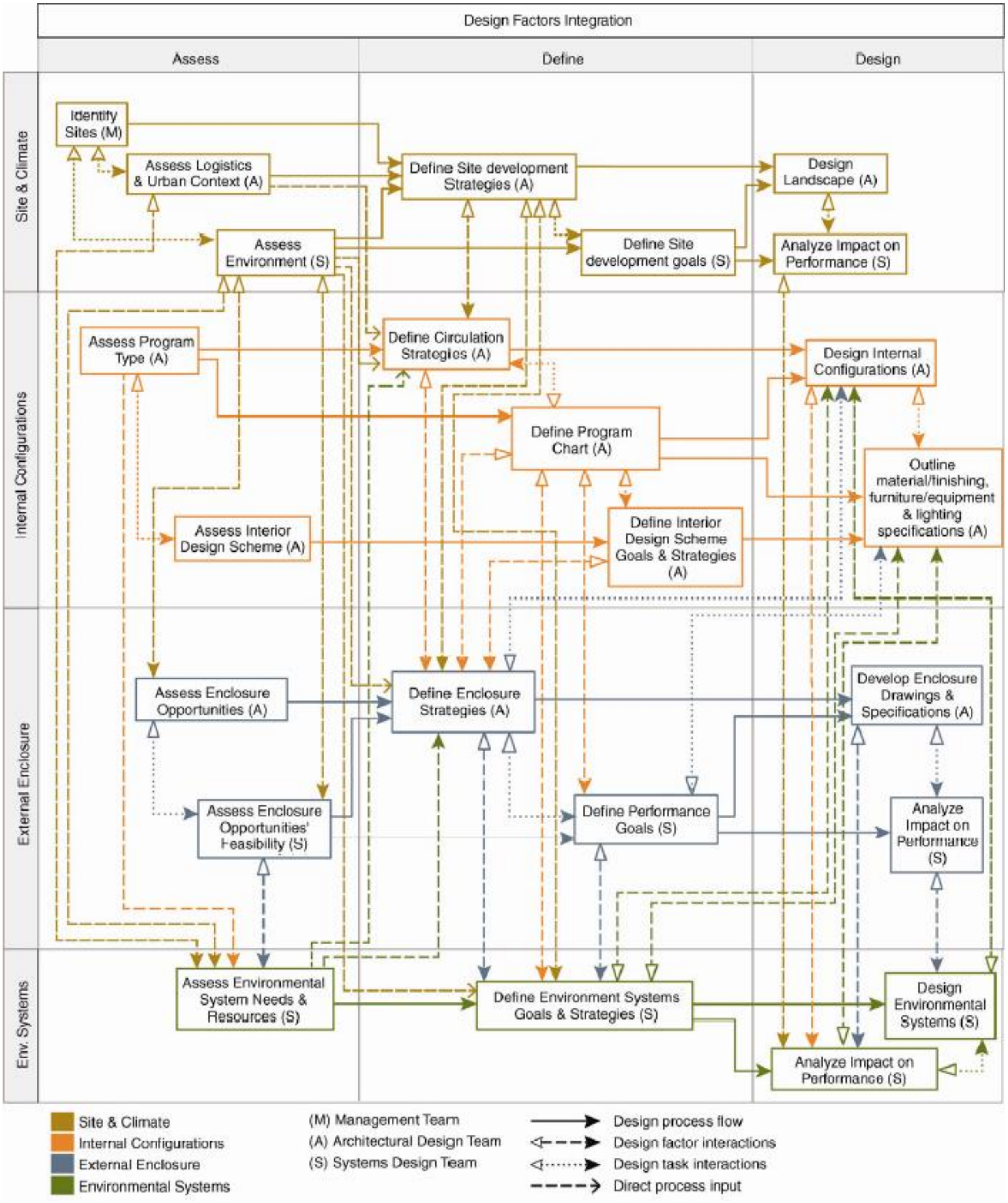


Figure 3.18 Root level MC design flow diagram (Pelken, et al., 2013)

If any task in the above design flow diagram is selected, the process view displays the process flow diagram starting from level 0. An example of “External Enclosure” design factor at the “Design” stage was used to illustrate the process view (Figure 3.19). This diagram presents how the input/process/output methodology is applied in the design process and how it guides the user to complete their design work.

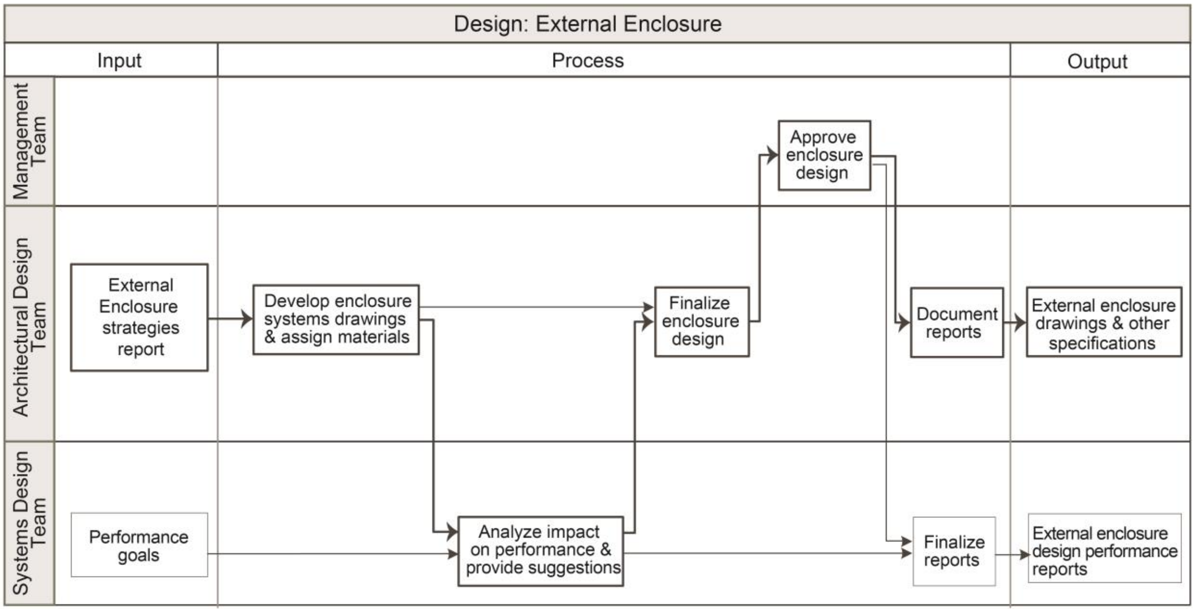


Figure 3.19 Process view format (Pelken, et al., 2013)

The design process diagram for the task (level 1) will be shown when the user selects one of the tasks on the diagram (level 0). The design team row where that task located will be expanded. For example, user clicks on “analyze impact on performance & provide suggestions” on THE previous example process diagram for external enclosure design at the root task level, then the next detailed level process diagram will show (Figure 3.20).

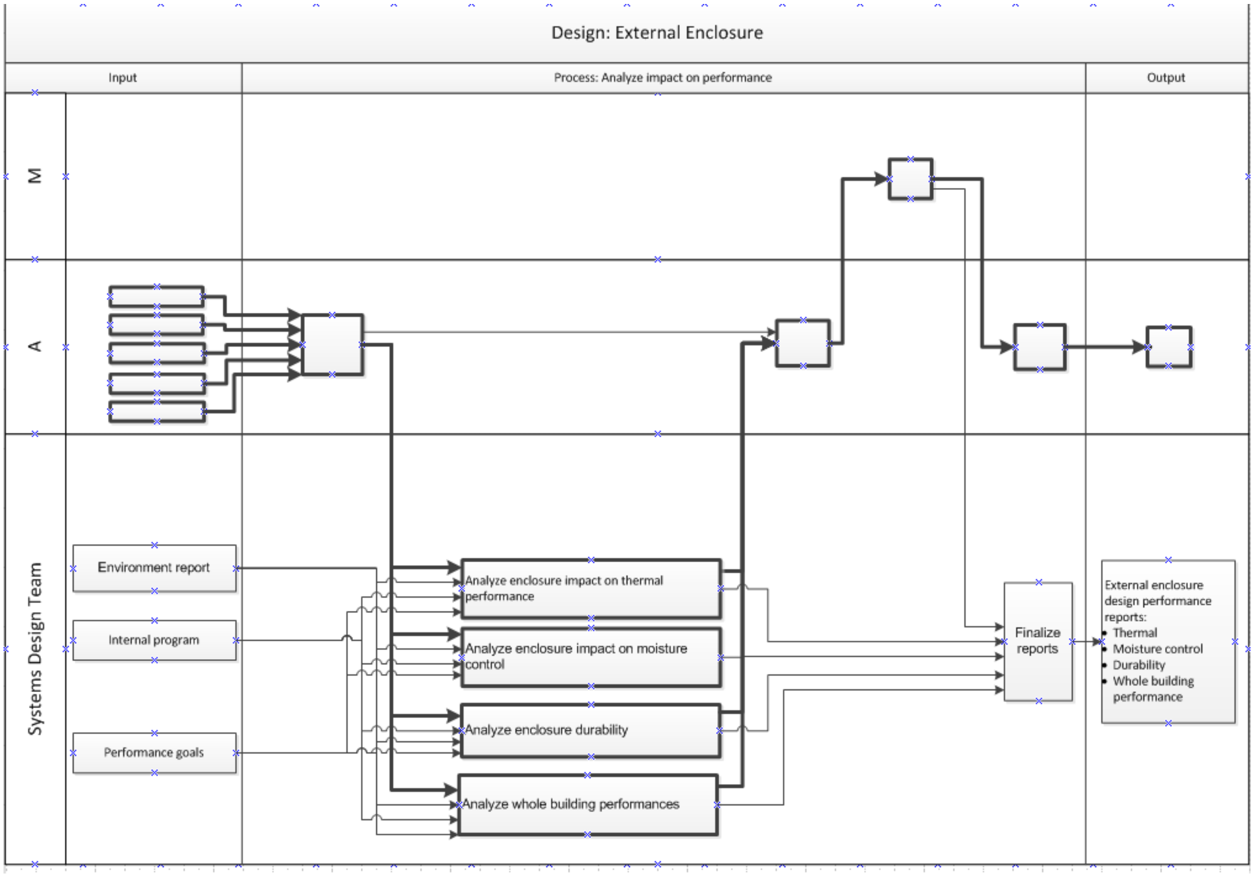


Figure 3.20 Design process diagram for task (level 1)

When the user keeps on clicking the process diagram for level 2 to n. The design process diagram for process activity (level 2 to n) will be shown as follows. For process diagram level 2 to n, only one row (one team) will be shown (Figure 3.21) to clearly elaborate all details.

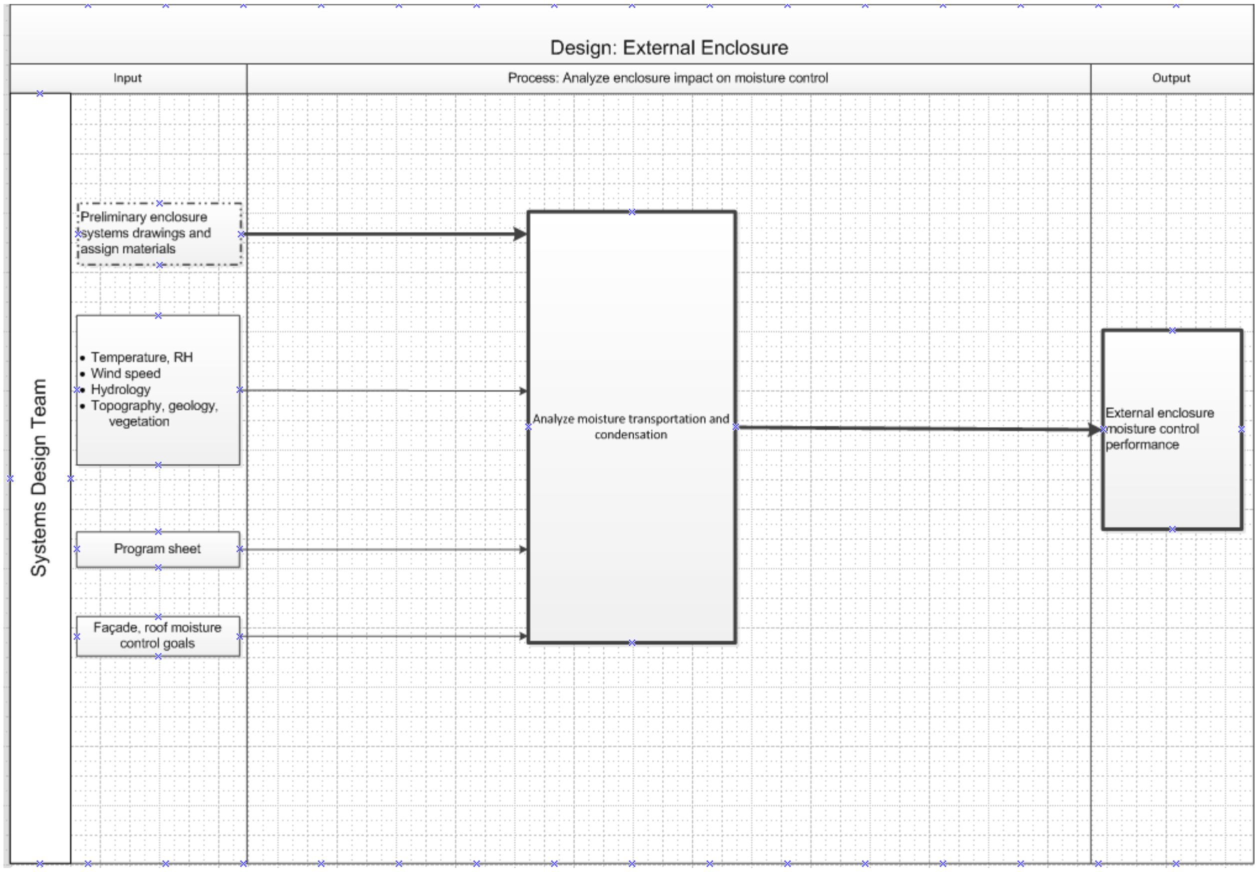


Figure 3.21 Design process diagram for process activity (level 2 to n)

3.2.2.3.3. Schedule view

This tab uses a Gantt chart to demonstrate the design process schedule that generated based on the process activities defined/customized in the Navigation view. It can help users to track the task progress and completion.

3.2.3. MC implementation

3.2.3.1. Data model

There are three major data models in VDS: the building structure data model, the MC process management data model, and the performance evaluation data model. Each of these three data models serves as its own functional requirements while coupling with the other data models to support whole VDS executions. This section focuses on the MC data model and its integration with building structure and performance data models.

3.2.3.1.1. MC data model

MC data model represents the design process including design stages, design factors, design actors, design tasks and their inputs and outputs, relationships between tasks, and task schedule (Figure 3.22). Class “CubeActivity” contains the basic attributes of the process is commonly inherited by three levels of tasks: “CubeRootTask”, “CubeTask” and “CubeProcessActivity”. “CubeTask” can be inherited by itself which gives opportunities to hold customizable multi-level task decomposition/aggregation properties in MC. “CubeProcessActivity”, the lowest action level process, defines actor, schedule information, various input and output information. “CubeDependsOn” is used to group detailed information and describe data flow and associated dependencies.

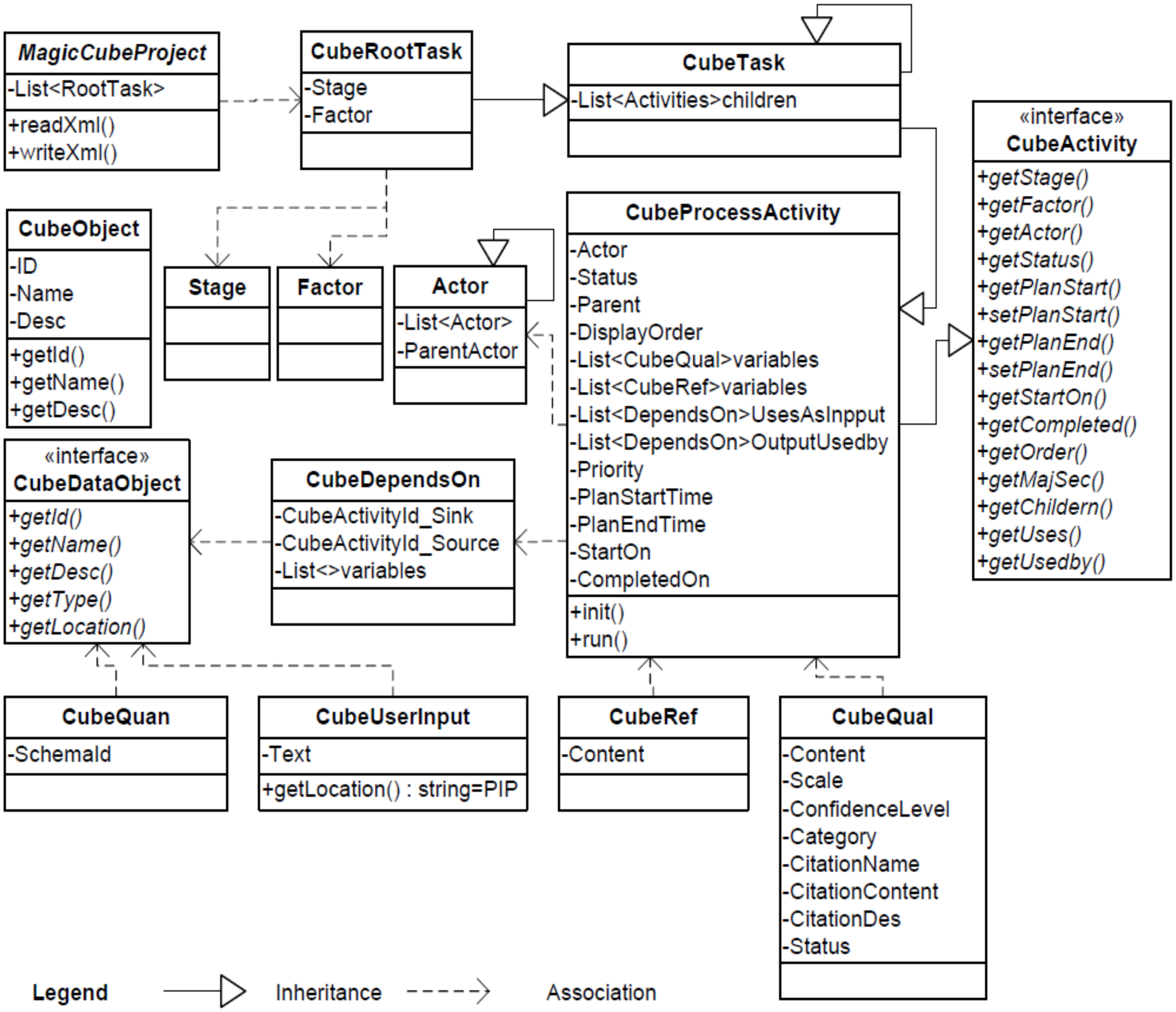


Figure 3.22 MC data model (Zhang, et al., 2013)

This data model enables the formation of the tree of design stages, factors and tasks that are decomposable to subtasks all the way down to the “Process Activity” (Figure 3.23).

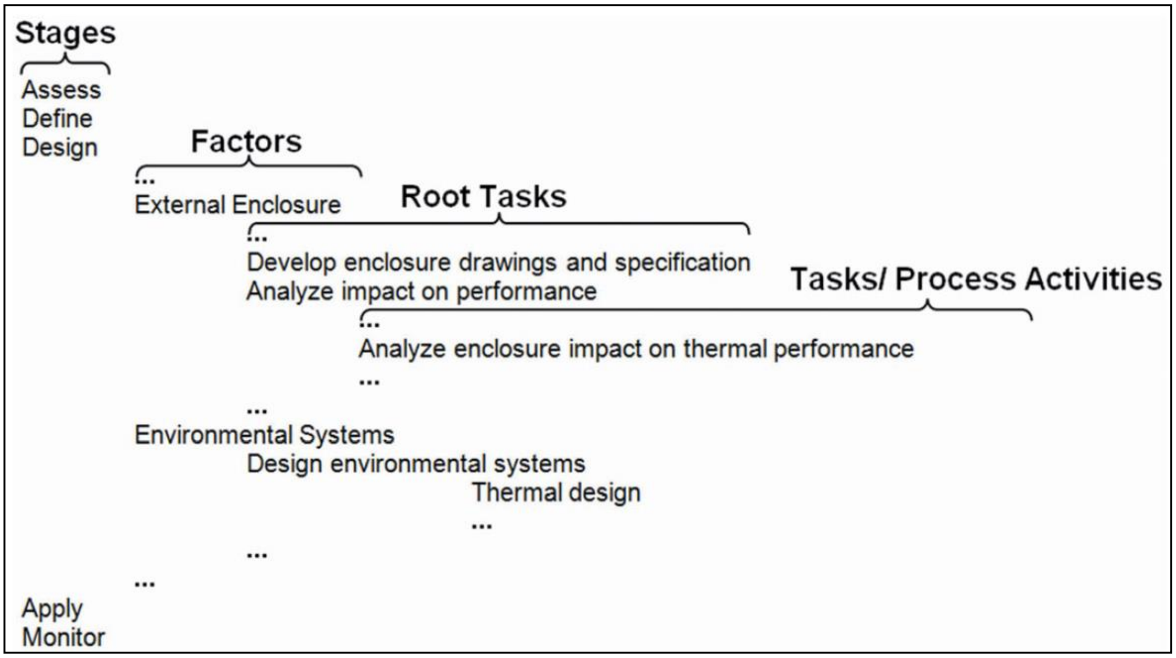


Figure 3.23 An example tree of stage, factor and tasks that are decomposed to subtasks until reaching the process activity level where all input and output parameters are defined (Zhang, et al., 2013)

The task decomposition feature allows users to define and manage tasks according to the wide variety of project needs vertically. The data model also enables the representation of the input-output dependencies between two different Process Activities.

3.2.3.1.2. Integration with VDS data model

MC design process data model couples with the building structure data model, performance evaluation data model, and other libraries to support executions of VDS. Intentions of VDS are reflected in the interactions among these three data models, such as information filtering and performance comparison supported decision making.

3.2.3.1.2.1. Integration with building structure data model

Building energy and IEQ simulations require a large amount of input information. All required inputs are allocated in the process activities throughout the entire design process and will be provided/assigned by the user along the design development. These simulations required quantitative building structure inputs will be passed from MC to VDS and displayed to the user in "Input Window" when that task/process activity is selected. In this way, the most helpful information can be provided to respective users regarding specific stage, factor, and task/process activity. As MC can't cover all quantitative inputs due to the uncertainties of various projects, MC added user-defined parameters that serve as complementary input in addition to building structure data model to help designers. The user-defined data are typically stored in document repository system independent of the building structure data model.

3.2.3.1.2.2. Integration with performance evaluation data model

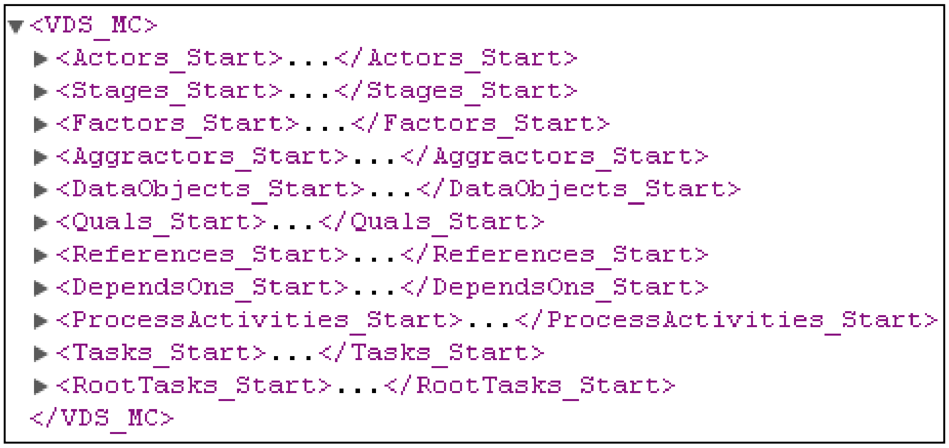
Besides the simulation required quantitative input, qualitative considered inputs are indispensable as it is not possible to quantify all the design factors and simulate their impact on the building performance. Like quantitative inputs, qualitative inputs referring from a knowledge-based qualitative library are assigned to process activities and will be passed to the "Input Window" when that task/process activity is selected. Qualitative inputs will share the information with the performance data model to support building performance evaluation.

3.2.3.1.2.3. Integration with References library

During the design process, references consist of any design helpful information that may be beneficial to share with all participated team members, it includes but is not limited to such formats: documentations, websites, etc. Each process activity also contains such reference information and displays it to users. References library is stored in MC.

3.2.3.1.3. Persistence data

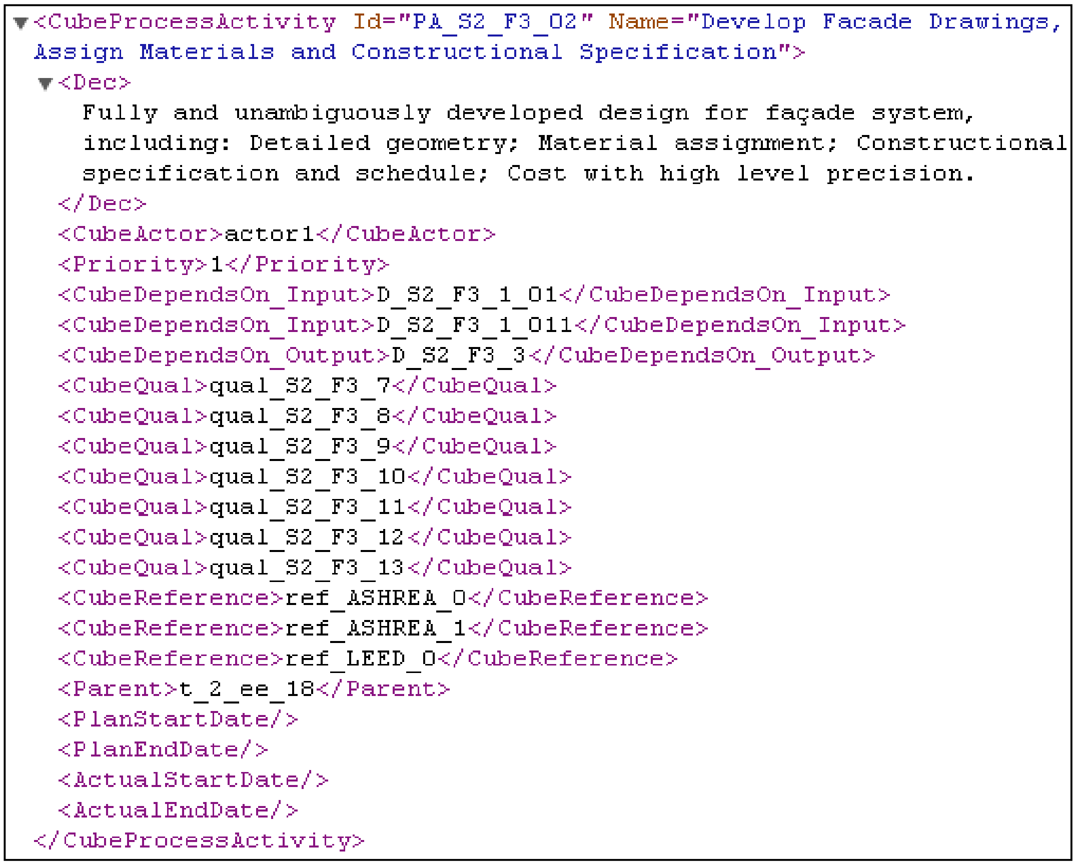
Widely used Extensible Markup Language (XML) is adopted by MC to save the design process template independent to VDS building structure data. Project template persistent data in MC starts with root tag <VDS_MC> and end with the same level end tag </VDS_MC>, all associated member data is listed as following tag groups (Figure 3.24).



```
▼<VDS_MC>
  ▶<Actors_Start>...</Actors_Start>
  ▶<Stages_Start>...</Stages_Start>
  ▶<Factors_Start>...</Factors_Start>
  ▶<Aggractors_Start>...</Aggractors_Start>
  ▶<DataObjects_Start>...</DataObjects_Start>
  ▶<Quals_Start>...</Quals_Start>
  ▶<References_Start>...</References_Start>
  ▶<DependsOns_Start>...</DependsOns_Start>
  ▶<ProcessActivities_Start>...</ProcessActivities_Start>
  ▶<Tasks_Start>...</Tasks_Start>
  ▶<RootTasks_Start>...</RootTasks_Start>
 </VDS_MC>
```

Figure 3.24 MC Project template persistence data architecture

Each member object has its unique ID, displaying name which is saved within a start-tag. Other attributes are saved as elements that data is between the start- and end-tags (Figure 3.25).

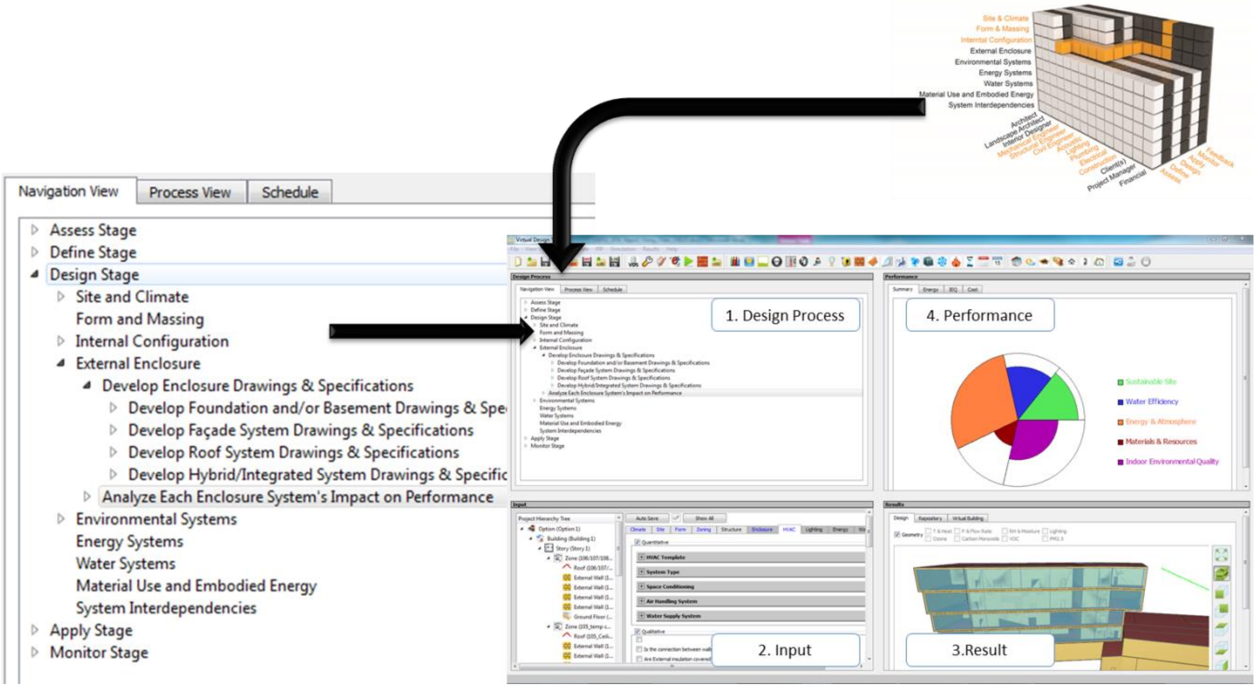


```
▼<CubeProcessActivity Id="PA_S2_F3_02" Name="Develop Facade Drawings,
 Assign Materials and Constructional Specification">
  ▼<Dec>
     Fully and unambiguously developed design for façade system,
     including: Detailed geometry; Material assignment; Constructional
     specification and schedule; Cost with high level precision.
   </Dec>
   <CubeActor>actor1</CubeActor>
   <Priority>1</Priority>
   <CubeDependsOn_Input>D_S2_F3_1_01</CubeDependsOn_Input>
   <CubeDependsOn_Input>D_S2_F3_1_011</CubeDependsOn_Input>
   <CubeDependsOn_Output>D_S2_F3_3</CubeDependsOn_Output>
   <CubeQual>qual_S2_F3_7</CubeQual>
   <CubeQual>qual_S2_F3_8</CubeQual>
   <CubeQual>qual_S2_F3_9</CubeQual>
   <CubeQual>qual_S2_F3_10</CubeQual>
   <CubeQual>qual_S2_F3_11</CubeQual>
   <CubeQual>qual_S2_F3_12</CubeQual>
   <CubeQual>qual_S2_F3_13</CubeQual>
   <CubeReference>ref_ASHREA_0</CubeReference>
   <CubeReference>ref_ASHREA_1</CubeReference>
   <CubeReference>ref_LEED_0</CubeReference>
   <Parent>t_2_ee_18</Parent>
   <PlanStartDate/>
   <PlanEndDate/>
   <ActualStartDate/>
   <ActualEndDate/>
 </CubeProcessActivity>
```

Figure 3.25 MC persistent member data example

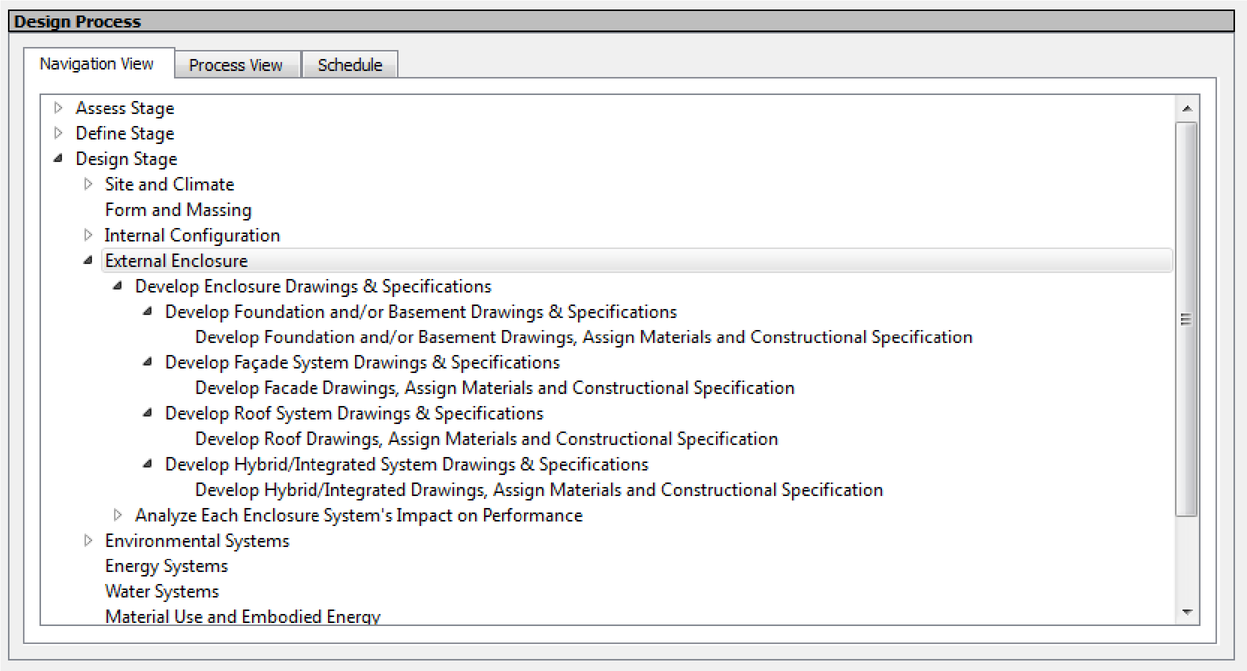
3.2.3.2. MC GUI

As introduced in section 3.1.1. MC GUI is in the “Design Process” window (upper left) as shown in Figure 3.26. This window includes a “navigation” tree (Figure 3.27) for task management (creation, deletion, and revision) as well as ease of navigation, a “process” page (Figure 3.28) for representing the relationships between tasks and the input and output of each task, and a “schedule” page (Figure 3.29) for tracking the task progress and completion. Figure 3.30 shows an example of the hierarchy of tasks and their associated inputs and outputs.



- Assess Stage
- Define Stage
- Design Stage
  - Site and Climate
  - Form and Massing
  - Internal Configuration
  - External Enclosure
    - Develop Enclosure Drawings & Specifications
      - Develop Foundation and/or Basement Drawings & Spe
      - Develop Façade System Drawings & Specifications
      - Develop Roof System Drawings & Specifications
      - Develop Hybrid/Integrated System Drawings & Specific
    - Analyze Each Enclosure System's Impact on Performance
  - Environmental Systems
  - Energy Systems
  - Water Systems
  - Material Use and Embodied Energy
  - System Interdependencies
- Apply Stage
- Monitor Stage

Figure 3.26 MC GUI in VDS



Design Process

Navigation View | Process View | Schedule

- Assess Stage
- Define Stage
- Design Stage
  - Site and Climate
  - Form and Massing
  - Internal Configuration
  - External Enclosure
    - Develop Enclosure Drawings & Specifications
      - Develop Foundation and/or Basement Drawings & Specifications
        - Develop Foundation and/or Basement Drawings, Assign Materials and Constructional Specification
      - Develop Façade System Drawings & Specifications
        - Develop Facade Drawings, Assign Materials and Constructional Specification
      - Develop Roof System Drawings & Specifications
        - Develop Roof Drawings, Assign Materials and Constructional Specification
      - Develop Hybrid/Integrated System Drawings & Specifications
        - Develop Hybrid/Integrated Drawings, Assign Materials and Constructional Specification
    - Analyze Each Enclosure System's Impact on Performance
  - Environmental Systems
  - Energy Systems
  - Water Systems
  - Material Use and Embodied Energy

Figure 3.27 Navigation View in Design Process Window

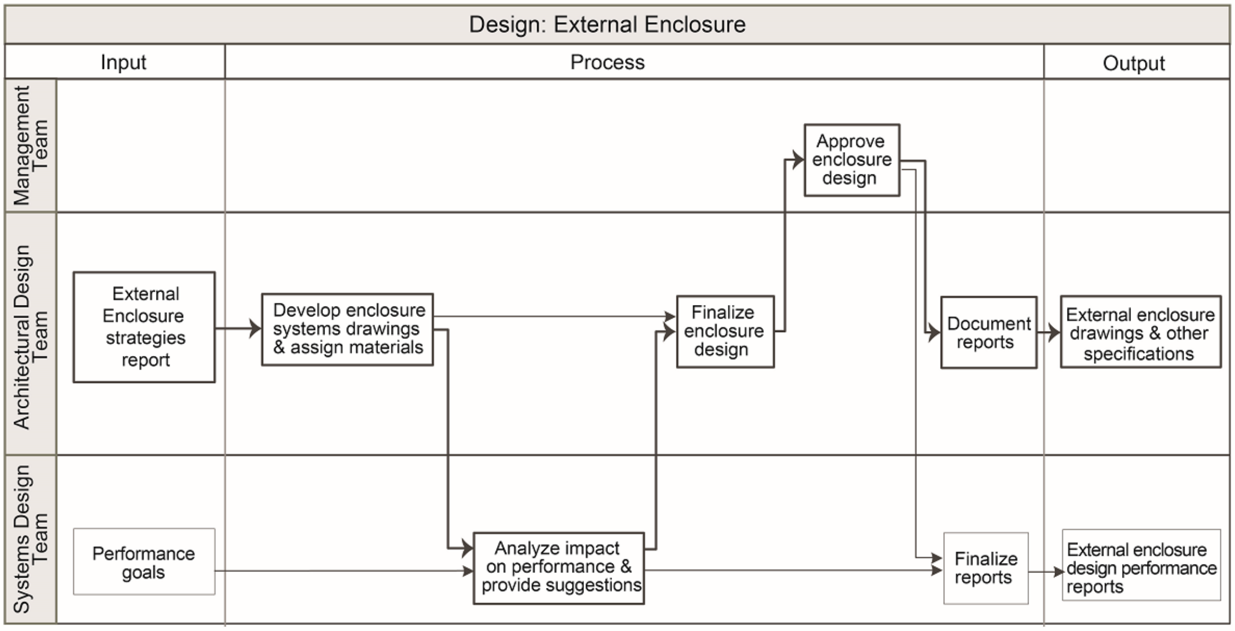
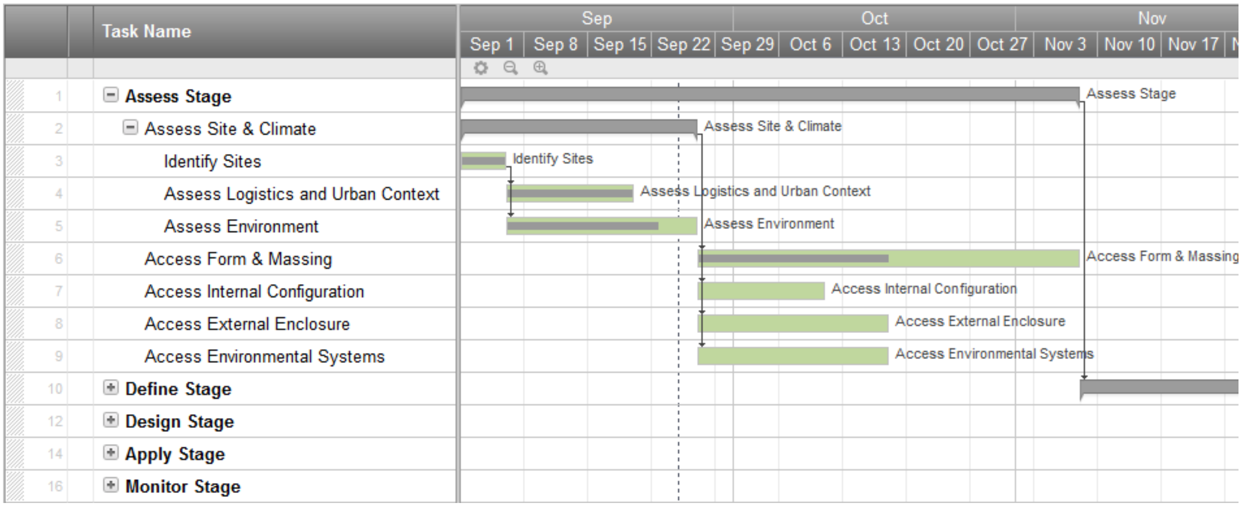
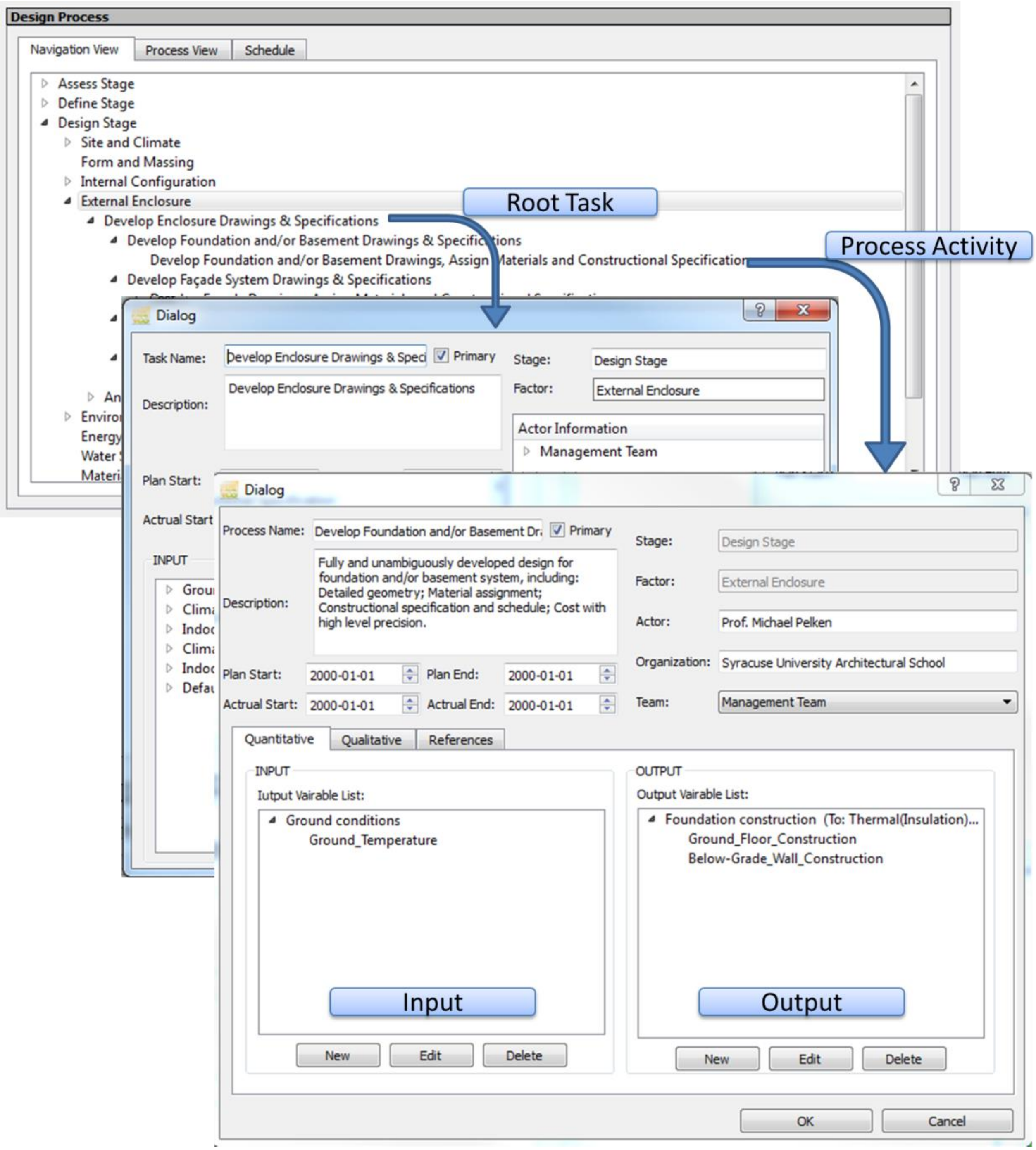


Figure 3.28 Sample of Process View in Design Process Window (Pelken, et al., 2013)



	Task Name
1	⊟ **Assess Stage**
2	⊟ Assess Site & Climate
3	Identify Sites
4	Assess Logistics and Urban Context
5	Assess Environment
6	Access Form & Massing
7	Access Internal Configuration
8	Access External Enclosure
9	Access Environmental Systems
10	⊞ **Define Stage**
12	⊞ **Design Stage**
14	⊞ **Apply Stage**
16	⊞ **Monitor Stage**

Figure 3.29 Sample of Schedule View in Design Process Window



Design Process

Navigation View

- Assess Stage
- Define Stage
- Design Stage
  - Site and Climate
  - Form and Massing
  - Internal Configuration
  - External Enclosure
    - Develop Enclosure Drawings & Specifications
      - Develop Foundation and/or Basement Drawings & Specifications
        - Develop Foundation and/or Basement Drawings, Assign Materials and Constructional Specification
      - Develop Façade System Drawings & Specifications

Task Name: Develop Enclosure Drawings & Speci ☑ Primary

Stage: Design Stage

Description: Develop Enclosure Drawings & Specifications

Factor: External Enclosure

Actor Information

- Management Team

Process Name: Develop Foundation and/or Basement Dr ☑ Primary

Stage: Design Stage

Description: Fully and unambiguously developed design for foundation and/or basement system, including: Detailed geometry; Material assignment; Constructional specification and schedule; Cost with high level precision.

Factor: External Enclosure

Actor: Prof. Michael Pelken

Organization: Syracuse University Architectural School

Plan Start: 2000-01-01

Plan End: 2000-01-01

Team: Management Team

Actrual Start: 2000-01-01

Actrual End: 2000-01-01

INPUT

Iutput Vairable List:

- Ground conditions
  - Ground_Temperature

OUTPUT

Output Vairable List:

- Foundation construction (To: Thermal(Insulation)...
  - Ground_Floor_Construction
  - Below-Grade_Wall_Construction

Figure 3.30 Hierarchy of tasks and their associated inputs and outputs

3.2.4. Case study and discussions

This section illustrates, comparing to the traditional design process, how the coordinated and integrated MC method could be applied to achieve a high-performance green office building design. A LEED Platinum rated, the Syracuse CoE Headquarters building that was built prior to the present study was used as a case study building. A series of interacted tasks from corresponding multi-design factor process flow for different design teams were established. These tasks effectively guide all members (with different backgrounds) navigate through the whole project, align their design intents, therefore facilitate collaborations. Design factor integration analyses were performed by process coupled performance simulations for multiple systems design.

In this section, an overview of the case building and its green building features were categorized according to the design factors and performance aspects defined in MC and VDS. Then, the MC integrated and coordinated design process is elaborated on by the explanation of a series of inter-connected "tasks", each of which is represented in the form of the established "Input-Process-Output" pattern. The illustration is limited to major tasks for selected factors at certain design stages. It intends to cover the frequently encountered analyses in performance-based building design. Lastly, selected design options are analyzed for each of the design factors in terms of their impact on energy and IEQ performance. The performance evaluation model introduced in early sections was used to compare the various possible designs with that of the reference building defined for the case building.

3.2.4.1. Overview of the case building and its green design features

The LEED Platinum Certified Syracuse CoE Headquarters building (Table 3-2) is a testbed for environmental and energy technologies and building innovations (Figure 3.31). It includes an array of green building features that can significantly reduce its energy consumption while providing a high level of indoor environmental quality. Selected green features of CoE headquarters building (Syracuse Center of Excellence, 2021) are classified systematically according to all VDS design factors and performance aspects mentioned in Table 3-3. Some of the features are associated with multiple factors and/or multiple performance aspects, indicating the interdependencies among design factors and their combined effects on the overall building performance. For example, hybrid ventilation, daylighting, etc.

Table 3-2 Overview of Syracuse CoE Headquarters building

Cost	$41 million (funded from state and private sources)
Size	55,000 square feet
Location	727 E. Washington Street, Syracuse, NY, 13210. The three-acre site on the corner of Almond and Washington streets is a designated “brownfield”, the former site of the LC Smith typewriter factory and Midtown Plaza. (Latitude: N 43° 3.0', Longitude: W 76° 8.5')
Number of Stories	5 Stories (Height75’)
LEED Rating	Platinum
Program	Offices; Classrooms; Public spaces; Indoor environmental quality (IEQ), Biomass fuel and other Research Laboratories.

Figure 3.31 South façade of Syracuse CoE Headquarters building

Table 3-3 CoE green features classified according to the VDS design factors and performance aspects

	Site sustainability	Water Efficiency	Energy and atmosphere	Materials and resources	Indoor environmental quality
Site and Climate	• "**Brownfield Remediation** - Environmental contamination associated with previous industrial site uses was remediated, restoring the site for sustained use by future generations." • "**Landscape Design** - Large sloping landforms provide a dynamic reflection of the building, as well as a means for safely encapsulating contaminated soil instead of shipping it to a distant landfill." • **Green Roof** - Plantings on the laboratory roof reduce the heat island effect.	• **Water Tank** - Rain and meltwater are collected from the roof and used to flush toilets, reducing both the consumption of drinkable water and the amount of water that is discharged to the sewer. • "**Stormwater Retention Tank** - The southwest corner of the property features a storm water retention tank to control run-off entering the sewer system." • **Green Roof** - Plantings on the laboratory roof provide rainwater retention.	• **Geothermal Pipes** - Heat exchanged with the ground helps heat the building in the winter and cools it in the summer, saving about 35% of energy compared to traditional systems. • **Easy access by occupants & visitors** - less emission due to transportation. • Wind and thermal buoyancy for natural ventilation.	• **Sustainable Construction Practices -** The construction team diverted 98% of construction waste from going to a landfill.	• **Urban Ecosystem Observatory** - The 150-foot Urban Ecosystem Observatory tower assess Syracuse's urban air quality, air flow, and how outside air affects air quality inside a building.
Form and Massing	• "**Building Shape and Form** - The building is relatively narrow, reducing brownfield site disturbance and excavation."		• "**Building Orientation** - To optimize the building's southern exposure in order to avoid solar energy drain during the colder months, the tower portion of the building is rotated 13-degrees from the urban street grid."		• **"Building Shape and Form -** The building is relatively narrow, with extensive windows providing a high level of occupant comfort with ample natural light and opportunities for views and natural ventilation."

Internal Configuration		• **Restrooms** feature waterless urinals, dual flush low-flow toilets and faucets.	• "**Lighting** - High efficiency compact fluorescent and LED lighting, controlled by a daylight harvesting (auto dimming) system and auto shut-off occupancy sensors, are used throughout the building." • Layout that facilitates different zone temperature settings	• **Restrooms** feature sustainable paper and cleaning products. • "**Furniture** made from recycled materials and FSC wood and wood products. Furniture is also 100% recyclable by the manufacturers upon return." • "**Regenerative Elevator** – The elevator generates electricity on the way down, which can then be used for going back up, used elsewhere in the building, or fed back into the grid."	• "**Open office configuration** allows for maximum daylighting, air circulation, and enhanced views." • **Green Roof** - Plantings on the laboratory roof, made up of six different varieties of sedum, provide a visible connection to nature.
External Enclosure	• Visual quality in the neighborhood (as a piece of urban fabric)	• **Green Roof** - Plantings on the laboratory roof provide rainwater retention.	• "**Insulation** - Solid façades include superior insulation to reduce heating and cooling loads." • **Windows -** The south façade features highly insulated glass with integrated electronically controlled blinds that provide solar heat and glare control. The ceramic white dots on the windows passively reduce glare and solar heat gain. • "**Roof** - The building roof is designed to reflect most of the sunlight, minimizing solar heat gain and reducing the cooling load. The roof is also designed to allow future installation of photovoltaic, building-scale wind turbines, and roof top HVAC units." • **Hybrid ventilation system** - Manual windows are provided to allow for	• "**Insulation** - Interior insulation uses 100% soy-based spray foam. Exterior insulation boards were created from sustainable natural fiber materials.	• "**Vapor Intrusion System** - Ventilation below the foundation prevents underground vapors from entering the building, eliminating a potential source of contaminants in indoor air."

			natural ventilation throughout the building.		
Environmental Systems			• "**Radiant Ceilings** - Most of the heating and cooling in rooms is provided via ceiling panels that are embedded with copper piping that efficiently carries warm or cool water." • **Demand-Controlled Ventilation** - The amount of fresh air delivered to a room varies depending on the number of people who are present, saving energy when rooms are partially occupied. • "**Underfloor Heating** - Hot water is circulated through tubes embedded in the lobby floor to provide efficient heating. • "**Underfloor Ventilation and Raised Flooring** - raised floor system, allowing for even air distribution with lower fan speeds." • **Energy Recovery Ventilator** - exchanges heat and moisture between outgoing and incoming air streams, significantly reducing the amount of energy required to condition incoming air. • **Geothermal Pipes** - Heat exchanged with the ground helps heat the building in the winter and cools it in the summer, saving about	• Use local supplier's manufactured mechanical systems such as: boiler and heat pumps to reduce the embodied energy use.	• "**Underfloor Ventilation and Raised Flooring** - Ventilation is provided close to occupants for improved thermal comfort using a raised floor system, allowing for even air distribution with lower fan speeds. The Tate raised floor system, situated 12 inches above the concrete deck, and also provides convenient wire routing." • **Demand-Controlled Ventilation** - The amount of fresh air delivered to a room varies depending on the number of people who are present, saving energy when rooms are partially occupied.

			35% of energy compared to traditional systems. - Use high efficiency boilers.		
Energy Systems			- "**Solar Power Prototype -** the building-integrated concentrating photovoltaic system tracks the motion of the sun and uses lenses to concentrate sunlight 500 times, generating both electricity and heat."		
Water Systems		- **Water Tank** - Rain and meltwater are collected from the roof and used to flush toilets, reducing both the consumption of drinkable water and the amount of water that is discharged to the sewer. - "**Storm Water Retention Tank** - The southwest corner of the property features a storm water retention tank to control run-off entering the sewer system." - **Green Roof** - Plantings on the laboratory roof provide rainwater retention.			
Material Use and Embodied Energy				- Recycled materials made furniture, carpet - Exterior insulation boards were created from sustainable natural fiber materials. - Use local supplier's manufactured mechanical systems such as: boiler and heat pumps to reduce the embodied energy use. - "**Structure** - The use of substantial cantilevers in the steel structure on the north,	

				south, and west sides of the building reduce the number of columns, overall steel tonnage, and required footings for the building.”	

3.2.4.2. Scope and approach

This section shows how the multi-disciplinary design teams could achieve a low energy and high IEQ building design with the MC and VDS supports, from conceptual to detailed design stage, while considering the interaction of multi-design factors and their combined effects on the building performance. The illustrations will be limited to the following scope:

- Three design stages: “Assess”, “Define” and “Design”;
- Five design factors: “Site and climate”, “Form and Massing”, “Internal Configuration”, “External Enclosure”, and “Environmental Systems”.

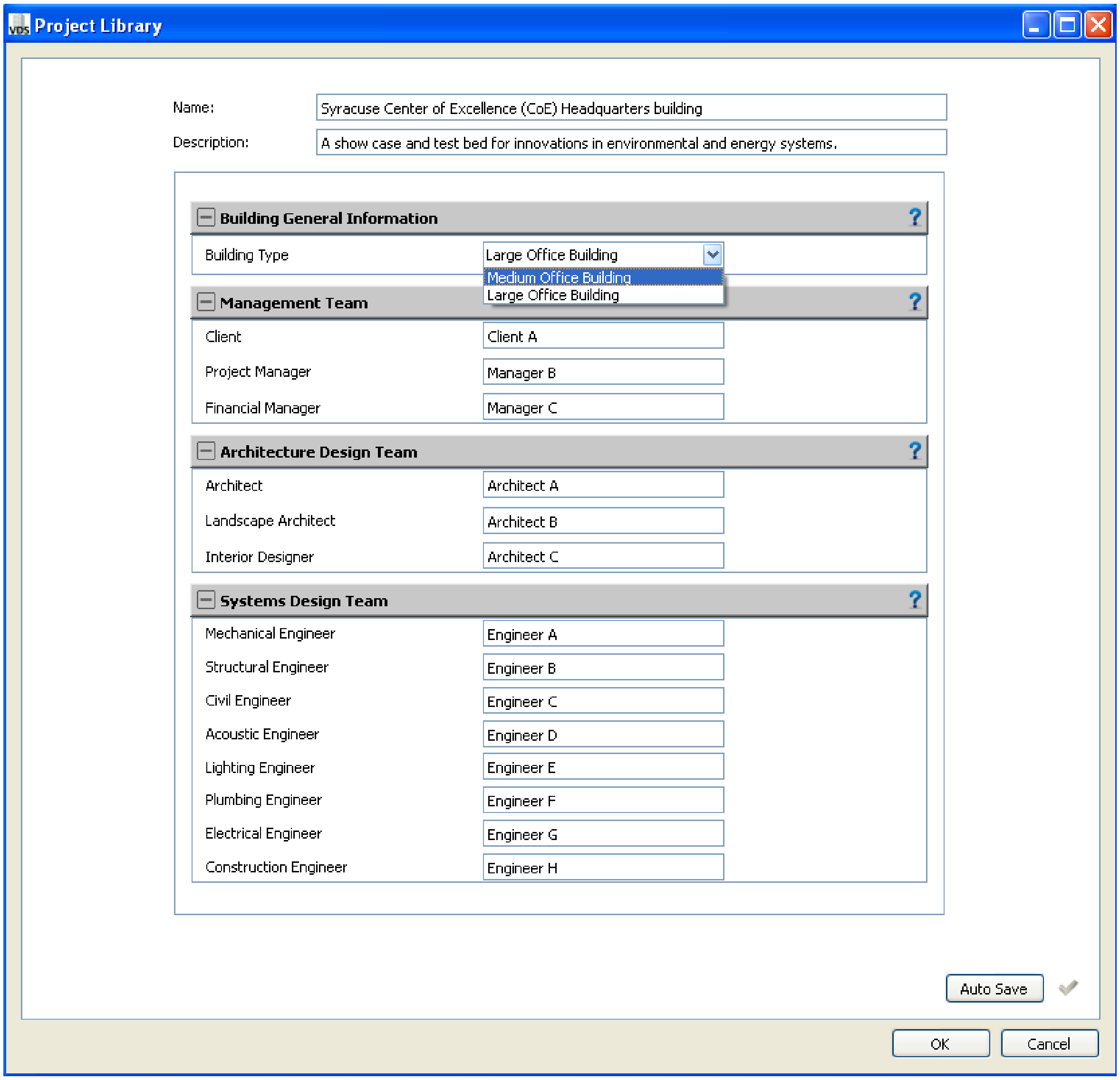
Five performance aspects introduced section 2.3 will be evaluated. The evaluation results will support decision making and further design development. The overall qualitative evaluation will be performed first to illustrate the usage of MC for systematic consideration of different design factors. Where applicable, the quantitative simulation will be performed with results that are intended to support the decision-making process for the building design and component development.

3.2.4.3. Design process and definition of tasks

3.2.4.3.1. Design process overview

The CoE building is meant to be a showcase and create a testbed for innovations in building integrated environmental and energy systems. Programmed spaces mainly include offices, semi-public spaces for meetings and conventions, and laboratories. With these general project objectives and space functionality requirements in mind, the first task for the management team is to set up the design process, determine the required team configuration and develop a work plan including tasks and schedule for the project.

As introduced in section 3.2.2, MC is organized by design teams, factors, and stages. Two of these three dimensions - design factors and design stages have been defined in the scope section for this illustration. For each new project, designers also need to provide basic building information such as building type, size, location, and required function, and assign tasks to team members according to the project type and procurement. MC provides a project setup window to input this information (Figure 3.32). For the illustration, building type “medium office” is selected for the CoE project. This selection will directly impact a series of default parameter settings for the RBM as introduced in section 3.1.2. Each of the three teams (management, architect, and system design) can be further divided for more specific roles. For example, the architect team may be further divided to represent architect, landscape architect, and interior designer. The team configuration may vary depending on project type, scale, and other requirements. The template offers opportunities to customize team configuration, but it is not necessary to specify each role for every project.



Name: Syracuse Center of Excellence (CoE) Headquarters building

Description: A show case and test bed for innovations in environmental and energy systems.

Building General Information

Building Type	Large Office Building

Management Team

Client	Client A
Project Manager	Manager B
Financial Manager	Manager C

Architecture Design Team

Architect	Architect A
Landscape Architect	Architect B
Interior Designer	Architect C

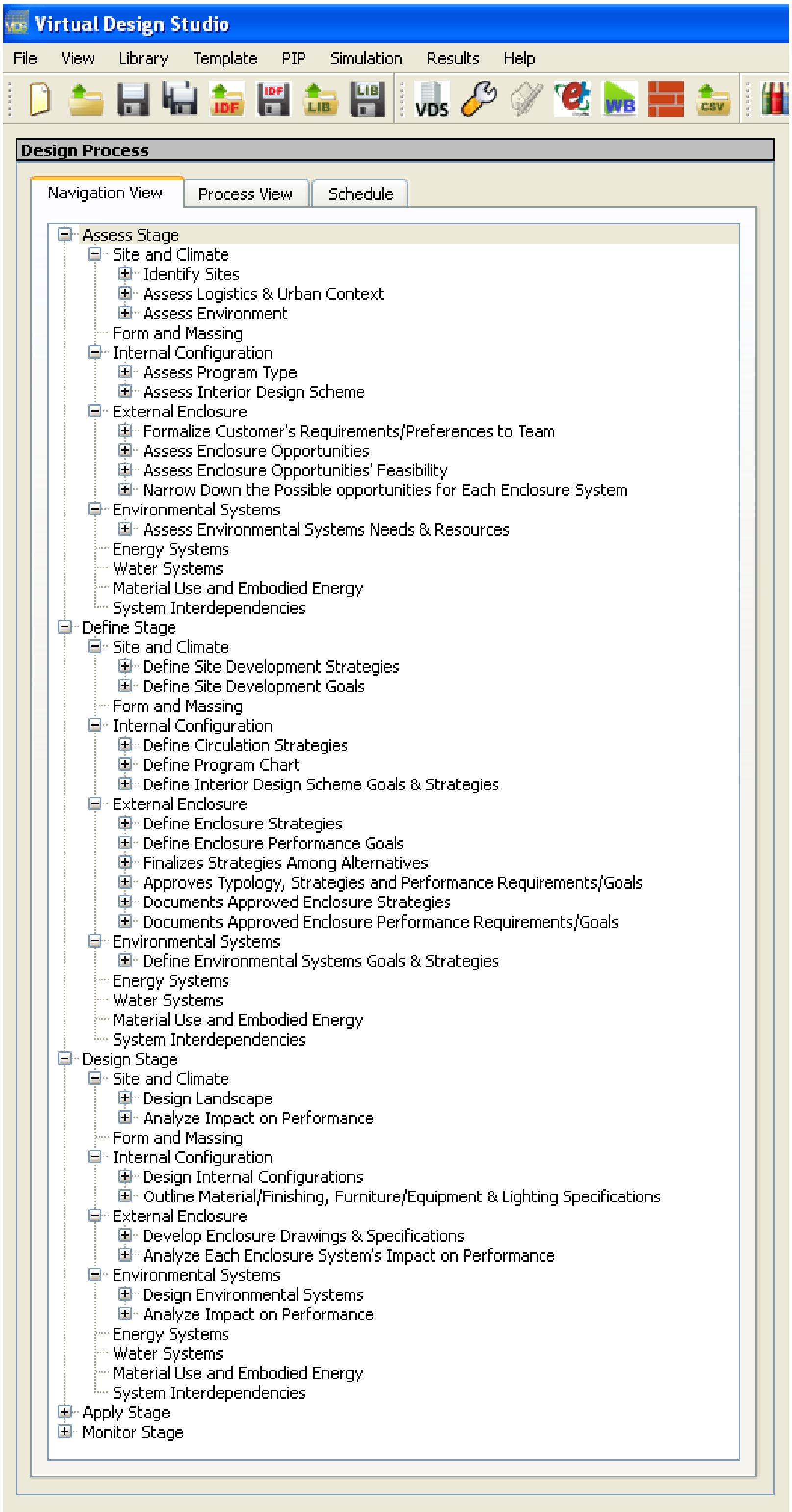
Systems Design Team

Mechanical Engineer	Engineer A
Structural Engineer	Engineer B
Civil Engineer	Engineer C
Acoustic Engineer	Engineer D
Lighting Engineer	Engineer E
Plumbing Engineer	Engineer F
Electrical Engineer	Engineer G
Construction Engineer	Engineer H

Figure 3.32 Project setup window

Once project type and team configurations are specified, it is the next task to set up the building design process in terms of tasks for each design stage. In the MC context, the management team in consultation with the architect and systems design teams is presumed to specify all the major tasks that need to be completed at the various design stages according to the various relevant design factors. The MC provides a framework for task planning, monitoring, and coordination throughout the design and systems development.

The scheduled tasks for the hypothetical CoE building design process are presented in a tree view in the MC “process window” (Figure 3.33). An overarching process diagram that corresponds to all design processes is shown in Figure 3.34. In addition to the scheduled individual tasks and the process flows (solid lines connecting the tasks), the anticipated team interactions and possible interdependencies between different design factors are also indicated in the process diagram. For example, In order to consider the use of natural ventilation to reduce energy consumption, the local wind and air quality conditions in the building site (output of the “Assess Environment” task) will be needed as input for the assessment of “Enclosure Opportunities” and “Environmental Systems Resources”.



- Assess Stage
  - Site and Climate
    - Identify Sites
    - Assess Logistics & Urban Context
    - Assess Environment
  - Form and Massing
  - Internal Configuration
    - Assess Program Type
    - Assess Interior Design Scheme
  - External Enclosure
    - Formalize Customer's Requirements/Preferences to Team
    - Assess Enclosure Opportunities
    - Assess Enclosure Opportunities' Feasibility
    - Narrow Down the Possible opportunities for Each Enclosure System
  - Environmental Systems
    - Assess Environmental Systems Needs & Resources
  - Energy Systems
  - Water Systems
  - Material Use and Embodied Energy
  - System Interdependencies
- Define Stage
  - Site and Climate
    - Define Site Development Strategies
    - Define Site Development Goals
  - Form and Massing
  - Internal Configuration
    - Define Circulation Strategies
    - Define Program Chart
    - Define Interior Design Scheme Goals & Strategies
  - External Enclosure
    - Define Enclosure Strategies
    - Define Enclosure Performance Goals
    - Finalizes Strategies Among Alternatives
    - Approves Typology, Strategies and Performance Requirements/Goals
    - Documents Approved Enclosure Strategies
    - Documents Approved Enclosure Performance Requirements/Goals
  - Environmental Systems
    - Define Environmental Systems Goals & Strategies
  - Energy Systems
  - Water Systems
  - Material Use and Embodied Energy
  - System Interdependencies
- Design Stage
  - Site and Climate
    - Design Landscape
    - Analyze Impact on Performance
  - Form and Massing
  - Internal Configuration
    - Design Internal Configurations
    - Outline Material/Finishing, Furniture/Equipment & Lighting Specifications
  - External Enclosure
    - Develop Enclosure Drawings & Specifications
    - Analyze Each Enclosure System's Impact on Performance
  - Environmental Systems
    - Design Environmental Systems
    - Analyze Impact on Performance
  - Energy Systems
  - Water Systems
  - Material Use and Embodied Energy
  - System Interdependencies
- Apply Stage
- Monitor Stage

Figure 3.33 Tasks of hypothetical CoE building design process study

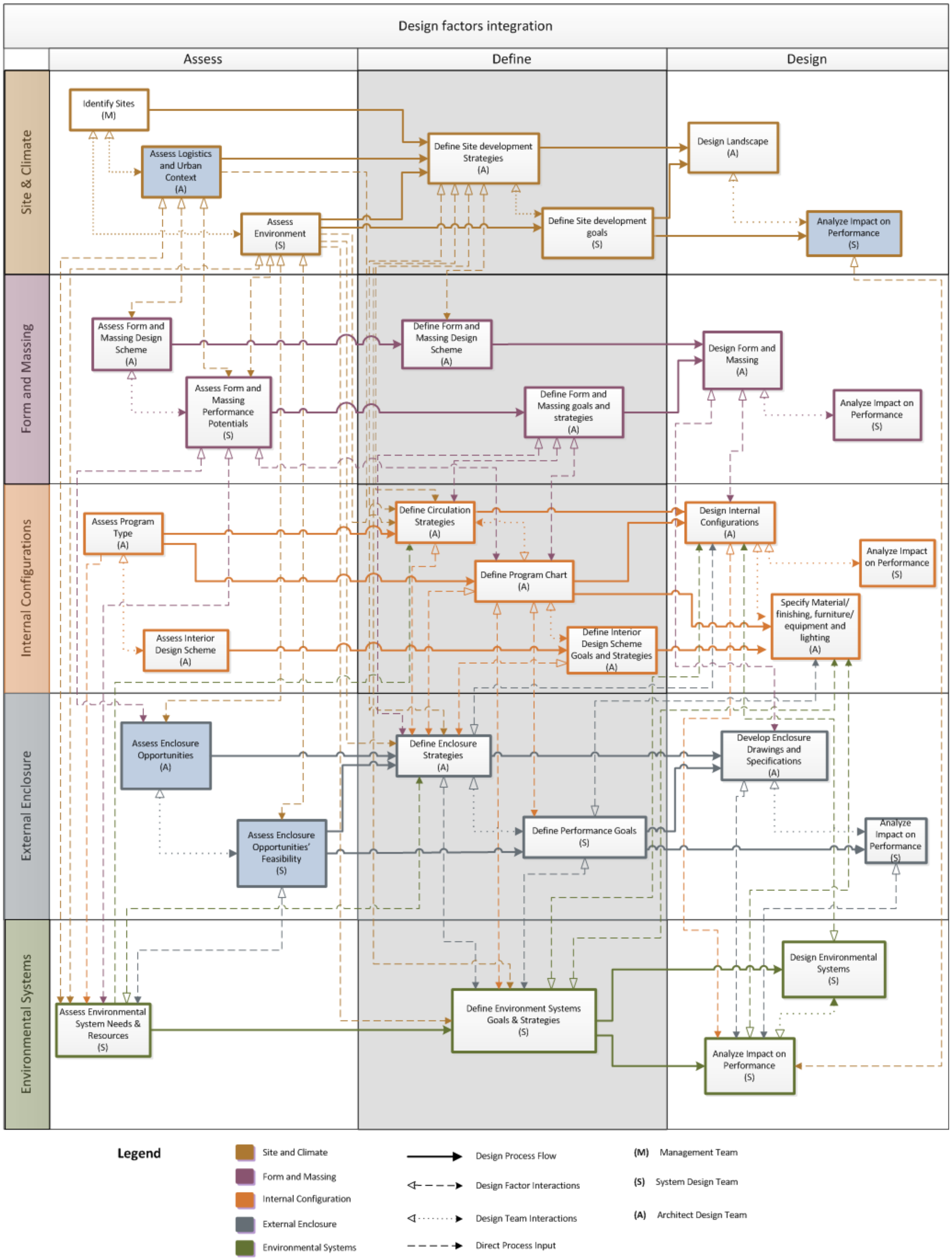


Figure 3.34 Overarching design process and system interdependencies diagram (Pelken, et al., 2013)

The design process matrix (Table 3-4) shows the selected major tasks that will be discussed in this chapter for the hypothetical design process. In the following subsections, tasks in each cell of the matrix will be discussed regarding task definition, task input and output, and respective interdependencies. The detailed performance evaluation and associated simulation analysis for comparing different design options will be discussed in section 3.2.4.4.

Table 3-4 Tasks selected for hypothetical CoE design process illustration

Design Factor	Assess	Define	Design
Site and Climate	• Identify Sites • Assess Logistics and Urban Context • Assess Environment		
Form and Massing	• Assess Form and Massing Preferences According to Building Typology • Assess Design Alternatives for Site Allocation and Massing Distribution • Assess Form and Massing Performance Potential for the Developed Options		
Internal Configuration		• Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships • Define Program Chart	

		• Define Performance Aspects for Different Room Programs • Define Interior Design Scheme Goals and Strategies	
External Enclosure		• Define Enclosure Strategies • Define Performance Goals	
Environmental Systems			• Design Environmental Systems with Preference Given to Efficient Passive and Hybrid System Solution • Analyze Impact on Whole Building Energy and IEQ Performance
Systems Interdependencies			• System integration (optimize all related components)

3.2.4.3.2. Site and climate

Planning sustainable buildings start with proper site selection. The location of a building affects a wide range of factors such as: building energy consumption, environmental impacts, indoor environmental quality, and renewable energy utilization. The location also impacts the energy consumed by transportation for occupants commuting, and the use/reuse of existing structures and infrastructures (WBDG Sustainable Committee, 2020). Therefore, it is important to address the site selection early on in the project development process. This also applies to the CoE building design case as the site was not determined at the beginning of the project, and two alternative sites were evaluated.

To identify and select the optimal site, conditions and available resources of each candidate site need to be comprehensively analyzed. Therefore, at stage "Assess", for design factor "Site and Climate", three tasks are planned by the management team: "Identify (suitable/potential) Sites", "Assess Logistics & Urban Context", and "Assess Environment" (Figure 3.35).

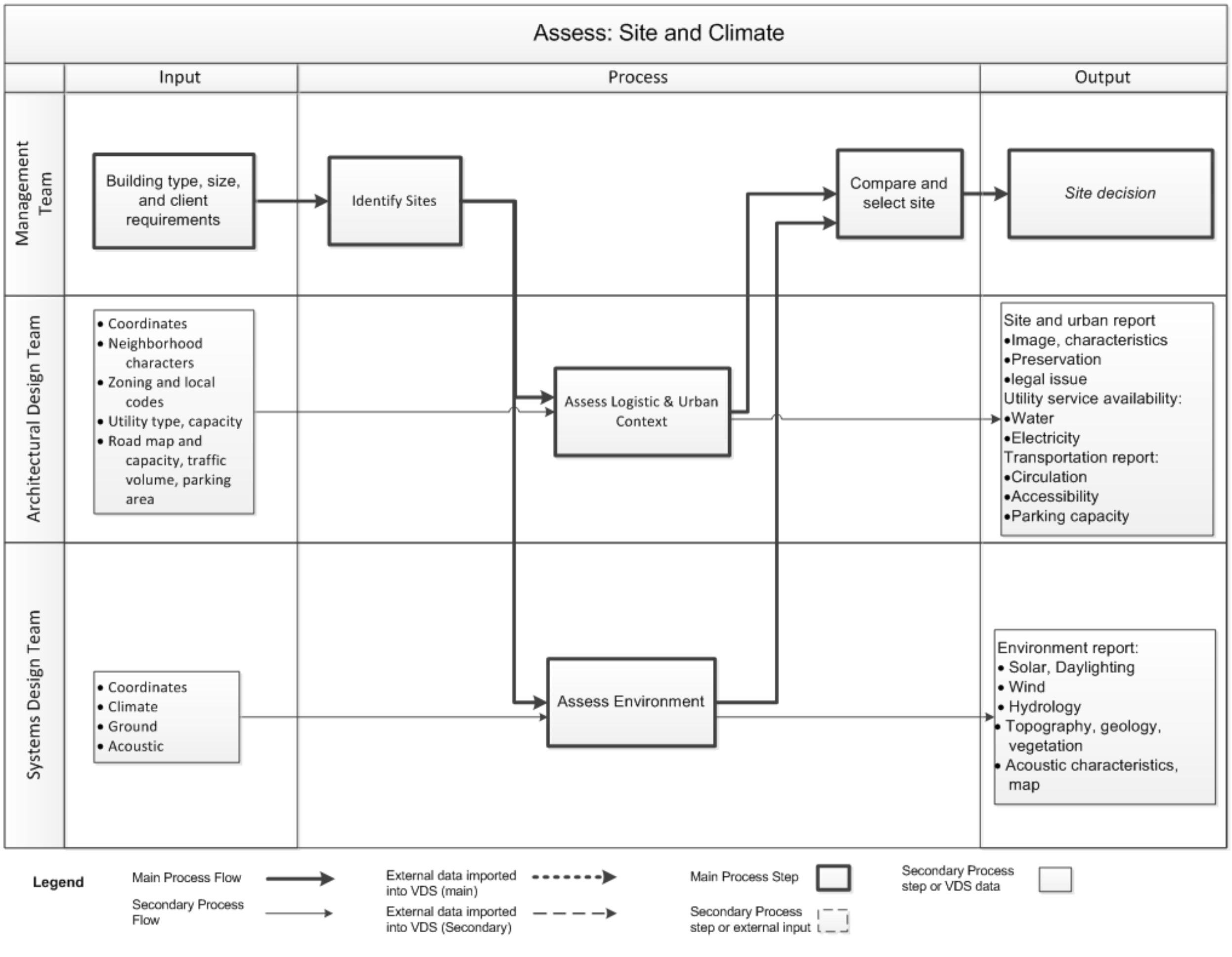


Figure 3.35 Process diagram for "Site and Climate" at "Assess" stage

The CoE design process starts with the task “Identify Sites” which is meant to provide the opportunities for all participated team members to understand the site as well as other fundamental project information that may be constrained by site conditions. This task is led by the management team including clients and project managers. Candidate site(s) can be identified based on an understanding of the basic project requirements such as input from the following areas: building type, size, functionalities, and other project-specific requirements. The output of this task -- candidate site(s), then is passed to the other two tasks “Assess Logistics & Urban Context” and “Assess Environment” for in-depth analysis. The client of the CoE building intended to build a demonstration building, create a testbed for environmental and energy technologies, and test the integration of building innovations. To meet the intent, two candidate sites were identified (Figure 3.36). They are located at corner of 690 & 81 highway, downtown Syracuse (Site A) and south campus of Syracuse University (Site B), respectively.

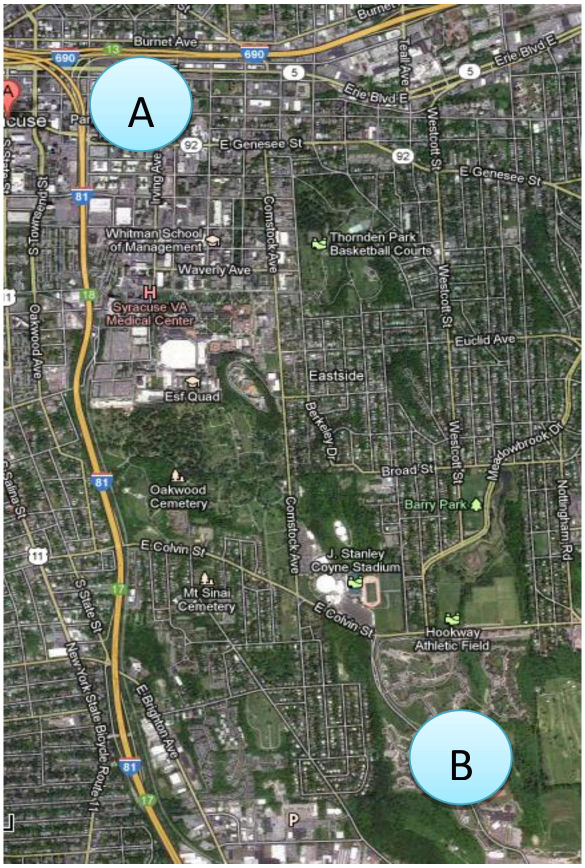
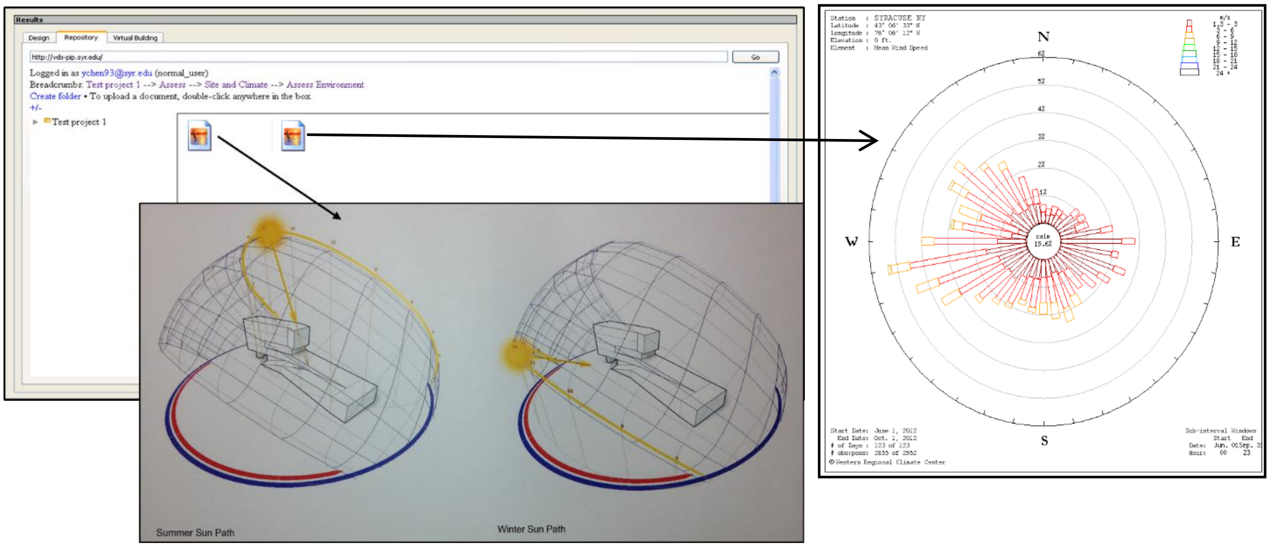


Figure 3.36 Candidate sites of CoE headquarters building

The purpose of task “Assess Logistics & Urban Context” is led by architects who fully explore and understand the logistics and urban context conditions of the candidate sites. Design teams can get to know the site characteristics, required historical preservation and other legal requirements by collecting site location, neighborhood conditions, zoning and local codes as input. Similarly, given the utility type and capacity information, the availabilities of utility services such as water, electricity, gas can be concluded. Reviewing the road map and capacity, traffic pattern and volume can provide information related to site circulation, accessibility and parking capacity. For CoE building project, “Site A” is located at downtown Syracuse while “Site B” is located at the south campus of Syracuse University. There are two highways (#81 and #690) passing by site A with convenient local road access while only a few local roads are connected to site B. Another noticing difference between these two candidate sites is: “Site A” is designated “brownfield”, it is the former site of the LC Smith typewriter factory and Midtown Plaza. Site B is a part of the south campus area, a designated industrial park that has not ever been developed. It is a much quieter and secluded site, typical of an “academic environment”, and can be readily accessed via campus bus. The site is nearby a golf course and has no apparent air pollution and noise issues. Situated on top of a hill, it also has a high elevation than Site A, and has stronger wind.

Besides an urban context and logistical analysis, the system design team will simultaneously perform the task “Assess Environment” which analyzes the environmental conditions for the candidate site(s). Site location, climate, air, ground, and acoustic conditions will be collected as input. The candidate site(s) profile regarding solar, daylight, wind, hydrology, geology, acoustic conditions will be generated. Due to the variety of projects and associated goals, the analysis performed by architectural and system design teams may partially cover the aspects mentioned above. For CoE building, task “Assess Environment” asks the user to input the site and climate conditions for the candidate sites including climate zone, summer design day, winter design day, latitude, longitude, and elevation. The information will be used for many later tasks.

Additional documentation that may help to complete the current task “Assess Environment” can be uploaded to the “Repository” on “Result Window” (Figure 3.37), e.g., sun path, the wind rose (Western Regional Climate Center, 2019).



http://vds-pip.syr.edu/

Logged in as ychen93@syr.edu (normal_user)

Breadcrumbs: Test project 1 --> Assess --> Site and Climate --> Assess Environment

Create folder • To upload a document, double-click anywhere in the box.

Station : SYRACUSE NY
Latitude : 43° 06' 33" N
Longitude : 76° 06' 12" W
Elevation : 0 ft.
Element : Mean Wind Speed

Start Date: June 1, 2012
End Date: Oct. 1, 2012
# of Days : 123 of 123
obs:poss: 2855 of 2952
©Western Regional Climate Center

Sub-interval Windows
Start End
Date: Jun. 01 Sep. 3
Hour: 00 23

Figure 3.37 Additional documentations uploaded to PIP: sun path (left), wind rose (right)

The site will be finally selected by comparisons among candidate sites against project criteria. Analysis from both architectural and system design teams will perform more detailed analysis to compare the different sites.

3.2.4.3.3. Form and massing

Form and massing refer to the shape, orientation and overall configuration of a building. The form placement in relation to its immediate site and neighboring buildings is a crucial aspect of building design (Crisman, 2016). In addition, building form and massing have the fundamental impact on achieving high-performance building because these early stage design decisions impact all design parameters and potential limitations for the later design. For example, daylighting potential, energy transfer characteristics and overall energy usage of a building (ASHRAE, AIA, IES, USGBC, DOE, 2015). The actual choice of building form and massing is a very complex process which may be affected by site constraints, building functionality requirements, project intents and sustainability objectives, etc.

At the “Assess” design stage of “form and massing”, tasks scheduled to manage the complexity mentioned are showing in Figure 3.38: “Assess Form and Massing Preferences according to Building Typology”, “Assess Design Alternatives for Site Allocation and Massing Distribution”, and “Assess Form and Massing Performance Potential for the Developed Options”.

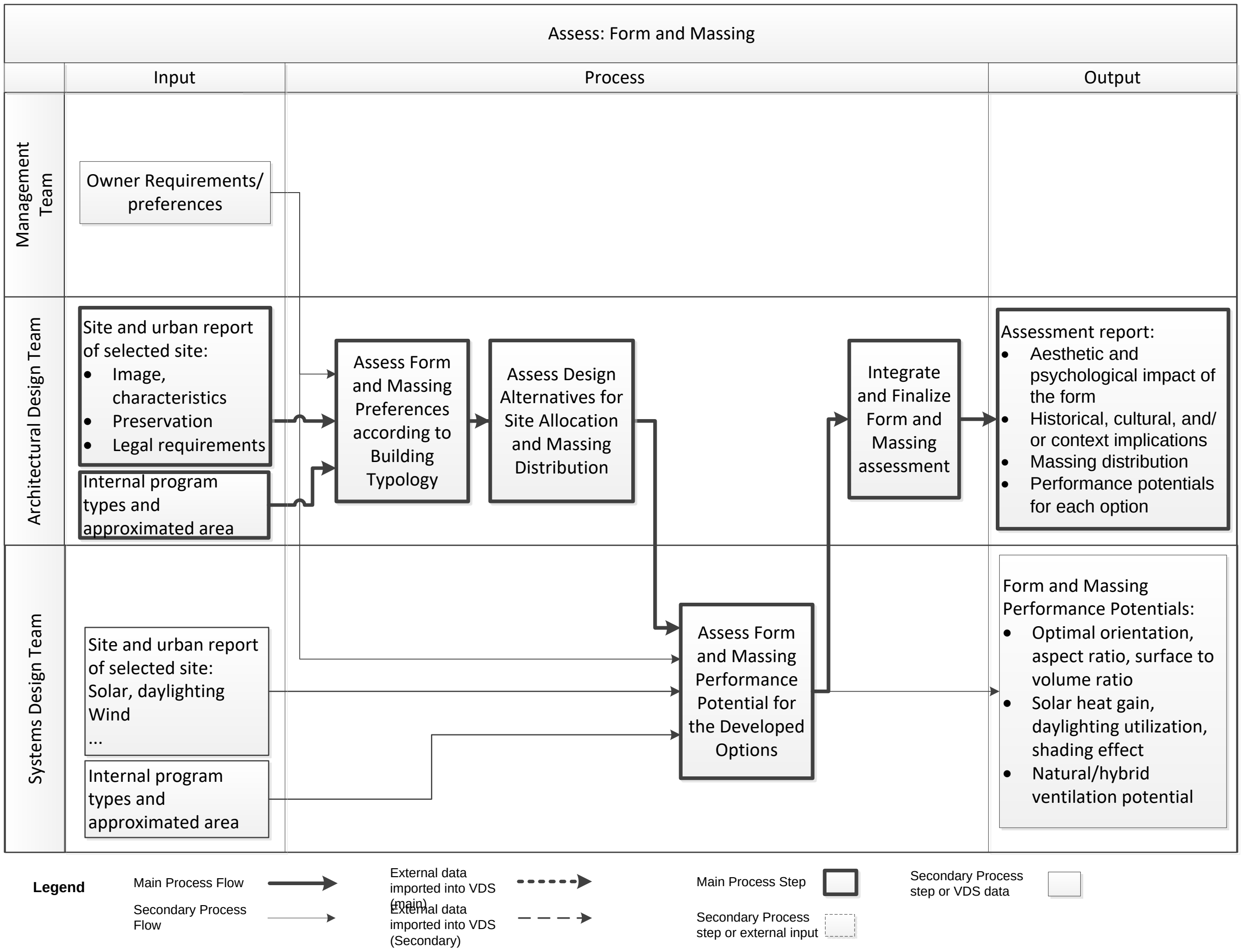


Figure 3.38 Process diagram for “Form and Massing” at “Assess” stage

Task “Assess Form and Massing Preferences According to Building Typology” is led by the Architectural Design Team. This task is meant to answer questions such as: “What should the aesthetic and psychological impact of the form design be? How should form relate to the surroundings? Should the building image be similar to or distinct from its neighbors? Are there historic, cultural, and/or context implications of the given form?” (Edith Cherry, 2021). To answer these questions, the results from task “Assess Logistics and Urban Context” of “Site and Climate” and “Assess Program Type” of “Internal Configuration” are used as the inputs. For example, Site A, located in downtown, was selected because of its visibility and potential impact on the local community in promoting sustainability and technology innovation. There were no specific historical, cultural, and/or context implications. The CoE building was intended to be a showcase and a testbed for environmental and energy technologies and building innovations. Required spaces included offices, classrooms, public spaces, and research laboratories from small scale to large scale.

Architectural Design Team leads the task “Assess Design Alternatives for Site Allocation and Massing Distribution”. In order to meet the form and massing preferences assessed by the previous task and project’s sustainable intent, this task tries to use different massing (volumetric) designs to assess the relations of the building with its site, surrounding context, and of the building with its sub-parts (massing elements). Some questions to be answered include: how much of the site area should be occupied by the building and overall development footprint (a tall building with a small footprint or shorter building with a larger footprint)? Should the building be divided into multiple massing elements? How much open space should be provided? The CoE building may be built relatively higher with a smaller footprint because its site is remediated from brownfield, the smaller footprint can avoid potential pollutant penetration from soil; a higher building can attract more attention so the sustainable goal of CoE could be better promoted to the community; a smaller building footprint also means less impact on the surrounding environment.

Task “Assess Form and Massing Performance Potential for the Developed Options” is led by the System Design Team. This task intends to explore the opportunities to minimize the building energy demand by integrating passive design potentials in form and massing design. The passive design potentials may include but not limited to:

- Optimize the building orientation, aspect ratio, façade orientation, floor depth, and surface to volume ratio to reduce the building’s energy consumption.
- Consider a suitable cross section for maximum use of day lighting and enhanced natural/hybrid ventilation.
- Consider less perimeter area in massing design because too many jogs and changes in the massing can lead to significant increases in the building perimeter, which means more materials to enclose the building and therefore, larger costs (Building and Construction Authority, 2010). An example is shown in Figure 3.39.

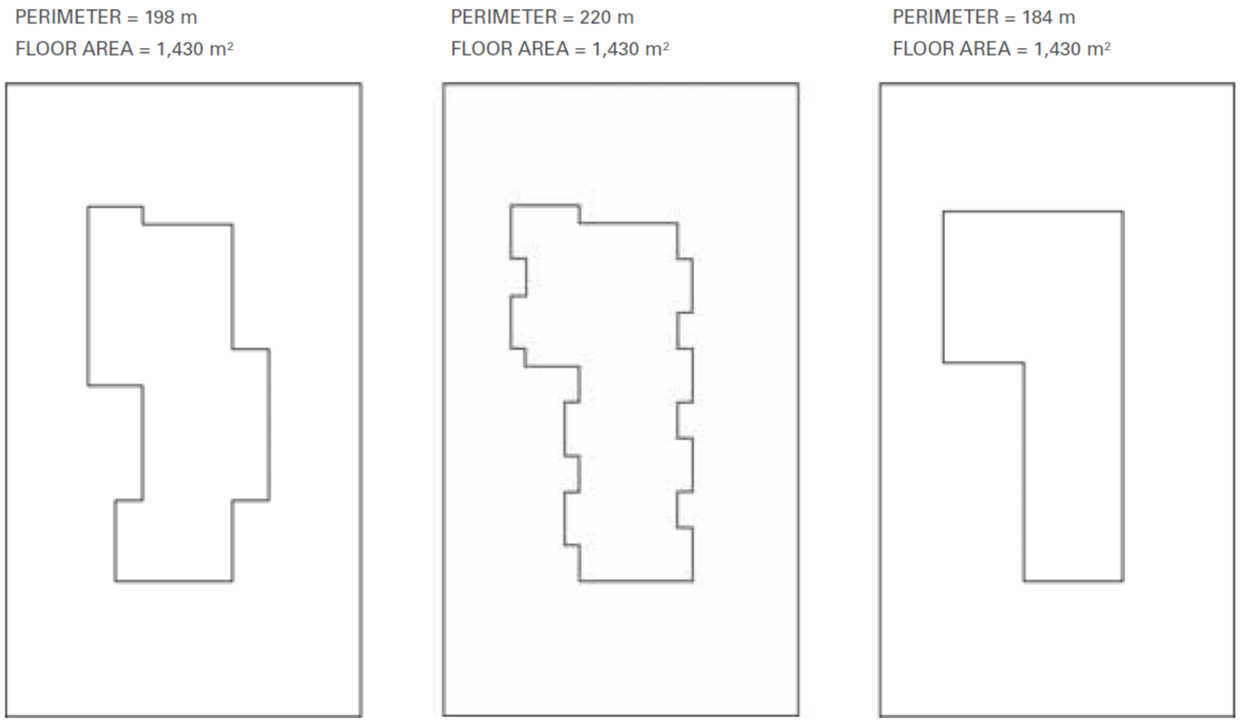


Figure 3.39 Same floor area with varying building perimeters (Building and Construction Authority, 2010)

Major input to this task is the site environmental profile from task "Assess Environment" of "Site and Climate". It includes sun path, prevailing winds, noise and pollutant sources, etc. The CoE building's latitude is N 43° 3.0', longitude is W 76° 8.5'. The sun path and wind rose of Syracuse is shown in Figure 3.37.

The output of this task provides the preliminary optimal range or recommendations on form and massing related parameters such as: orientation, aspect ratio, surface to volume ratio, etc. These related parameters help the later development in the next stage and will impact design factors such as "Internal configuration" and "External enclosure" design.

3.2.4.3.4. Internal configuration

Internal configuration deals with the programmatic zoning related design factors. The Architectural Design Team leads the development of internal configuration design tasks, allocating the interior spaces based on the understanding of the functional needs of the project and associated relationships among the spaces.

At the “Assess” stage, critical project functional information/requirements that may affect “internal configuration” design has been collected, such as the client’s organizational structure and relationships, space usage and area requirements, space accessibility (regarding security/privacy), activities and associated schedules, necessary equipment, etc. The CoE building is mainly occupied by office staff and researchers. The approximate space areas are (ft^2): laboratory 16000, office 7000, public spaces 4000, mechanical room 2000, classrooms 1000, etc. Common office requirements and accessibilities standards are applied to most of the spaces. The office portion of the building will be operated under a regular office hour schedule, while the research labs are expected to be operated under more flexible schedules depending on the research and experimental needs.

At the “Define” stage, tasks for “Internal configuration” are meant to produce the master/general level program chart in order to guide the “Internal configuration” detail design at the “Design” stage. Circulation strategies will be defined by analyzing activity patterns to develop the master/general level program chart. Additional interior design goals and strategies may also be established. Therefore, corresponding tasks “Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships”, “Define Program Chart”, “Define Performance Aspects for Different Room Programs”, and “Define Interior Design Scheme Goals and Strategies” are planned (Figure 3.40). Strategies, program charts, performance aspects, and goals defined for "Internal Configuration" from this stage will also have impacts on many decisions of other tasks related to different design factors. For example, the fenestration design of "External Enclosure" and mechanical systems design of "Environmental Systems".

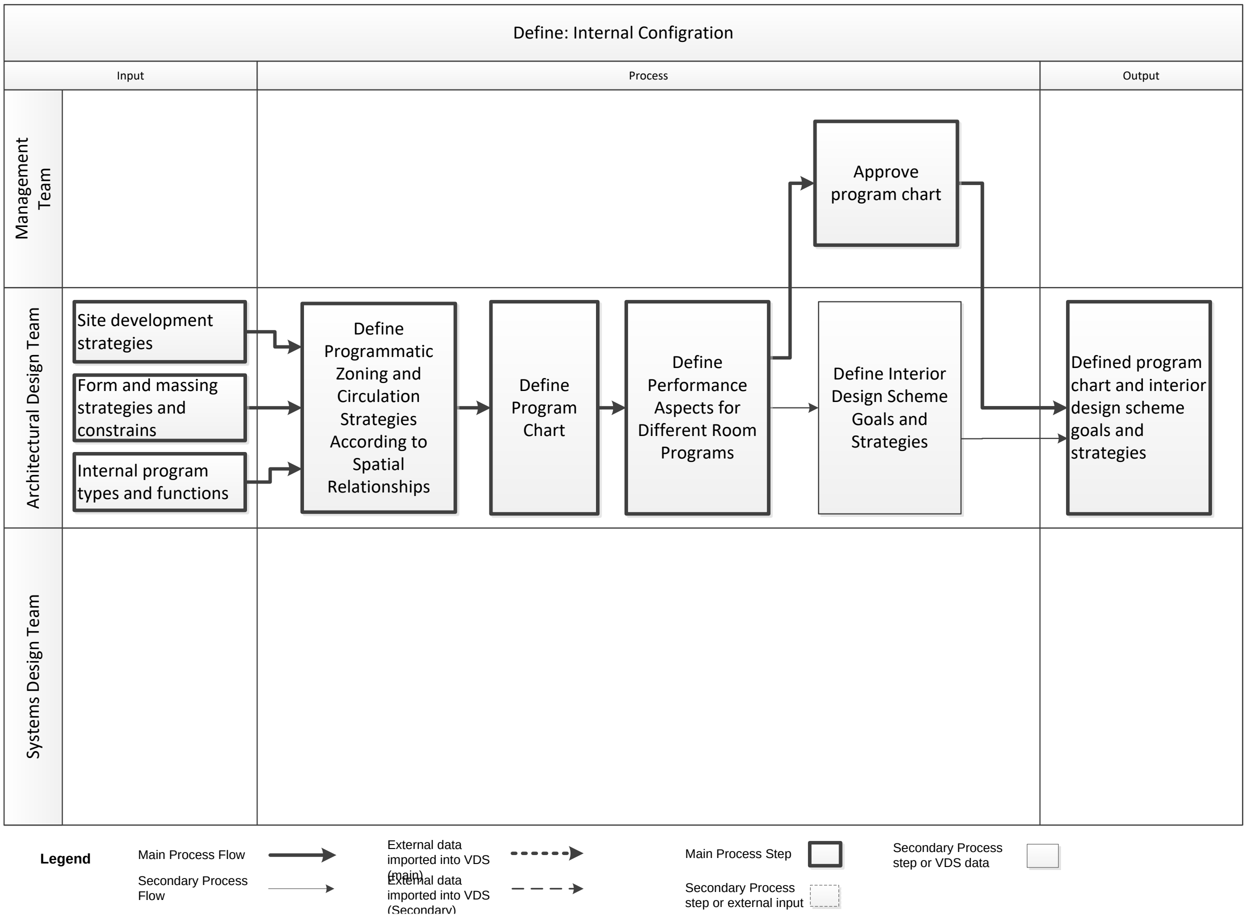


Figure 3.40 Process diagram for "Internal Configuration" at "Define" stage

The task "Define Programmatic Zoning and Circulation Strategies According to Spatial Relationships" intends to identify, consider and define strategies for occupant circulation in the building (i.e., the flow of people). Its outputs will be used in the development of the program chart development in task “Define Program Chart”. It uses the collected functional and other information/requirements from the “Assess” stage, examines patterns of activity in the facility and considers how those patterns create spatial relationships (WBDG Functional/Operational Committee, 2018). The CoE building’s space requirements include offices, classrooms, public spaces, and research laboratories from small scale to large scale. To accommodate these functional requirements and allow for good circulation among these spaces, the preliminary building form is divided into two primary masses. The offices and field laboratories that are intended to simulate full-scale office environments for testing of IEQ conditions are allocated in what is labeled the “tower”, while the various specialized experimental facilities are to be located in the open spaces under the sloped ramp wing, called the “barn”.

The task “Define Program Chart” is meant to develop master/general level program chart(s) to help determine structural and building functional modules that may be more accommodating for furniture and equipment placement. "Bubble diagram" is frequently used during this task. These "bubble diagrams" indicate relationships between spaces with different functionalities to help in deciding where to locate them (Gretchen Addi, 2000). An example is shown in Figure 3.41 for the CoE building in which bubbles represent the space and lines indicate their relationships. Different offices share similar functions and are more private compare to research laboratories, so they are grouped together and located further from the reception area. Research laboratories are allocated more closely to service/support rooms such as mechanical rooms and storage rooms since researchers will frequently work among these rooms. Classrooms are allocated behind the reception area for public access convenience.

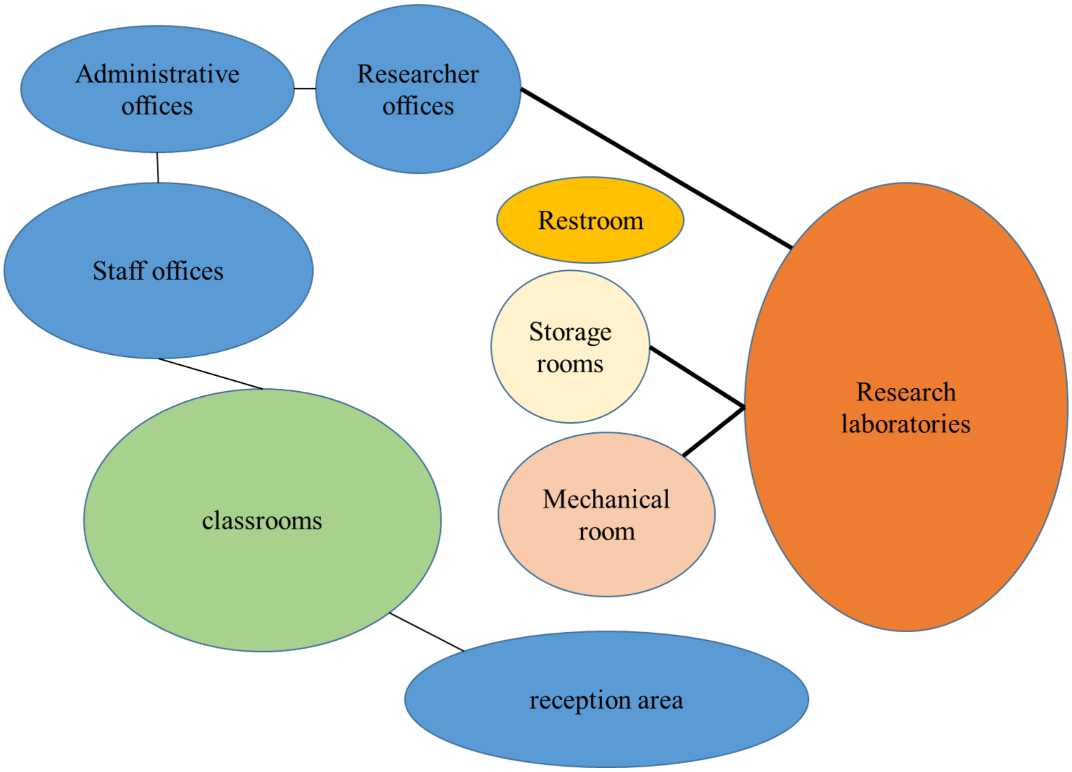


Figure 3.41 "Bubble diagram" example for CoE building

Besides "bubble diagram" methodology, some examples of common categories of internal configuration strategies also need to be considered, including (Edith Cherry, 2021):

- “Centralization and decentralization: What function components are grouped together and which are segregated? For example, in some offices, the location for copy machines is centralized, while in others there are copiers for each department.”

- “Flexibility: What types of changes are expected for various functions? Do facilities need to change over a period of a few hours? A few days? A summer recess? Or is an addition really needed?”

- “Flow: What goods, services, and people move through the project? What is needed at each step of the way to accommodate that flow?”
- “Priorities and phasing: What are the most important functions of the project? What could be added later? Are there ongoing existing operations that must be maintained?”
- “Levels of access: Who is allowed where? What security levels are required where?”

For the CoE building, the above-mentioned strategies are considered in the task “Define Program Chart”: in terms of “Flexibility” and “Flow” strategies, the specialized laboratory facilities may encounter frequent reconfigurations for different research subjects. The reconfiguration potentially requires a high volume of goods, services, and people to move through the building. Therefore, it is a good choice to allocate them under the sloped ramp wing which is on the ground floor and separated from the main offices. In terms of “Centralization and decentralization” and “Levels of access” strategies, administrative offices that require more privacy and have close relationships with other rooms such as conference, class and social functional rooms are centralized on the same floor in the tower, shown in Figure 3.42.

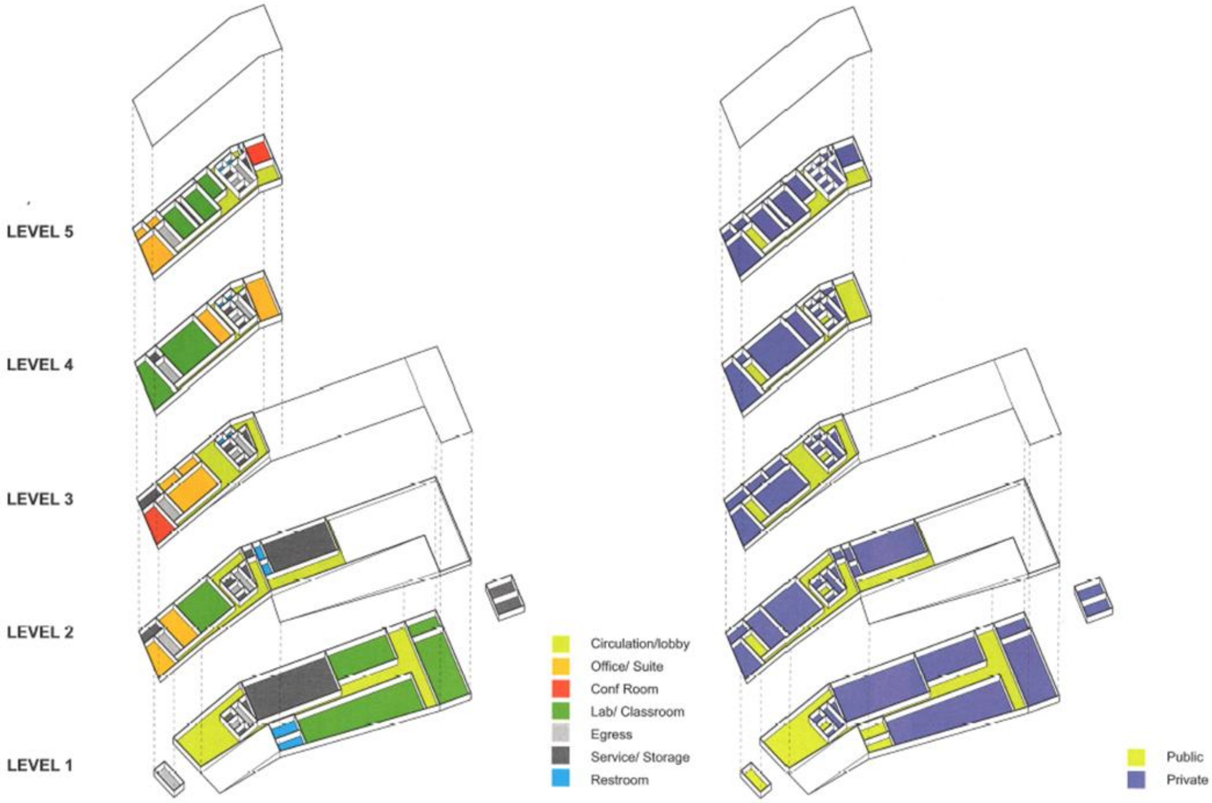


Figure 3.42 CoE program and organization (Augustine, 2011)

Based on the master/general level program chart(s) considering the above qualitative strategies, detailed quantitative analysis regarding energy performance may be performed to finally select the master level program chart.

Because there are many different types of rooms in a building, and each type of room has its own performance requirements, task "Define Performance Aspects for Different Room Programs" is scheduled to specify those requirements for each (type) room. For example, in order to meet different environmental conditioning settings of certain experiments, research laboratories in the CoE building may require the support of separated HVAC systems from the central systems, so the laboratories can be controlled individually without interfering the whole building operation.

During or after the development of the master/general level program chart, task "Define Interior Design Scheme Goals and Strategies" may establish the goals and strategies for specifying/selecting interior finishing, furnishings, and equipment in order to design a healthy, comfortable, productive, and aesthetical interior environment.

3.2.4.3.5. External enclosure

The external enclosure of a building separates the outdoor environment from indoor spaces. It provides the protection of occupants by controlling and balancing external and internal forces. Functions of the external enclosure can be grouped into four sub-categories (Straube, 2006): support functions (support structural loadings), control functions (control, regulate and/or moderate mass and energy flow), finish functions (meet visual, esthetic requirements), and distribution functions (distribute services or utilities). Due to the responsibilities for such large amount of functions, external enclosure design has great influence on the whole building performances.

External enclosure typically includes the physical components: roof system(s); façade system(s), including wall system(s) and fenestration; basement and/or foundation system(s); and hybrid system(s) which interact(s) with above system(s). In order to achieve the high-performance enclosure design, not only each of these systems needs to be carefully analyzed, but also the interactions between these components and their combined effects on the performance need to be considered.

Because of not only the function, but also inter-related components integration requirements, at the “Define” stage, it is critical to define the strategies and performance goals for external enclosure design. These strategies and performance goals will heavily influence enclosure potential performance and guide the detailed design in the following “Design” stage. The corresponding planned tasks are: “Define Enclosure Strategies” and “Define Performance Goals” (Figure 3.43). Each of these tasks will be further decomposed for specifying each enclosure components, respectively. Because enclosure interacts with exterior environmental and building interior space conditions, the general input for these tasks are: exterior - assessed urban context and environmental conditions from factor “Site and Climate” and stage “Assess”; interior - programming and space usage information from factor “Internal Configuration” and stage “Define”. The preliminary geometry information from the factor “Form and Massing” and stage “Assess” also impose constraints on enclosure design.

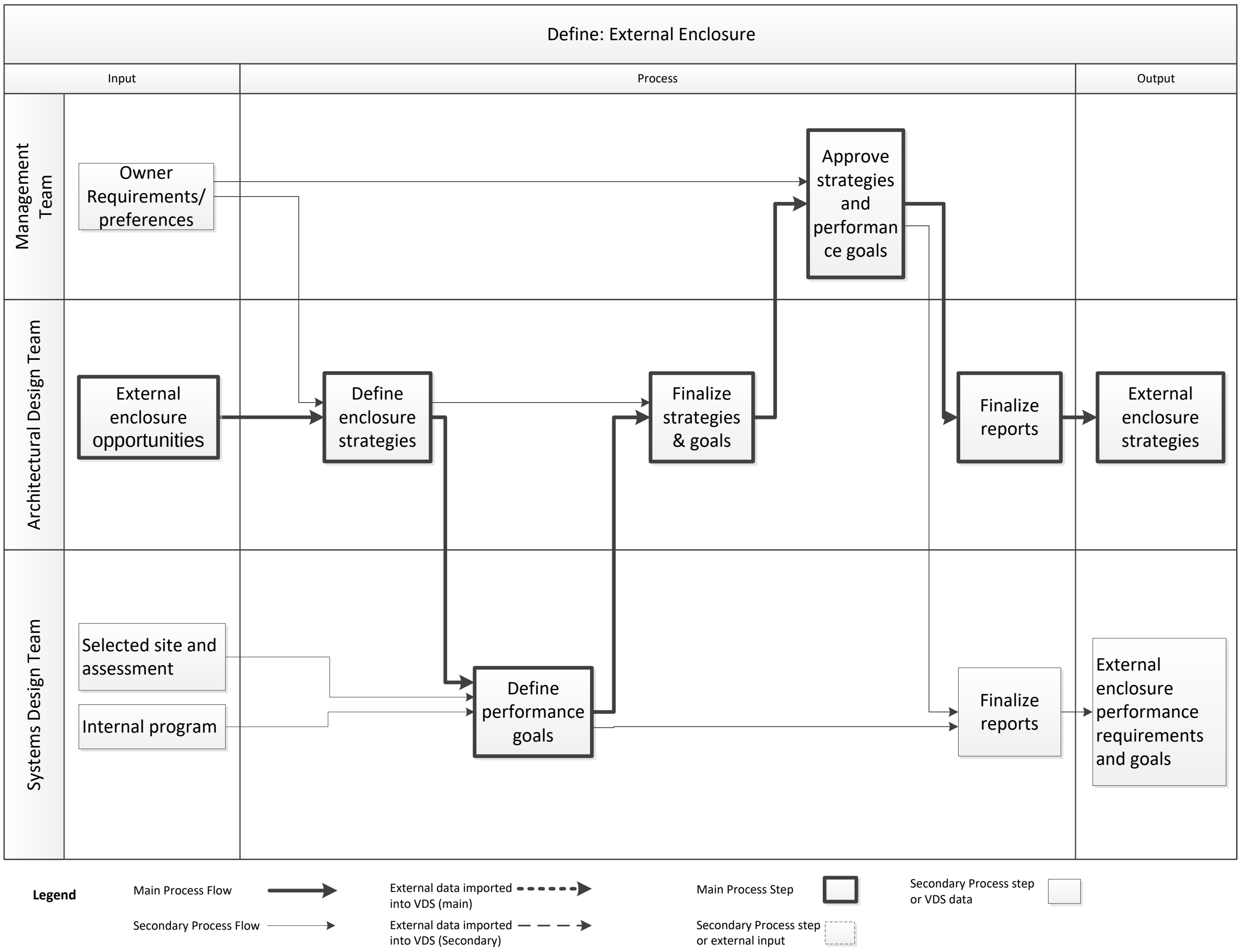


Figure 3.43 Process diagram for “External Enclosure” at “Define” stage

Task “Define Enclosure Strategies” is led by the architect design team. It intends to make decisions on typology for each enclosure component (roof, façade, basement/foundation, and hybrid system(s)) and select the strategies which can maximize the utilization of site resources to satisfy all functional requirements as well as promoting sustainability in building design. For example, the Architectural Design Team may have considered the following strategies in CoE building design:

- For roof system(s), increasing surface reflectivity to reduce the HVAC loading and mitigate the heat island effect, using the green roof and stormwater collection system to reduce the water runoff as well as water usage demand.

- For Façade system(s), architects may weigh the insulation improvement of wall and window system(s) against the construction and operation cost. They may also adjust the window size, select appropriate glazing types, and adding shading devices in order to balance daylighting potential, glare, and solar heat gain. For the basement/foundation system(s), thermal, moisture, and pollutant control need to be carefully considered. Especially, CoE project is developed on a brownfield, the ground floor insulation needs to prevent the pollutant intrusion from the contaminated soil.

- For hybrid system(s), operable window(s) need to be integrated if natural ventilation is applied. The Architectural Design Team will closely collaborate with the systems design team along the process to approve the feasibilities of defined strategies for each enclosure component.

The task "Define Performance Goals" is led by the System Design Team. In this task, the System Design Team is supposed to provide technical feedback/support for Architectural Design Team's decision on strategy selections. At the same time, the system team will define the performance goals for each external enclosure component with focus on control functions, especially the flow of heat, air, moisture, and pollutant. Daylight control and utilization, acoustics control, and potential renewable energy generation systems (such as the turbine and photovoltaic systems) which are closely related to enclosure design will be discussed as well. To perform the analysis, the required input parameters will be based on the actual design and assigned to this task. However, as the actual enclosure and whole building design are not completed at the "Define" stage, a considerable amount of input will use RBM settings to perform the analysis.

When the above two tasks are completed, one or more types of enclosure components would have been identified and selected. The corresponding design strategies and goals for each component would also be defined. All these selections and strategies will be used as input for detailed drawings development for the external enclosure systems at the design stage.

3.2.4.3.6. Environmental systems

At the "Design" stage, since most architectural features have been determined (such as building form and massing, external enclosure, internal space configurations), the design shifted from architectural design to building environmental systems design. The design factor "Environmental Systems" is primarily responsible for HVAC systems design. For medium-size office building, like case-building CoE, the major objectives of HVAC systems are to provide and maintain thermal comfort and indoor environmental qualities to its occupants in an energy-efficient manner.

At the "Design" stage, the System Design Team needs to find appropriate, constructible, controllable, affordable, and maintainable HVAC&R solutions (Charles E. Gulledge III, 2020). In the meantime, these solutions must be integrated and coordinated with parallel design factors like Internal Configuration and External Enclosure, etc. In order to design HAVC systems, as well as integrate the design with other closely related design factors, there are two tasks "Design Environmental Systems" and "Analyze Impact on Performance" scheduled (Figure 3.44). The first task is to design the HAVC systems, and the second to evaluate the whole building performance of various HAVC system design options.

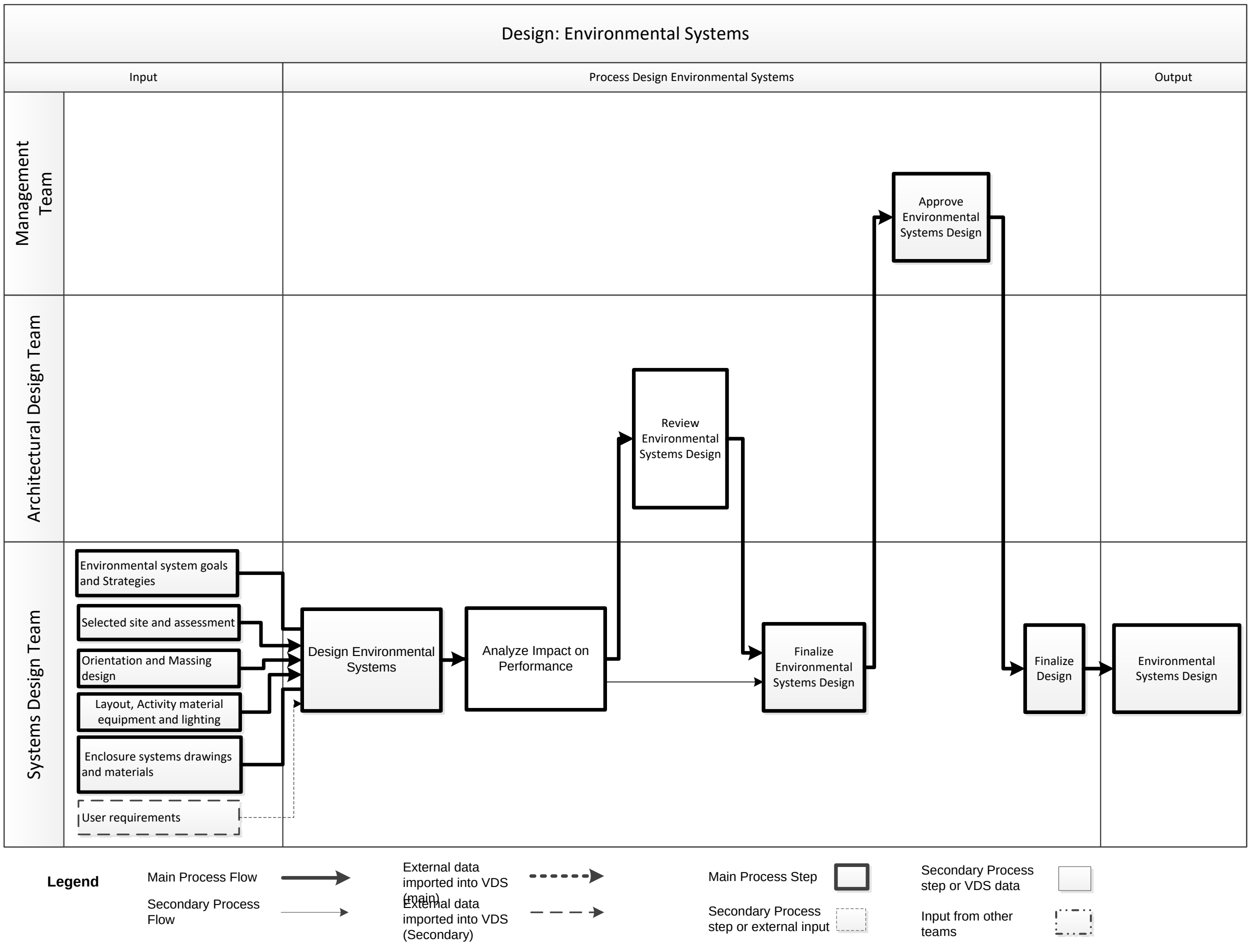


Figure 3.44 Process diagram for “Environmental Systems” at “Design” stage

Major activities (subtasks) involved in the task “Design Environmental Systems with Preference Given to Efficient Passive and Hybrid System Solution” include finalize heating and cooling load requirements, identify system type and specification, finalize HVAC design and

HVAC system drawings. The input, process, output information for each of the activities are as follows:

- Finalize heating and cooling load requirements: calculate heating and cooling load based on climate condition, actual building construction, zoning, activity and schedule as well as required indoor thermal conditions. For CoE building, all offices need to be fully conditioned, but some large-scale laboratories' which are likely to not be fully occupied may only need partial conditioning. The determined load requirements are then used for the final equipment selection and sizing.

- Identify system type and specification: select equipment type and sizing, review of mechanical room requirements, air distribution system space requirements such as supply and return plenums, ducts, and terminals. For the CoE building, central plant heating and cooling services are not applicable. Moreover, the sustainability intents of CoE building strongly recommend high-efficiency systems.

- Design HVAC system drawings: develop final drawings outlining HVAC design, layout drawings locating mechanical rooms risers, and primary services routes, reflected ceiling plans, final duct layouts, production of larger-scale detailed drawings, co-ordination of all HVAC drawings with, structure and architecture.

- And finalize HVAC design: based on the reviews from the Architectural Design Team, finalize HVAC systems design. This includes finalizing the HVAC system, mechanical room as well as duct layout design.

The task “Analyze Impact on Whole Building Energy and IEQ Performance” closely collaborates with the task “Design Environmental Systems” to verify the HVAC design alternatives’ impact on whole building energy and IEQ performance. It represents the integrated and coordinated design process methodology of MC. In this task, with the variation of HVAC design alternatives for the proposed building will be modeled and simulated. The simulation uses the case building climate conditions, geometries, envelope structures, internal zoning, presumed operation schedules, etc. Results generated from this task provide information for optimizing the design of the HVAC system.

3.2.4.3.7. Design integration/optimization: systems interdependencies

A high-performance building design can be only achieved when not only each individual design factor (or building system) is appropriately designed, but also all design factors are integrated and coordinated concurrently throughout the design process.

To reduce energy consumption while maintaining high-level indoor environmental quality, passive design strategies are frequently considered. One of the passive design strategies is to take the advantage of the renewable resource – solar. There are two aspects associated with solar-related design that can be integrated into the whole building design: light (daylight) and heat (solar radiation). Both aspects need to be evaluated from the beginning of the design process among multiple design factors.

As shown in Figure 3.45, we use solar-related design as an example to illustrate the interdependencies among design factors and how design impacts different performance aspects. In order to use solar resources, conditions such as sun path, angle, solar intensity, surrounding buildings context which may block the sunlight need to be evaluated in factor “Site and Climate”. Building surface to volume ratio, aspect ratio, orientations of roofs and façades which directly determine incident of sunlight and heat transfer through the enclosure require coordination among “Form and Massing”, “External enclosure”, and “Internal Configuration”. In factor “Internal Configuration”, zoning (especially perimeter zoning) needs to simultaneously accommodate thermal comfort and lighting requirements for occupancies, which can be strongly affected by light and heat associated with sun light. The designed indoor space immediately impacts “Indoor Environmental Qualities” such as thermal comfort, visual qualities. It also impacts the “Energy and Atmosphere” because of the artificial lighting load required to supplement natural lighting. In factor “External Enclosure”, the effects of fenestration size, glazing type, U-value, solar heat gain coefficient, visible transmittance, related shading devices, and other opaque wall assemblies’ U-value and thermal mass on the space load and IEQ need to be considered. In factor “Environmental Systems”, given the above architectural design, HVAC systems will be designed according to heating and cooling loads determined by the combined effect of building form, enclosure, and internal zoning. The operational energy consumption of the designed HVAC systems directly impacts the “Energy and Atmosphere” as it is a major portion of total building energy consumption.

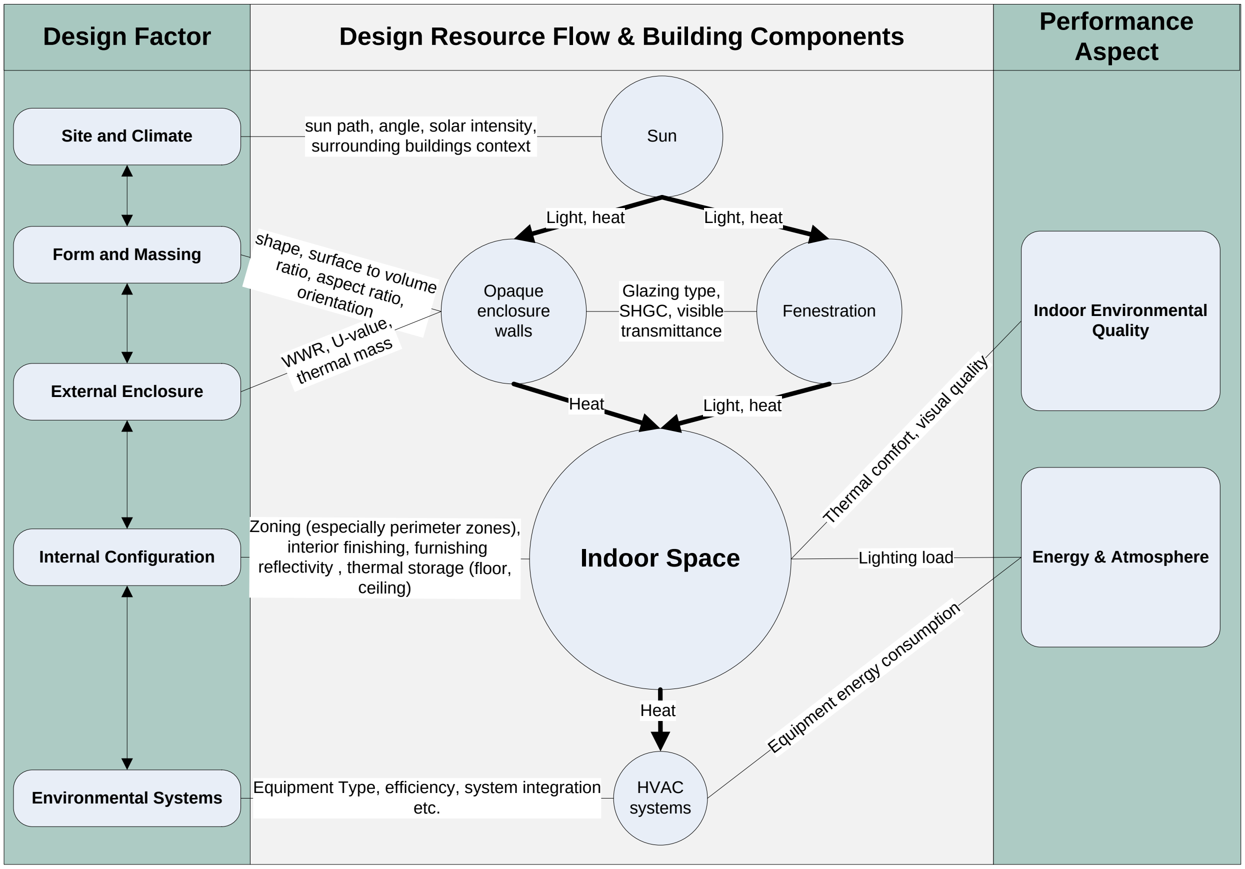


Figure 3.45 Interdependent design factors of solar related design

However, to concurrently integrate and coordinate both aspects of solar-related design are very complex, not only because each of them influences the design/decisions of multiple design factors, but also these influenced design factors may compete or even conflict with each other. For instance: reducing the enclosure exposure (building form with the small surface to volume ratio) of the building form can reduce the heating/cooling load because of less chance of thermal exchange. But it may also cause increasing of lighting energy consumption because of less of sunlight exposure, artificial light needs to be provided to compensate for lighting requirements.

In MC, besides individual design factors which map to the certain aspects (parts) of the physical building components, the factor "System Interdependencies" is proposed to deal with overall building (system) efficiencies related to individual design factors (subsystems) and their coordination, integration, and operation. Each factor has a task named "Impact on performance" to analyze how design variations of that particular factor can improve performance of itself, as well as the contribution of performance improvement at the whole building level.

3.2.4.4. Design analysis and performance evaluation

3.2.4.4.1. Site and climate

The tasks "Assess Logistics & Urban Context" and "Assess Environment" comprehensively analyzed site and climate conditions for two candidate sites for CoE building. The selection from these two candidate sites mainly impacts on performance aspects "site sustainability", "Energy and Atmosphere", "indoor environmental quality". Detailed comparisons between these two candidate sites are listed in Table 3-5.

Table 3-5 Candidate sites performance aspect

	Site sustainability	**Energy and Atmosphere**	**IEQ**
Site A (Downtown Syracuse)	**Pros:** • Downtown area offers good accessibility to a variety of services and community. • Nearby highway also improves the public exposure which can	**Pros:** • Low elevation of site A provides more opportunities for ground heat sour pump (GSHP) utilization (For example: less drilling depth, less total pipe length).	**Pros:** **Cons:** • Contamination associated with previous industrial site uses may pollute indoor environment.

	enhance the visibility of the sustainability activities of CoE. • Remediate the brownfield which can restore the site for sustained use by future generations. **Cons:** • Limited use of ground due to toxic soil content	**Cons:** • Limited opportunity for natural ventilation due to less wind and more ambient air contamination. • Less potential for power generation by wind	• Ambient air pollution level is higher due to the traffic. • Ambient noise level is higher due to the traffic.
Site B (South campus of Syracuse University)	**Pros:** • Convenient access for faculty and students • No contamination from the ground **Cons:** • Not as accessible to the public as Site A.	**Pros:** • More natural ventilation due to better air quality and higher wind speed • Potential for wind power generation **Cons:** • Less likely to use ground water source due to higher elevation	**Pros:** • Ambient air pollutant level is lower. • Ambient noise level is lower. **Cons:**

There are pros and cons from both candidate sites in terms of potential impacts on the sustainability goals. In the end, site A nearby downtown Syracuse was selected, largely due to the strong emphasis on the needs to better facilitate community engagement and collaboration between academia and industrials as well as its visibility as a symbol of research and technology transfer for sustainable/green building development for the region, state and beyond.

3.2.4.4.2. Form and massing

Many opportunities exist for the task "Assess Form and Massing Performance Potentials" at the "Assess" stage. The analysis focused on two form and massing related parameters: aspect ratio and orientation which have significant impact on building energy performance, for instance: solar heat gain, daylighting potential. An "East-West bar form" design concept (Figure 3.46) in which the South-facing façade is 100% transparent to maximize daylighting and winter solar heating and west and east facades are 100% opaque to minimize glare. The systems team analyzes this architectural conceptual design and compare it with the RBM that represents the major attributes of a large population of existing building stocks (National Renewable Energy Laboratory, 2011). The detailed settings for the design factor are listed in Table 3-6.

Table 3-6 Aspect ratio and orientation analysis settings at "Assess" stage

<table>
<tr><th></th><th colspan="2">Assess Stage</th></tr>
<tr><td>Site and Climate</td><td colspan="2">• Syracuse climate condition.
• No surrounding buildings.
</td></tr>
<tr><td>Form and massing</td><td>Aspect ratio</td><td></td></tr>
</table>

	Orientation	**Recommended values need to be evaluated**
Internal Configuration	5-story open floor plan "East-West bar form" design; Lighting is controlled by step dimming and the indoor luminance level is controlled at 500 lux.	
External Enclosure	Walls system: light weight construction assembly; Windows system: double glazing;	
Environmental Systems	HVAC systems are not designed, the district heating and cooling were used for simplicity.	

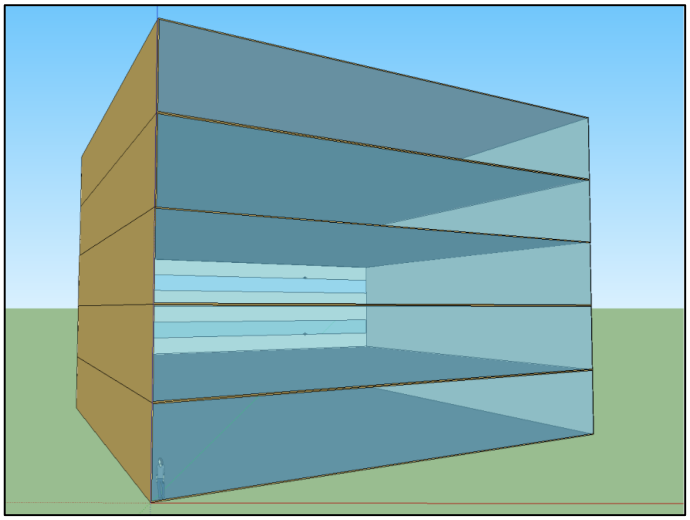
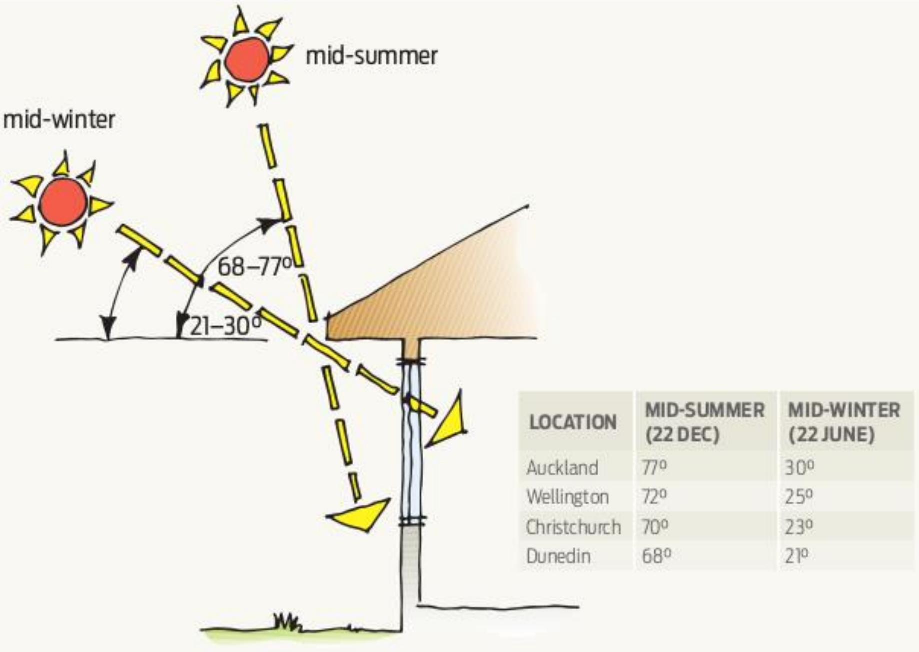


Figure 3.46 Architectural conceptual "East-West bar form" design

The combined orientation and aspect ratio effect on annual energy consumption (heating, cooling, and lighting) is shown in Figure 3.48. The architectural conceptual building rotates from 0° to 90° with 30° increment. While rotating, they are also stretched from a square to a rectangular footprint building (aspect ratio from 1 to 5). In total, there were 20 proposed design cases tested for their performance.

The heating energy of architectural conceptual design accounts for the largest portion of total energy use (Figure 3.48). Heating energy consumption increases with aspect ratio because of the more exposed envelope area. Comparing to the RBM, this trend of architectural conceptual design is amplified by the large window area on the South façade due to their lower heat resistance than the wall. It also indicates that South facing windows can introduce more solar radiation into the rooms, which is very helpful for heating energy reduction, so the optimal orientation is 0º -- for each given aspect ratio, the heating energy always increases with orientation with more rotation.

Cooling energy consumption also increases with aspect ratio and orientation increase. It shows clearly that the smaller the aspect ratio (less exposure area), the less the cooling energy -- for the same orientation, cooling energy increases when the building form is stretched. Results also show that this increasing trend is more obvious when the building rotates from 0º to 90º than in the RBM. This is because more window area is exposed to solar radiation from West/East directions. During the summertime, the sun angle is quite large so the solar radiation heat gain from the South façade is less compare to the West/East (Figure 3.47), although South façade is directly facing the sun most of the time during the day.



LOCATION	MID-SUMMER (22 DEC)	MID-WINTER (22 JUNE)
Auckland	77°	30°
Wellington	72°	25°
Christchurch	70°	23°
Dunedin	68°	21°

Figure 3.47 Summer & Winter solar comparison on South façade (Trevor Pringle, 2020)

Comparing to the RBM, without windows on West and East facades, all architectural conceptual models still use less lighting energy. The architectural models follow the trend of "the larger the aspect ratio, the less the lighting energy". For all orientations, there is a significant amount of lighting energy saving when building form is stretched from aspect ratio 1 to 2. However, the saving is no longer dramatic when further increasing the aspect ratio, for example, lighting energy are almost identical for cases with aspect ratio at 4 and 5. This is because building with aspect ratio 1 has the deepest floor depth, once the lighting control limit is not met, artificial lighting will be used to meet the setpoint requirements. The floor depth becomes smaller when the aspect ratio increases which means easier daylighting access for the zone. When floor depth is small enough, the contribution of daylighting for lighting energy saving becomes very limited as increasing the light intensity above the setpoints does not save additional lighting energy.

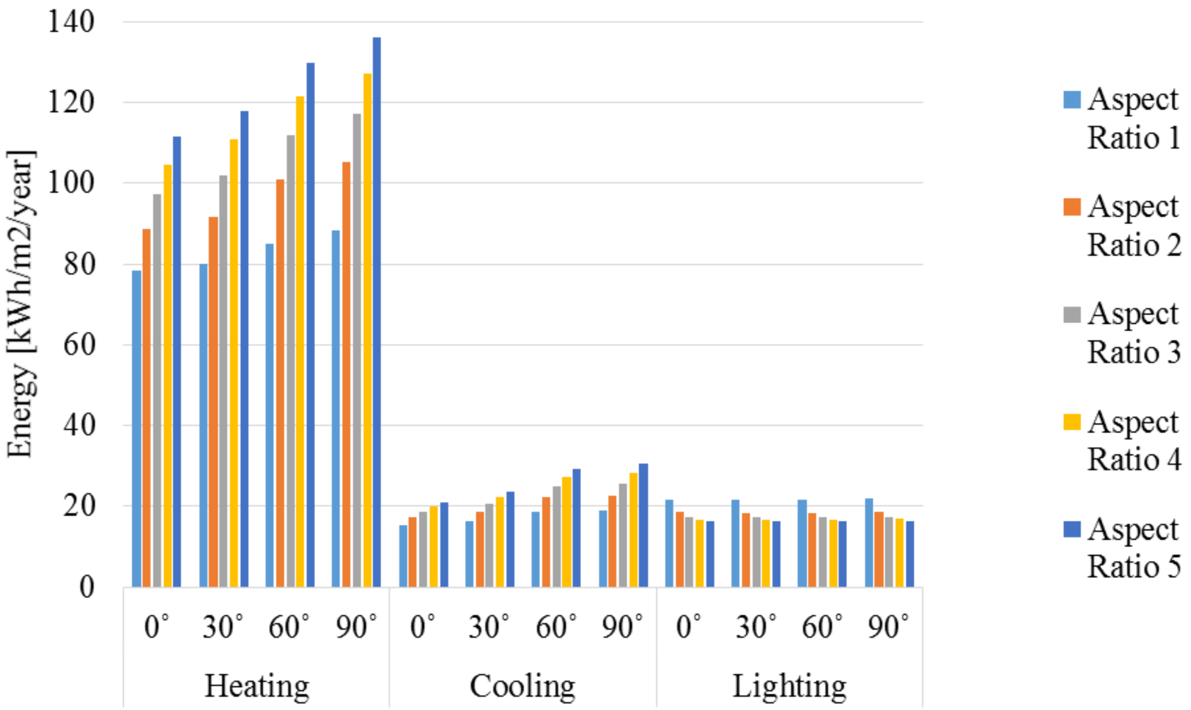
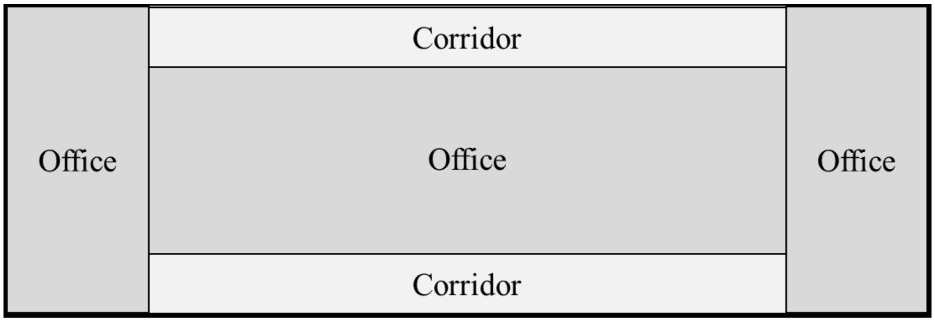


Figure 3.48 Architectural conceptual design energy performance (Meng, et al., 2014)

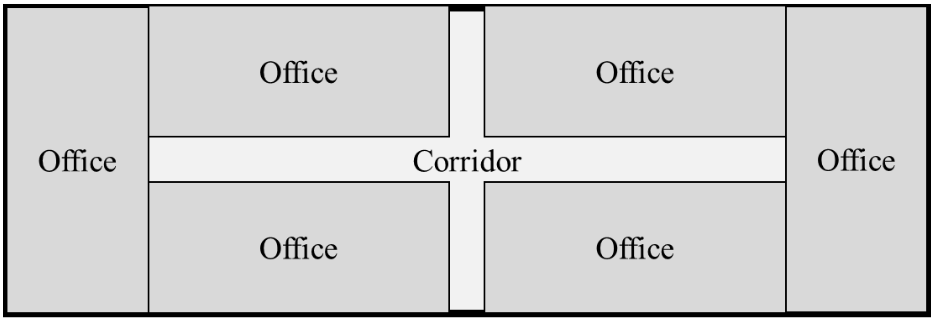
All the above analysis suggested that the compact building model with aspect ratio 1 and orientation at 0º is the most energy efficient form. For the same aspect ratio design, increases of the window area on the South façade and removal of windows on the West and Ease façades would improve energy performance significantly.

3.2.4.4.3. Internal configuration

Internal configuration heavily impacts the building performances in "Energy and atmosphere" and "Indoor environmental quality". Take interior programming as an example, allocate the office spaces along the perimeter area or centralize all of them in the middle of the floor plan may achieve very different daylighting potential, natural ventilation potential, space conditioning configurations. Therefore, two internal configuration (zoning) strategies are evaluated when Task “Define Program Chart” is performed. The first one, which is also called “external circulation design”, is to put corridors close to building envelope and office rooms in the middle of the floor. And the second “internal circulation design” is to have corridors in the middle of the floor but have offices and conference rooms close to the building envelope. The two zoning strategies are illustrated in Figure 3.49.



External Circulation



Internal Circulation

Figure 3.49 External & Internal circulation design

The impacts of exterior and interior zoning designs on “Energy and atmosphere” and “Indoor environmental quality” are listed in Table 3-7. Each design has its advantages and disadvantages. The architectural design team will focus on other performance aspects such as

"Indoor environmental quality" and actual functionality requirements to make their decisions regarding the internal configuration.

Table 3-7 Performance comparisons of exterior and interior zoning

	Energy and atmosphere	**Indoor environmental quality**
Exterior circulation	**Pros:** • Can use corridor as the buffer zone to reduce heating/cooling load. **Cons:** • Less opportunities of integrating passive design to reduce the energy consumption, such as: daylighting, natural ventilation	**Pros:** • Less noise interference from outside (also depends on façade treatment). **Cons:** • Reduce the daylighting potential and visual quality of the perimeter zones.
Interior circulation	**Pros:** • Higher chance to use daylighting which can save lighting energy. • Higher chance to use natural ventilation which can reduce heating/cooling load. **Cons:** • Depends on façade build up, perimeter zones may increase the heating/cooling load due to the heat transfer through building enclosure.	**Pros:** • Better visual quality for perimeter zones (if corridor is not fully glazed). • Higher chance to use natural ventilation which can improve the indoor air quality. **Cons:** • Depends on façade build up, more complex HAVC system design and operation may be required to maintain perimeter zones' thermal comfort. • Require more carful glare and noise control for perimeter zones.

3.2.4.4.4. External enclosure

As mentioned in section 3.2.4.3.5, the external enclosure is an interface between the interior and the exterior environments, so its design relates to a broad scope of design strategies/parameters not only from enclosure design itself but also from many other design factors such as form and massing, internal configuration, and environmental systems. Because of this, the external enclosure design will affect a wide range of performance aspects. In this section, two roof systems design strategies were evaluated.

In the task “Define Enclosure Strategies”, the architect design team may consider a conventional roof system, more sustainable roof strategies like white/cool roof or other sustainable roof types like green roof in order to improve the performance. The comparisons among them are listed in Table 3-8 with focus on more roof design related aspect: “Site Sustainability”, “Water Efficiency”, “Energy and Atmosphere”.

Table 3-8 Performance comparisons of roof strategies

	Site Sustainability	**Water Efficiency**	**Energy and Atmosphere**
White/cool roof (Wikipedia, 2021)	**Pros:** • Help in mitigating the heat island effect. • Offsetting of the warming impact of greenhouse gas emissions. **Cons:** • Increase the air conditioning demands and energy usage of nearby buildings because of reflected solar radiation form white roof.	N/A	**Pros:** • Reduce cooling load. • Reduce air pollution and greenhouse gas emissions. **Cons:** • May increase heating load as white/cool roof reflects solar which would help warm the building.

Green roof (Intensive) (Wikipedia, 2021)	**Pros:** • Help in mitigating the heat island effect. • Create natural habitat. • Help filtering air pollutants.	**Pros:** • Reduce storm water runoff. • Reduce site water usage **Cons:** • Increase weight of roof and hence required building structure. • Increase waterproofing systems complexity. • Require more maintenance.	**Pros:** • Reduce cooling load. • Reduce heating load. • Improved thermal comfort in buildings that do not have air conditioning.

There are two main issues with white roof application: reflected solar radiation from the white roof may cause energy use increase or glare issues for surrounding buildings; solar heat gain needs to be balanced between heating and cooling demand as higher heat gain is desirable in winter, but not in summer. Because there are only a few buildings around the site of the CoE building, most of them are lower than the tower of CoE building, so the white roof can be applied to it without causing energy use increase or glare issues for surrounding buildings. In addition, most of the building roofs are covered by snow for a long period of time during the winter in Syracuse, so there is no solar heat gain balancing question of white roof application. Therefore, white roof can be used on top of the office tower of CoE building to minimize the solar heat gain and reducing the cooling load.

The green roof technology can be applied to the sloped ramp wing because it can mitigate the heat island effect; provide better visual comfort for occupants in office rooms; help to filter the air pollutants coming from the nearby highway; reduce the stormwater runoff; and reduce both heating and cooling load Figure 3.50. In addition to the benefit of applying white and green roof systems, both the tower and lab wing portion of the building could also incorporate skylight and rainwater collection systems to further improve the sustainability.

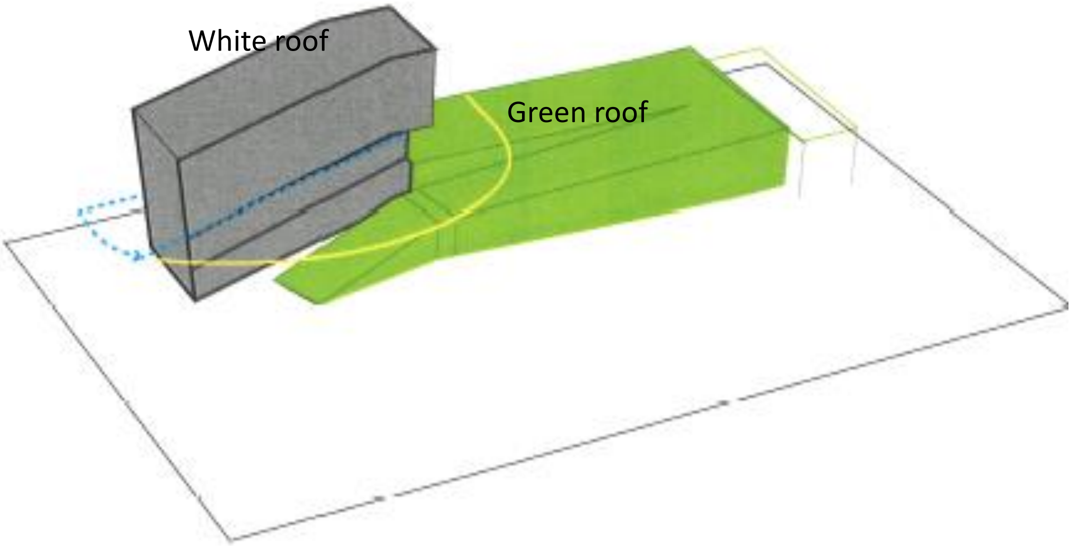


Figure 3.50 White roof and green roof defined for CoE building (Augustine, 2011).

3.2.4.4.5. Design integration/optimization (external enclosure & environmental systems)

Besides enhancing design team collaboration, MC also promotes design factor integration by defining task interdependencies. A design factor integration example between External Enclosure and Environmental Systems is shown in Figure 3.51. Two tasks “Develop enclosure drawing and specifications” and “Design environmental systems” are assumed to be concurrently performed by an architect and an engineer, respectively. The architect leads the External Enclosure design with feedbacks from the engineer regarding the enclosure impacts on possible weak linkages for thermal bridges and moisture condensation as well as overall energy savings and IEQ performance, while the engineer leads the Environmental Systems design with feedbacks from the architect on enclosure materials and assemblies (e.g., fenestration size, allocation, and type). They could also explore and discuss opportunities for integrating enclosure design with the environmental control system, e.g., integrate operable windows on the facade for hybrid/natural ventilation, applying adjustable shading, etc.

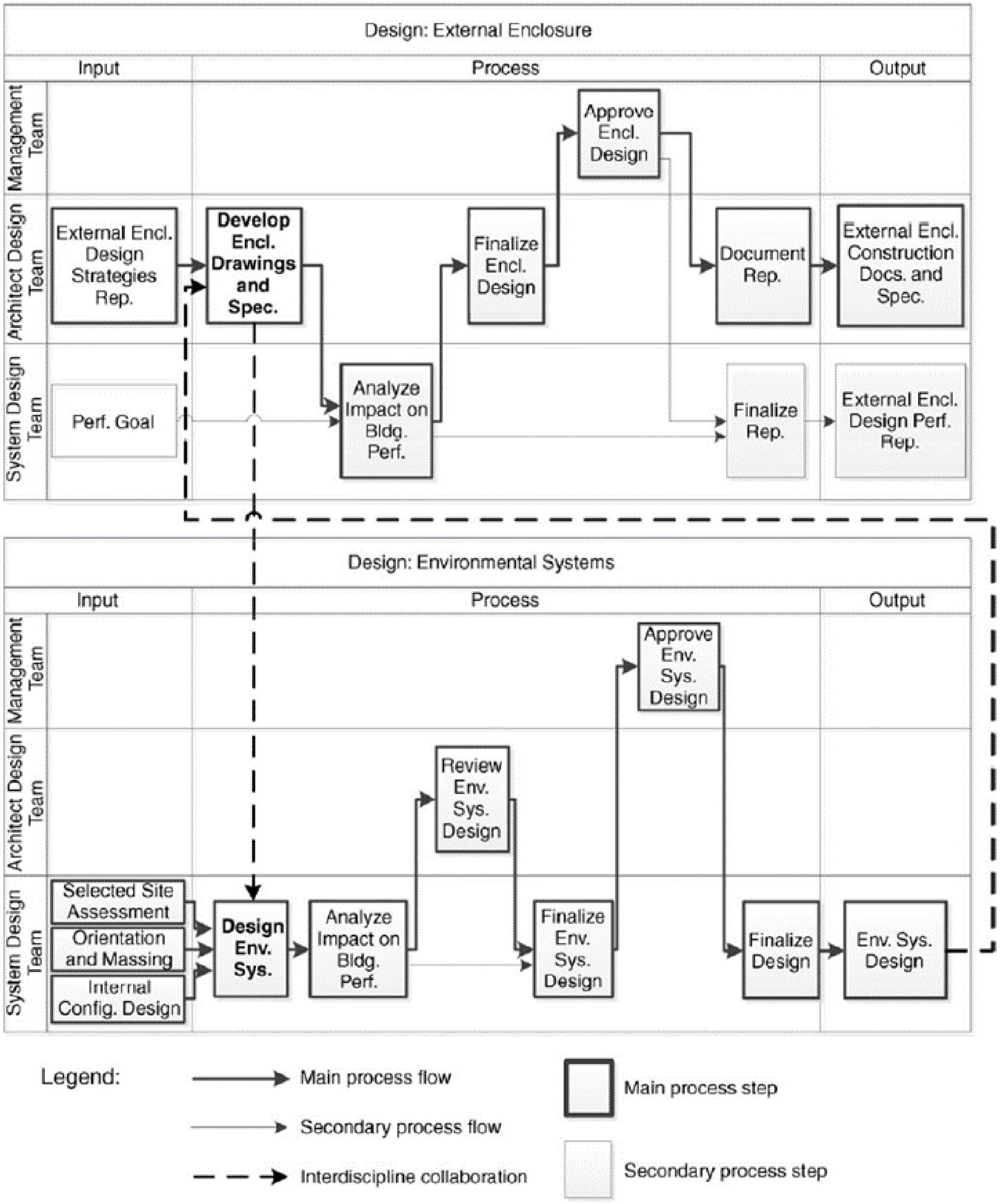


Figure 3.51 Design integration example of External Enclosure & Environmental Systems

(Zhang, et al., 2013)

Window size (represented by WWR) and type (associated with different U-value and visible transmittance) were selected as example design parameters to show how the building enclosure design affects the environmental system design in terms of heating/cooling load, and lighting. The same RBM is used. The WWR and window types are used as the input to examine their effect on Environmental Systems design in terms of heating/cooling load, and lighting. Three values of WWR are selected: 20%, 33%, and 50% which are lower, equal to, and higher than the RBM, respectively. Three types of double-pane windows are selected, their properties are listed in Table 3-9.

Table 3-9 Properties of windows (Meng, et al., 2014)

Window Type	Type 1	Type 2	Type 3
Material	Clear 3 mm	Clear 6 mm	LoE Clear 6 mm
U-Value (W/m^{2}k)	3.64	1.84	1.84
Solar Transmittance	0.84	0.78	0.43
Visible Transmittance	0.898	0.881	0.770

For the same type of window, heating energy consumption increases when WWR changes from 20% to 33%, and then it decreases when WWR expands to 50% (Figure 3.52). Such trend is more apparent for type 1 window than type 2. This is because heat loss through the windows cannot be compensated by increased solar gain with only a small increase in WWR (from 20% to 33%). Window type 1 always has a higher heating load than type 2 because it has much higher U-value than type 2. Window type 2 and 3 have the same U-value which is much lower than window type 1, but their solar transmittance is very different. Much less transmitted solar radiation helps reducing a significant amount of cooling energy when type 3 window is used. Although there is a small reduction in solar heat gain in winter due to the low-E window, there is more heating energy saved by reflecting radiant infrared energy back to the indoor space. The window transmitted solar and heat loss of winter design day is shown in Figure 3.53 (summation of all windows on 4th floor, WWR 50%). Type 3 window receives less transmitted solar than type 2 during daytime, but its heat loss is far less when the solar radiation is not intensive or no solar radiation (at night). So, in total, type 3 window saves more energy than type 2 in heating as well as cooling.

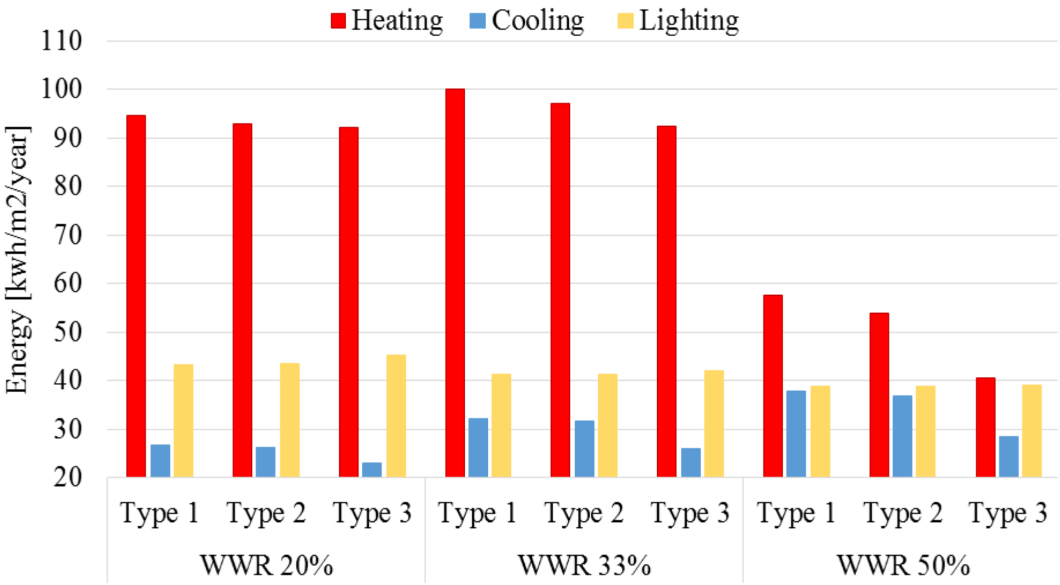


Figure 3.52 Enclosure design impact on heating, cooling, and lighting (Meng, et al., 2014)

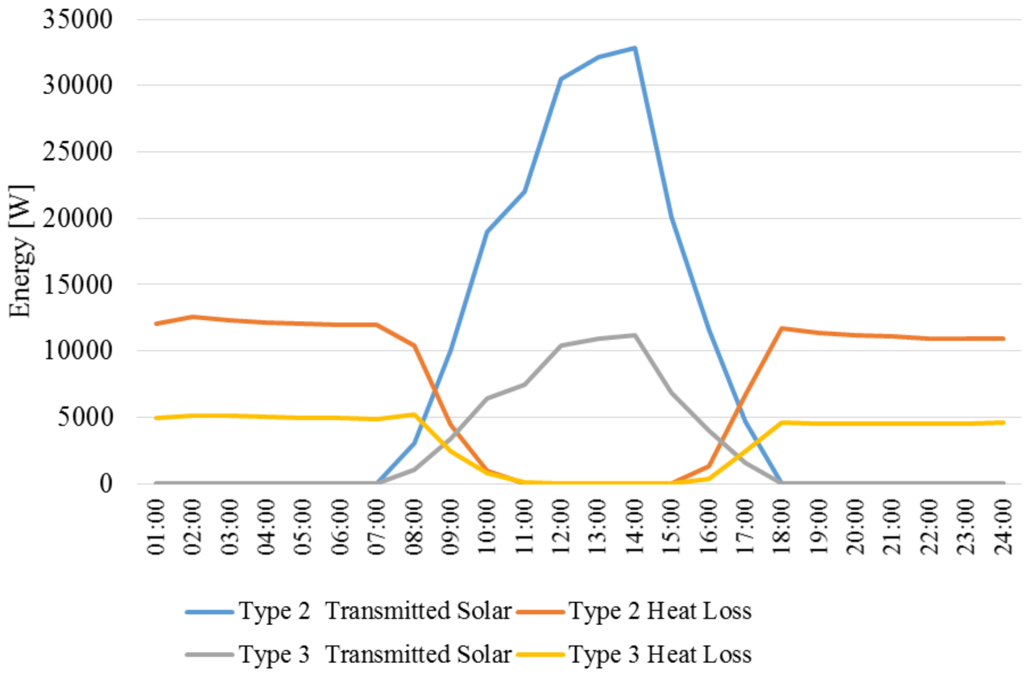


Figure 3.53 Type 2 and 3 window winter design day transmitted solar and heat loss comparison (Meng, et al., 2014)

Cooling energy use increases when WWR increases. It is because the larger window area allows more solar heat to pass through the window. It is worth noticing that window with low-E coating (type 3) can effectively reduce both heating and cooling load. Compare to heating and cooling load, WWR as well as window type have very limited impact on lighting energy use. In addition, since the cooling load is very low compares to heating load, if outdoor air quality and wind speed, direction meet certain level, the system team may suggest the architectural team to integrate hybrid ventilation for cooling energy saving when the enclosure is designed which also results in different environmental design.

3.2.5. Conclusions

MC facilitates multi-disciplinary team coordination, multi-factor integration from early to the final design. Task-based structure supports design process decomposition, information aggregation, and representation. Effective design guidance can be provided by the MC design process and simulation-supported performance evaluation. More comprehensive real-world design cases could be investigated in further studies to evaluate the effectiveness of the MC process.

CHAPTER 4. A SIMPLIFIED AND SCALABLE HEAT-FLOW BASED APPROACH FOR OPTIMIZING THE FORM, MASSING AND ORIENTATION FOR HIGH PERFORMANCE BUILDING DESIGN

This chapter introduces a simplified and scalable heat-flow based approach for form, massing and orientation in early stage design of HPBs. RBM is first defined with pre-selected building materials and HVAC systems for the intended climate and site conditions. The energy performance of this RBM is estimated by the whole building energy simulation. Heat fluxes from the enclosure are extracted from RBM simulation. A simplified and physics-based correlation model was developed to predict how these fluxes would be affected by the shape of the building geometry, WWR, and orientation of a proposed building design, which can significantly differ from the RBM. Based on building space heat balance, the predicted heat fluxes were then used to predict the energy consumption of the proposed building design.

4.1. Introduction

Decisions made during early design stage (Figure 4.1) can significantly affect and limit later design choices (Meng, et al., 2014). For example: building form and massing design affect enclosure and environmental systems design.

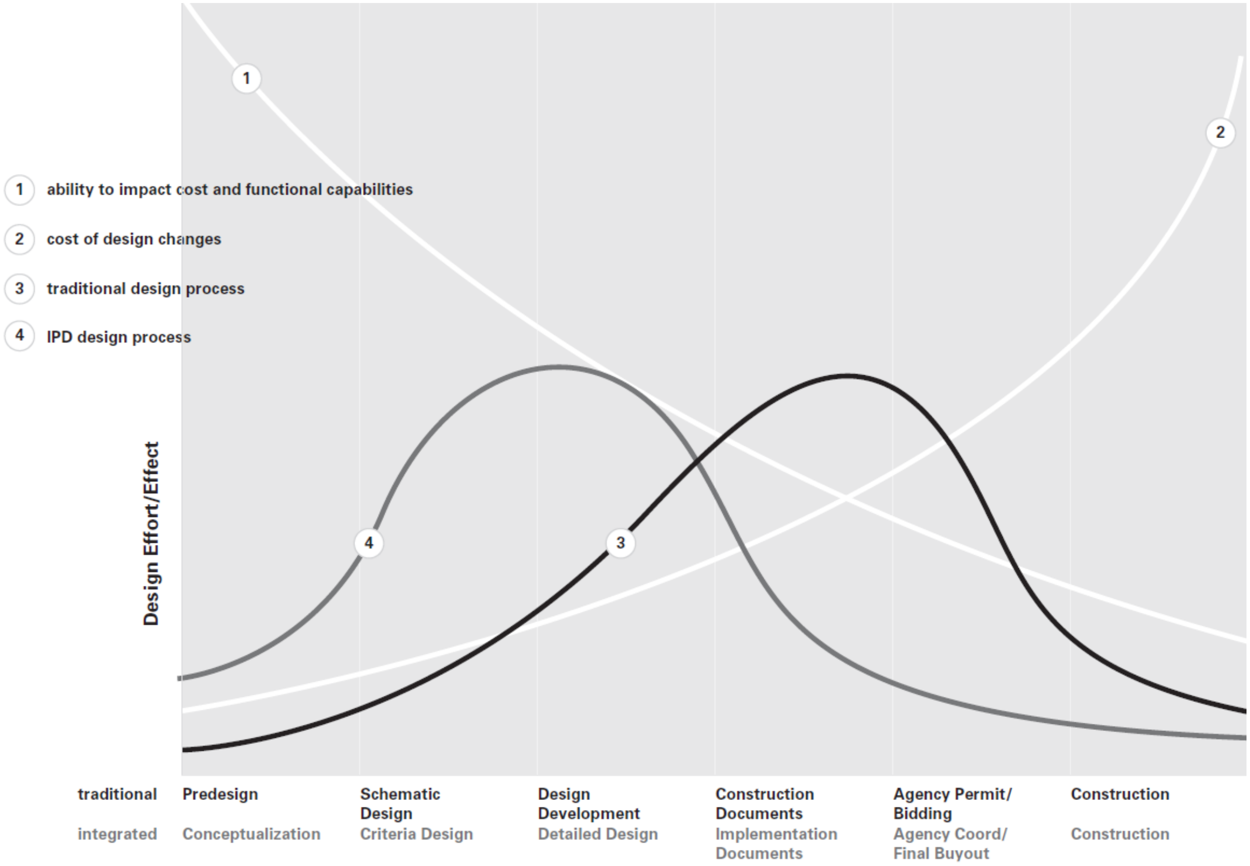


Figure 4.1 Early Stage Design Impact (American Institute of Architects, 2007)

Although detailed whole building energy simulation can be used to inform designers to achieve better performance, it is generally too time-consuming for the early design stage in which fast feedbacks on design choices are needed while insufficient design details are available for such simulations. Other methods using statistics or artificial intelligence techniques have been developed (Kadir Amasyali, 2018). However, their applications are limited to design parameters that were selected to build the model. In addition, the model development requires a large amount of data with sufficient historical conditions (cover full operational range). The objective of this study was to develop a simplified and scalable heat-flow based approach to support the early stage HPBs design integration and optimization.

As introduced in Chapter 3, the whole building was categorized into multi-design factors (site and climate, form and massing, internal configuration, external enclosure, environmental systems, energy systems, water systems, material use and embodied energy, and system interdependencies). While considering all design factors, this chapter focused on the integration of important form and massing design (include orientation, aspect ratio, WWR, and placements on different facades) for given the enclosure (wall, window types) and environmental systems design.

4.2. Methodologies

The external enclosure of a building separates the outdoor environment from indoor spaces. It regulates the heat flows passing through it. For example, conducted heat flow through opaque walls and solar radiation through windows. In order to integrate form and massing design and provide fast performance feedback, it is very important to quickly quantify heat flows through the building enclosure.

4.2.1. Heat balance

The method in this study originated from fundamental heat balance principles, as shown in Figure 4.2 and Equation 4.1. In order to maintain the indoor air temperature at setpoint (left part of the equation), the zone air energy loss/gain through building enclosure ($\dot{Q}_i$) and internal loads ($\dot{Q}_{internal}$) via multiple heat transfer mechanisms (including radiation, conduction, and convection) should be balanced by HVAC systems ($\dot{Q}_{HVAC}$) which directly determines the energy consumption needed for the space air conditioning.

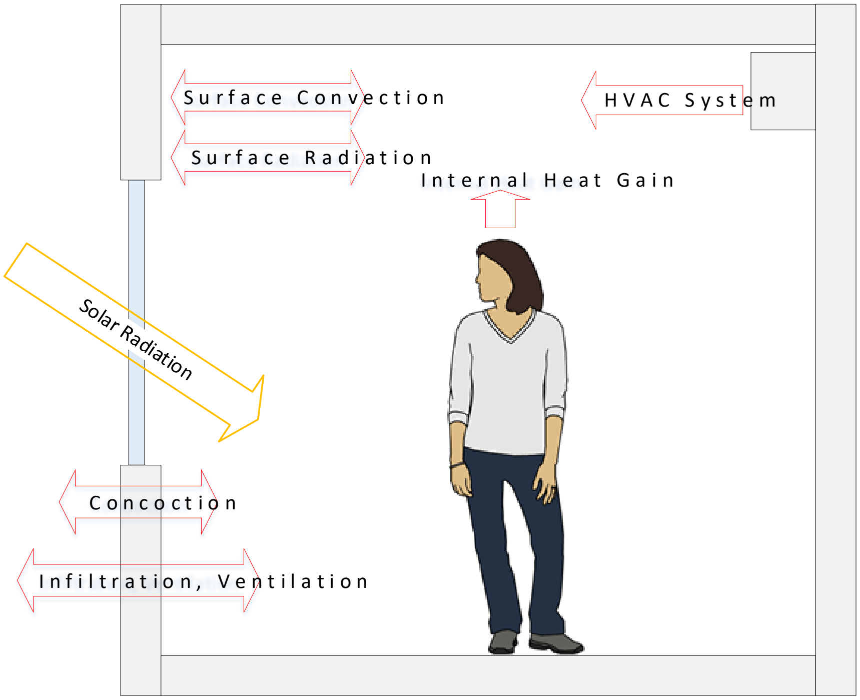


Figure 4.2 Building (Zone) energy balance (Meng & Zhang, 2016)

$$(V \cdot \rho_{air} \cdot C_p)\frac{dT_z}{dt} = \sum_{i=1}^{N_{surfaces}} \dot{Q}_i + \sum_{i=1}^{N} \dot{Q}_{HVAC,i} + \sum_{i=1}^{N} \dot{Q}_{internal,i} \qquad \text{Equation 4.1}$$

Where:

$(V \cdot \rho_{air} \cdot C_p)\frac{dT_z}{dt} = energy\ stored\ in\ zone\ air$

$V = zone\ volume$

$\rho_{air} = \ zone\ air\ density$

$C_p = zone\ air\ specific\ heat$

$T_z = zone\ air\ temperature$

$\sum_{i=1}^{N_{surfaces}} \dot{Q}_i = sum\ of\ the\ zone\ surface\ convective\ loads$

$\sum_{i=1}^{N} \dot{Q}_{HVAC,i} = HVAC\ (air\ system)\ supplied\ energy\ to\ the\ zone$

$\sum_{i=1}^{N} \dot{Q}_{internal,i} = \ internal\ loads$

The heat transfer through the enclosure is a very complex and dynamic process; so is their calculations. Instead of directly calculating heat flows, this method predicts building energy performance using heat flow predicted from correlations against RBM. The hierarchical heat flow and energy prediction overview is shown in Figure 4.3. Heat fluxes through all enclosure components (roof, facades, and ground floor) were extracted from RBM and aggregated from zone up to the whole building level. Then the total energy required to balance the gain/loss was obtained by correlations between the relative change of energy consumption from the RBM and the change in design parameters. EnergyPlus was used to perform whole building simulation in this study to obtain the data for the correlation development. For projects located at various locations, the corresponding Typical Meteorological Year 3 (TMY3) weather data file were used to provide hourly values of solar radiation and meteorological elements for a 1-year period (S. Wilcox, 2008)

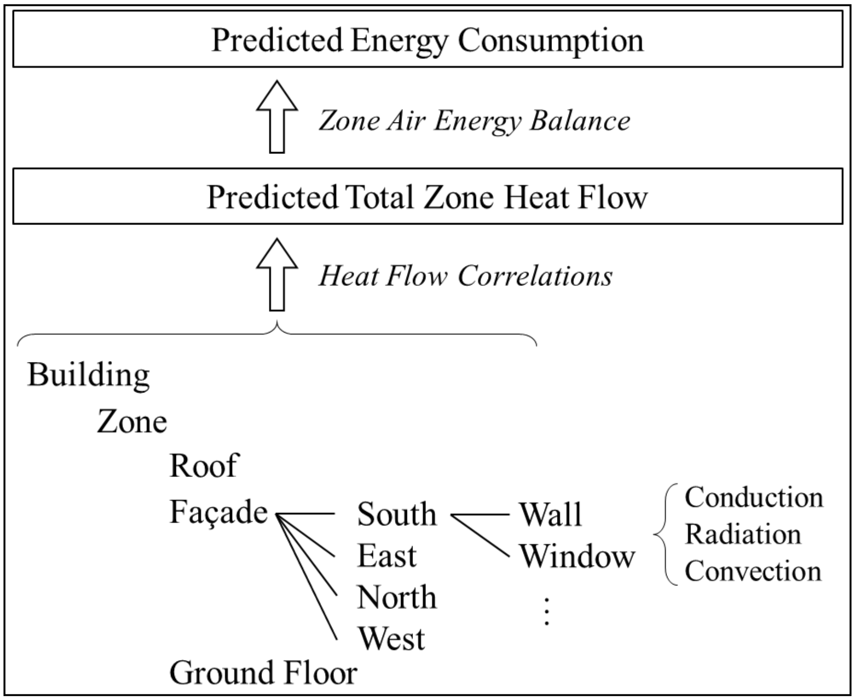


Figure 4.3 Hierarchical energy & heat flow prediction method overview (Meng & Zhang, 2016)

4.2.2. Heat flow prediction

Heat flow passing through building enclosure depends on both inside and outside space conditions as well as the assembly thermal properties (thickness, conductivity, specific heat, etc.). Figure 4.4 and Figure 4.5 are examples showing various heat transfer processes that affect the energy flow through a typical wall assembly and window system (U.S. Department of Energy, 2018). They include outside temperature, wind speed and direction, and surface condition impacted convections; direct, reflected, and diffused sunlight absorbed on surfaces; longwave radiation received from the adjacent environment, etc. The inside surface involves additional received longwave radiation from internal sources (people, equipment, and lightings). Heat flow passing through windows can be even more complex, involving solar radiation transmitted through windows (beam and diffused), absorbed by windows themselves and beam covered interior surfaces, reflected and redistributed on inside surfaces etc.

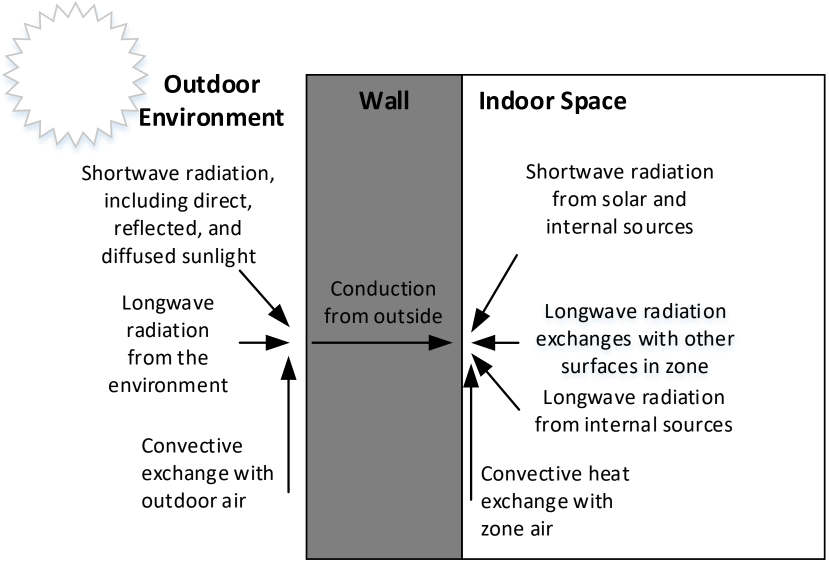


Figure 4.4 Heat transfer of wall (Meng & Zhang, 2016)

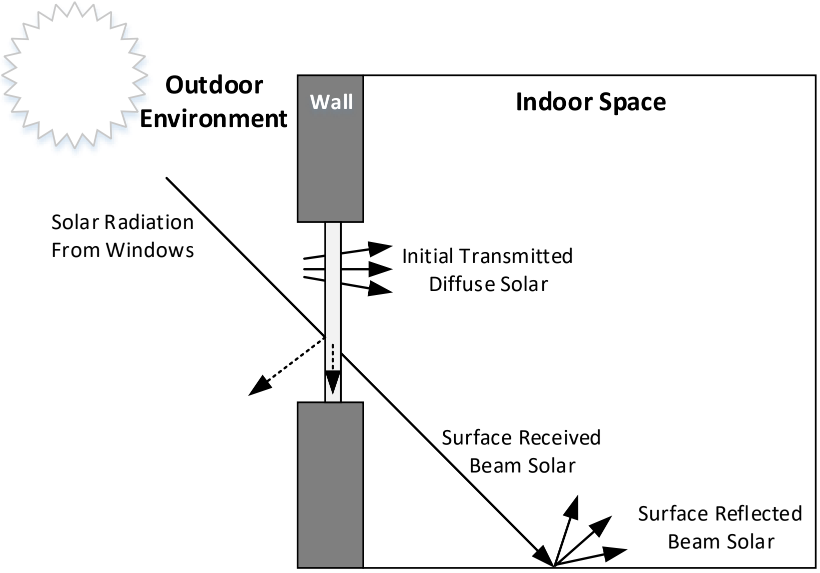


Figure 4.5 Heat transfer of window (Meng & Zhang, 2016)

In order to facilitate fast estimation, instead of directly calculating heat flows, the following method was developed to predict the heat flows using extracted heat fluxes from pre-simulated RBM and correlation functions to capture effects of building orientation:

a) To extract the heat fluxes of each building enclosure component, the developed method systematically decomposed the whole building enclosure according to their heat transfer characteristics:

   - Roof is always facing the sky and fully exposed to solar radiation which is hardly affected by building rotation;
   - Façades (walls, windows) are heavily influenced by their directions due to different amount of radiation received and transmitted;
   - Ground floor has relatively stable outside boundary conditions (underground temperature); but its inside surface can be affected by window size and placement on different facades which introduce solar radiation with varied transmitted intensities.

Therefore, the developed method classified building enclosure surfaces as: roof, wall/window facing four directions (S, E, N, and W), and ground floor.

b) The orientation impact on heat transfer of enclosure is captured by heat flow coefficient $C_{ori,\ x}$ for each type of enclosure. It is defined as the heat flow ratio, shown in Equation 4.2, between rotated (the same orientation as the proposed building design) and original RBM (0 degree). Rotated RBM has the same orientation as the proposed design. For example, if a proposed design is oriented at 20 degrees (counterclockwise from North), the same orientation RBM will be simulated and compared with original RBM (at 0 degree). This heat flux coefficient $C_{ori,\ x}$ allows quick calculations of each enclosure surface's heat flow.

$$C_{ori,\ x} = q_{ori,\ x} / q_{ori,\ 0} \qquad \text{Equation 4.2}$$

Where:

$C_{ori,\ x}$ = heat flow coefficient,

$q_{ori,\ x}$ = heat flow of the RBM with the same orientation of proposed design, per unit area

$q_{ori,\ 0}$ = heat flow of the RBM, per unit area

x = the orientation

Total predicted heat flow of proposed design ($Q_{pre,\ x}$) is calculated by summation of heat flow of each type of enclosure as defined in Equation 4.3 below.

$$\dot{Q}_{pre,\ x} = \sum_{i=1}^{n} \dot{q}_{ori,\ 0,\ i} * C_{ori,\ x,\ i} * A_{pro,\ i} \qquad \text{Equation 4.3}$$

Where:

$\dot{Q}_{pre,\ x}$ = total predicted heat flow of proposed design

$\dot{q}_{ori,\ 0,\ i}$ = the extracted surface heat flow of the RBM, per unit area

$C_{ori,\ x,\ i}$ = heat flow coefficient

$A_{pro,\ i}$ = surface area of proposed design

n = the nth enclosure surface of the proposed design

Because the surface area of each type of enclosure can vary between RBM and proposed design, $A_{pro,\ i}$ is used to accommodate the surface area differences and provide the scalability of this heat-flow based approach.

4.2.3. Heating Energy Prediction

As introduced in Figure 4.2 and Equation 4.1, HVAC systems supplied energy ($\dot{Q}_{HVAC,i}$) is provided to balance the energy loss/gain through building enclosure ($\dot{Q}_i$) as well as the internal heat gains ($\dot{Q}_{internal,i}$). Because RBM and proposed design operate at the same climate, internal heat gain conditions and space setpoint for thermal comfort conditions, as a first of approximation under steady-state with negligible internal heat gains, it can be assumed that energy consumption by the HVAC system is proportional to heat loss or gain from the enclosure, shown in Equation 4.4.

$$E_{pre,\ x} \ /\ E_{ref} = C_{flow} \qquad \text{Equation 4.4}$$

Where:

$E_{pre,\ x}$ = heating energy consumptions of the proposed design (with x degree orientation)

E_{ref} = heating energy consumptions of the RBM

C_{flow} = heat flow ratio that can be calculated from Equation 4.5

$$C_{flow} = \frac{(\dot{Q}_{pre,\ x} + \dot{Q}_{int})}{(\dot{Q}_{ref} + \dot{Q}_{int})} \qquad \text{Equation 4.5}$$

Where:

$\dot{Q}_{pre,\ x}$ = predicted total heat flow of proposed design

$\dot{Q}_{ref}$ = simulated total heat flow of RBM

$\dot{Q}_{int}$ = = internal load (heat gain/loss)

The energy consumption of the proposed design $E_{pre,\ x}$ can then be estimated using C_{flow} and simulated E_{ref} using Equation 4.4.

4.3. Case study

Syracuse CoE building (introduced in section 3.2.4) was used as a case study to illustrate this developed method. It is featured with rotated building orientation, shallow plate, and large windows on the south façade in order to implement passive energy-saving strategies. At the early design stage, in order to utilize the passive strategies by integrating form and massing design with other systems, the architectural team proposed a design with rectangular footprint, 20-degree orientation (counter-clockwise), aspect ratio at 3, and 50% WWR on the south façade and 33% for the rest of the facades.

The RBM was first automatically generated in VDS. It shared the same floor area, enclosure assemblies, and HVAC systems with the proposed design. To accommodate the 20-degree impact of form rotation, an RBM with 20-degree rotation was simulated. Then the heat flows of enclosure surfaces of both reference models were extracted for 24 hours (10-minute interval), including 10 surfaces in total: roof, walls and windows on four facades (S, E, N, and W), and ground floor. Following Equations 4.2 to Equations 4.5, the heat flows and heating energy were predicted, and corresponding results are shown in Figure 4.6 and Figure 4.7, respectively.

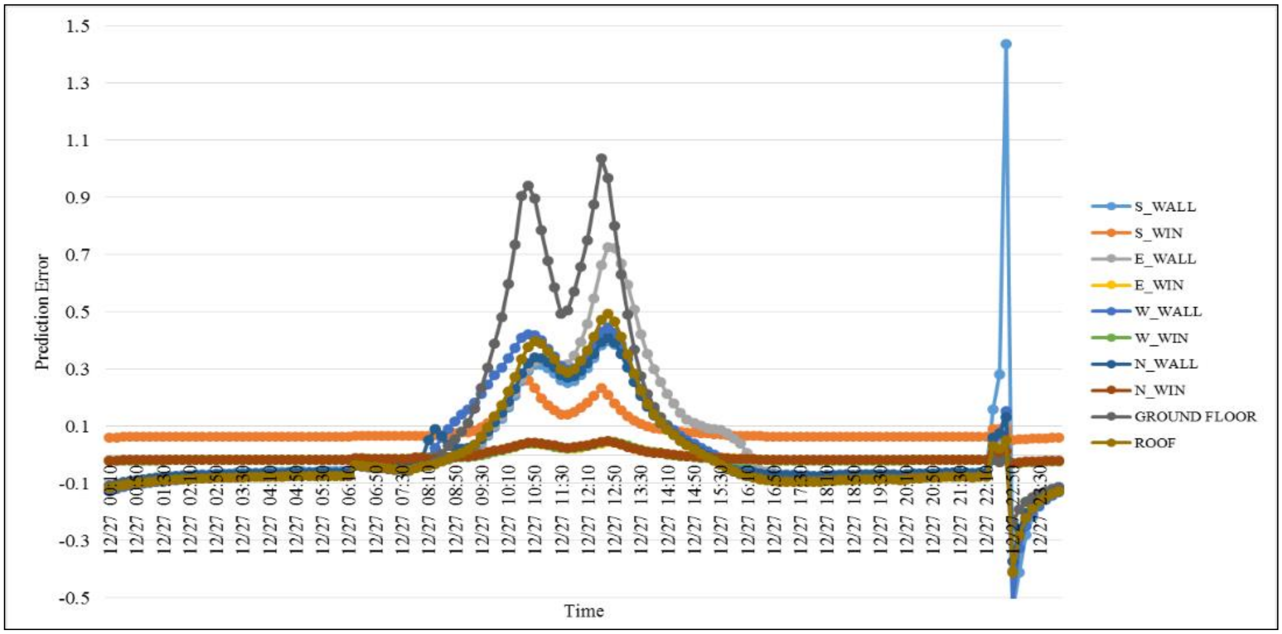


Figure 4.6 Predicted heat flow error of proposed design (Meng & Zhang, 2016)

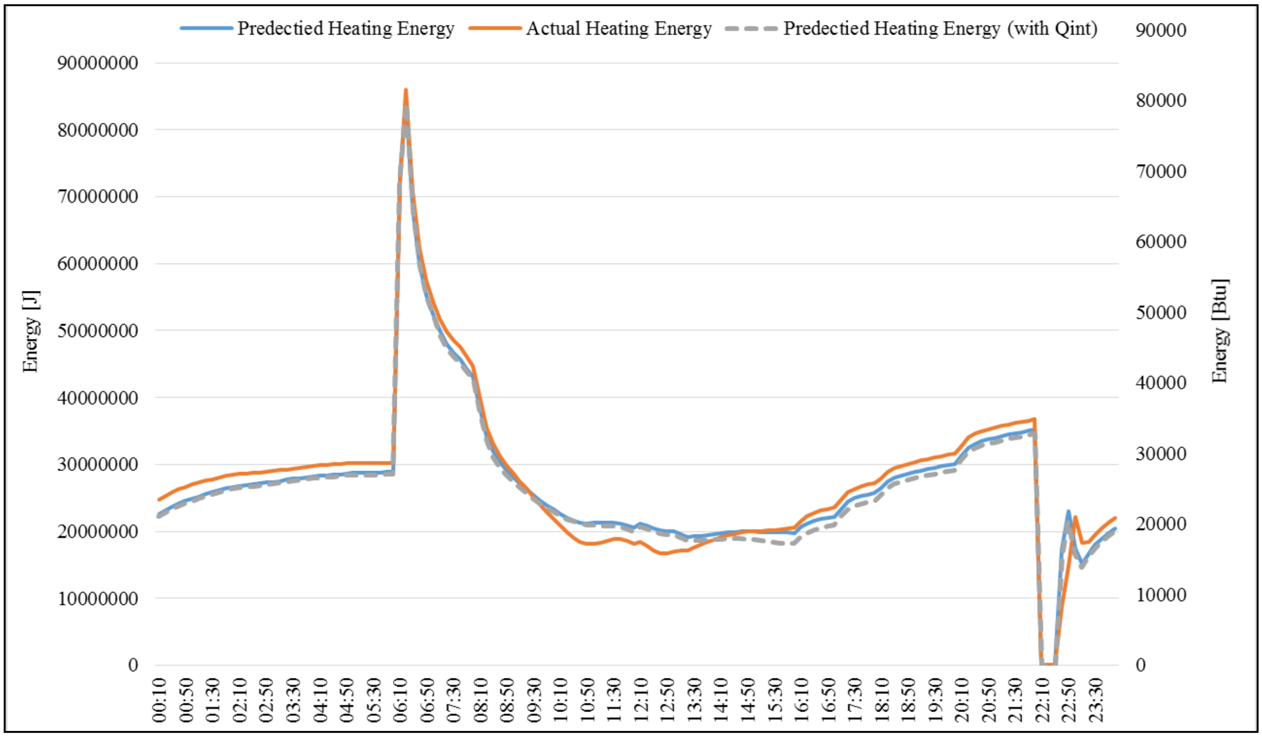


Figure 4.7 Predicted heating energy of proposed design (Actual vs Predicted) (Meng & Zhang, 2016)

Heat flow prediction in Figure 4.6 shows all surfaces are following similar variation trends, error peaks appear before and afternoon during daytime and keep very low during the night. The ground floor gives a much higher prediction error than the rest of the enclosure surfaces (with peak value around 103%). Roof and walls are on the second tier that ranges from 25% to 72%. Comparing to all the opaque surfaces, windows give quite low errors. The spikes occurring around 22:30 are caused due to sudden setpoint change-which the heat transfer dynamics can't be well captured by simulation software due to intrinsic drawbacks of the steady-state model used.

Heating energy prediction is quite well as shown in Figure 4.7. It captures the trends and overlaps with actual energy for most of the time. However, due to the heat flow prediction errors that occurred before and after noon, it is over predicted about 17% to 20% during this short period of time. Overall, the averaged prediction error of heating energy is -0.2%. The dash line is showing the heating energy prediction with internal heat gain considered; it slightly reduces the over prediction error around noon.

4.4. Discussion and result analysis

4.4.1. Surface temperature comparison

In order to further improve prediction accuracy, both inside and outside enclosure temperatures were examined in depth because the temperature difference is the driving force of heat transfer. Due to the greater error of opaque surfaces than transparent surfaces, roof, walls (S, E, N, and W), and the ground floor were examined.

The outside surface temperatures of walls are shown in Figure 4.8 to Figure 4.11. It indicated that orientation effect on the outside surface temperatures of all facades was well represented by rotating the RBM to the same angle of proposed design: outside surface temperatures of rotated RBM overlap with proposed design throughout the day but differs from RBM (0 degree). Outside surface temperatures of roof and ground floor were the same all the time due to the same solar (or no solar) they received.

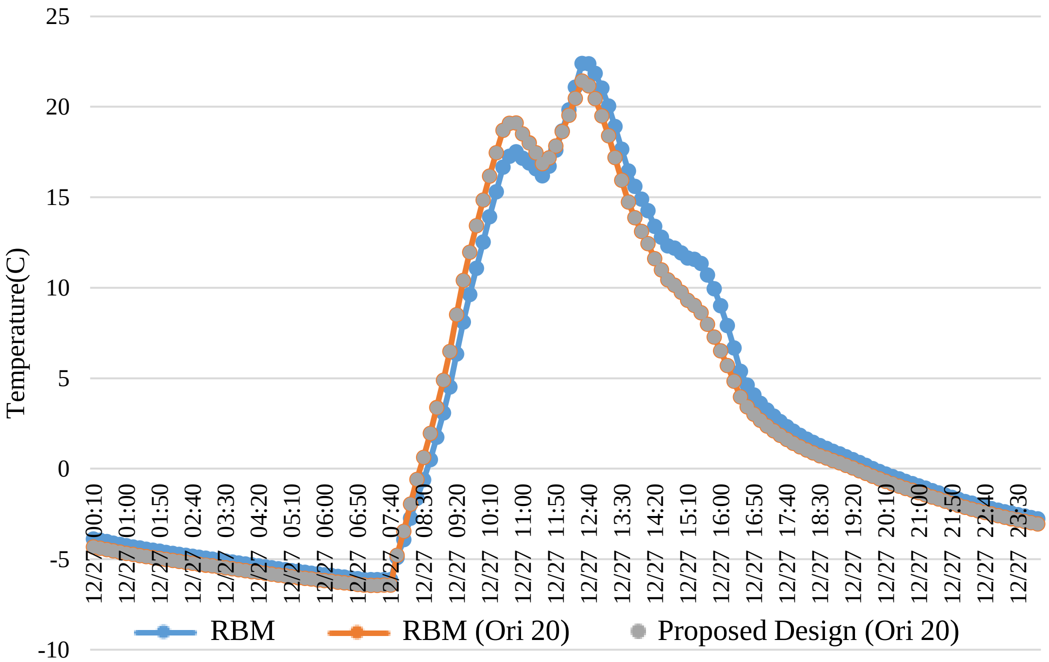


Figure 4.8 South wall surface outside temperature (Meng & Zhang, 2016)

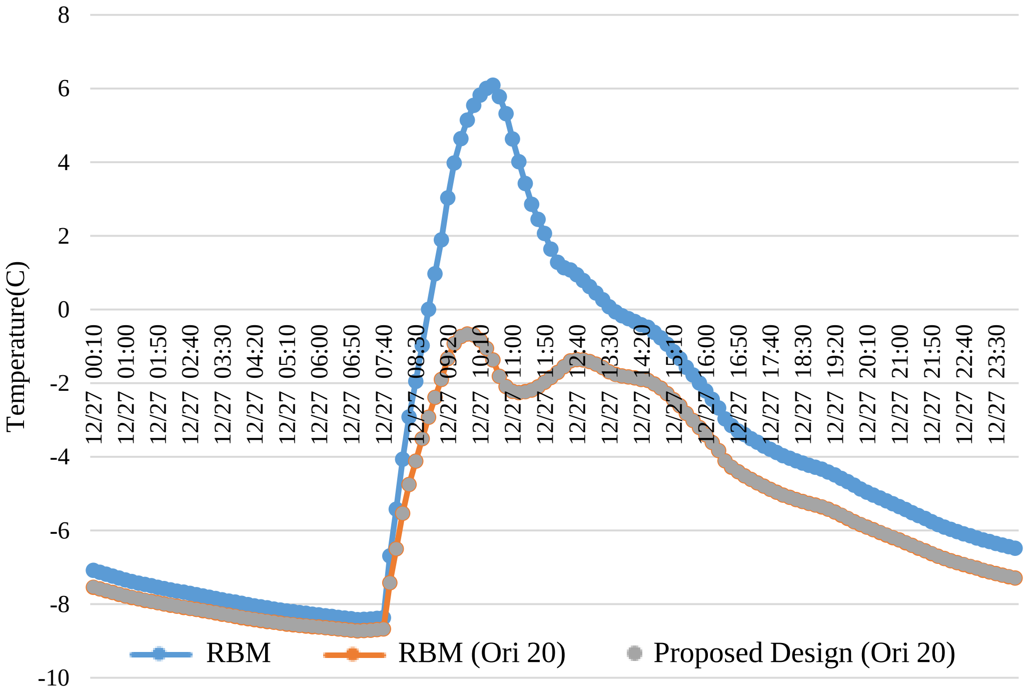


Figure 4.9 East wall surface outside temperature (Meng & Zhang, 2016)

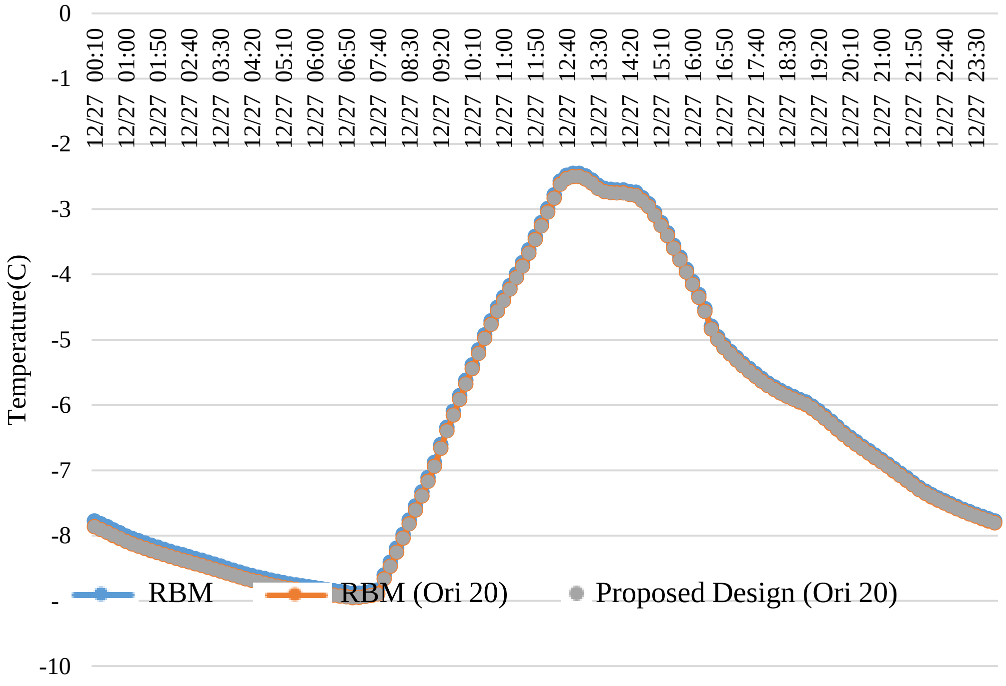


Figure 4.10 North wall surface outside temperature (Meng & Zhang, 2016)

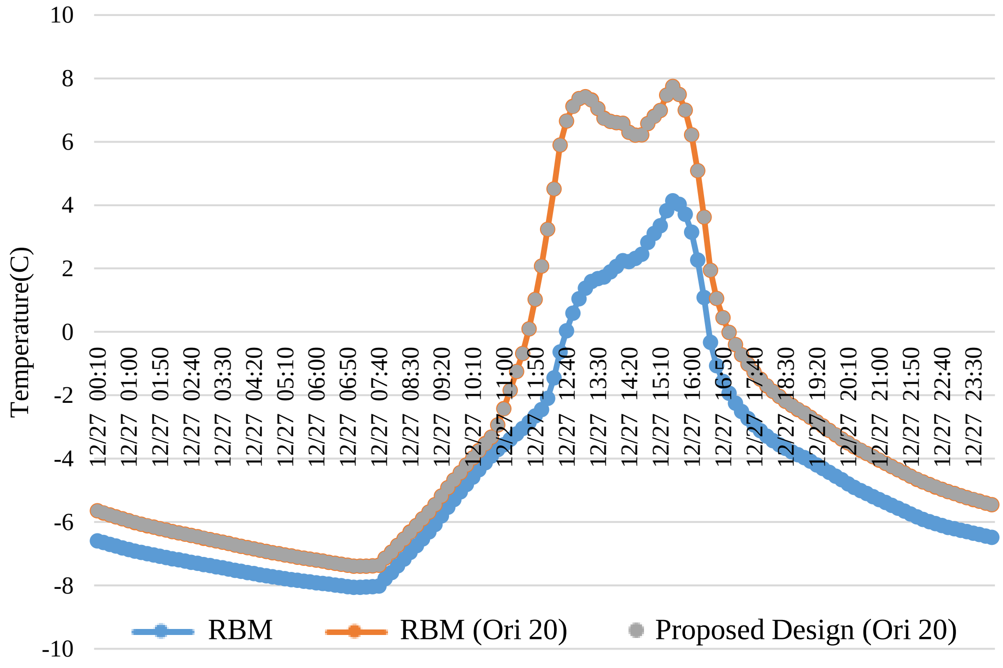


Figure 4.11 West wall surface outside temperature (Meng & Zhang, 2016)

Then focus moved to the inside surfaces. A plan view demonstrating the area difference of beam solar coverage of the ground floor is shown in Figure 4.12. Inside surface temperatures of opaque surfaces of RBM and proposed design are shown in Figure 4.13 to Figure 4.15. The inside surface temperature differences are quite similar to heat flow predictions that are represented in Figure 4.6. This is because the proposed design has a larger south façade window (50%) than RBM (33%), so at the same time point, the proposed design introduced additional solar energy from the south window into the building which eventually is distributed on all inside surfaces via projection and reflection. This additional solar energy was not considered for the inside surface energy balance in the previous prediction. Therefore, heat flows were overestimated for the proposed design. The ground floor temperature difference is most noticeable which also matches well with the heat flow over estimation. The proposed design ground floor surface temperature is about 1 °C (1.8 °F) higher than RBM before and after noon. It is because the south window introduced beam solar was directly projected onto the ground floor and raised the surface temperature. It can be also observed that temperature differences between RBM and proposed design are very similar for the south, north wall, and roof. Because they are not directly exposed (or only exposed for a very short period of time) to beam solar entered from the south window, the differences are caused by reflected solar with much less intensity than beam solar. West and east walls have greater temperature difference before and after noon, respectively. As the sun rises from East and sets from West, it projects beam solar on the west wall in the morning and the east wall in the afternoon.

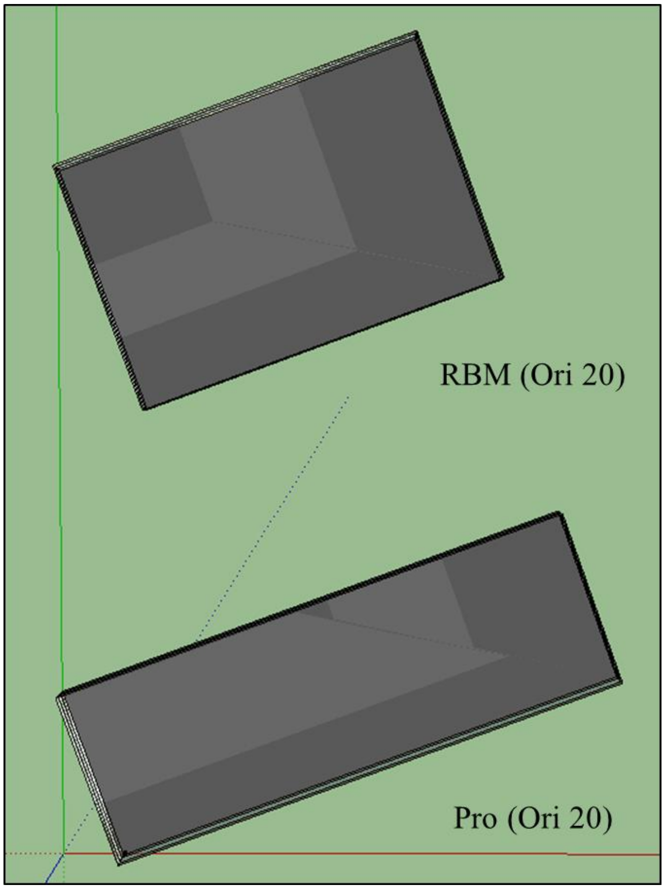


Figure 4.12 Ground floor received beam solar comparison (plan view) (Meng & Zhang, 2016)

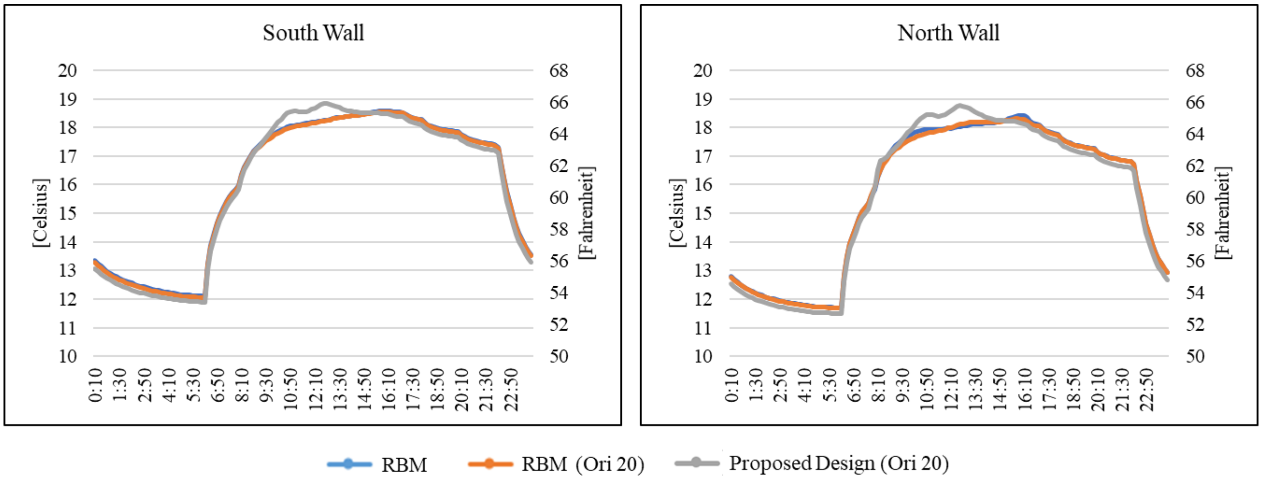


Figure 4.13 South and North wall surface inside temperature (Meng & Zhang, 2016)

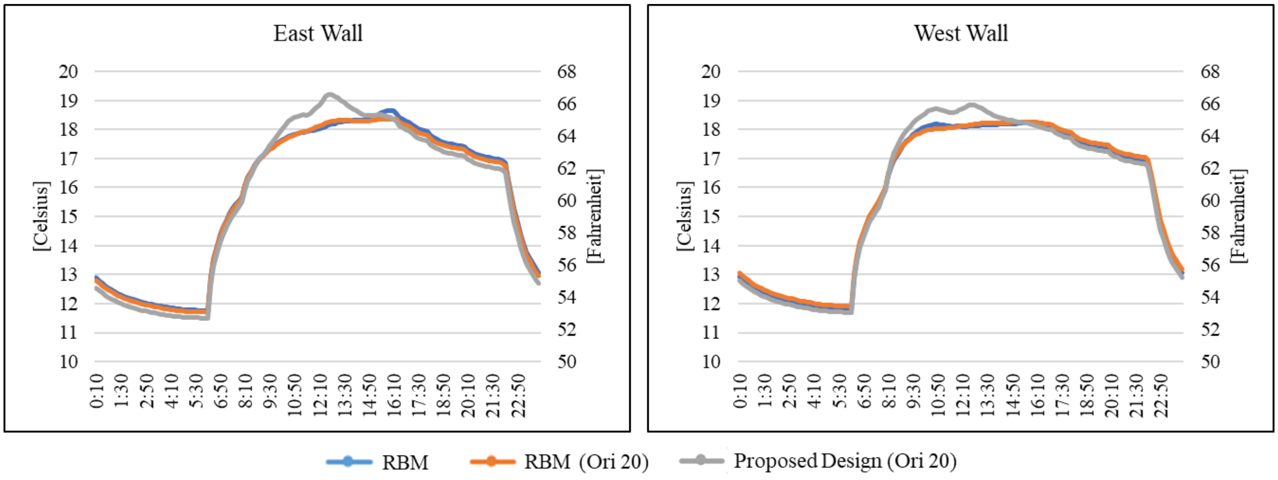


Figure 4.14 East and West wall surface inside temperature (Meng & Zhang, 2016)

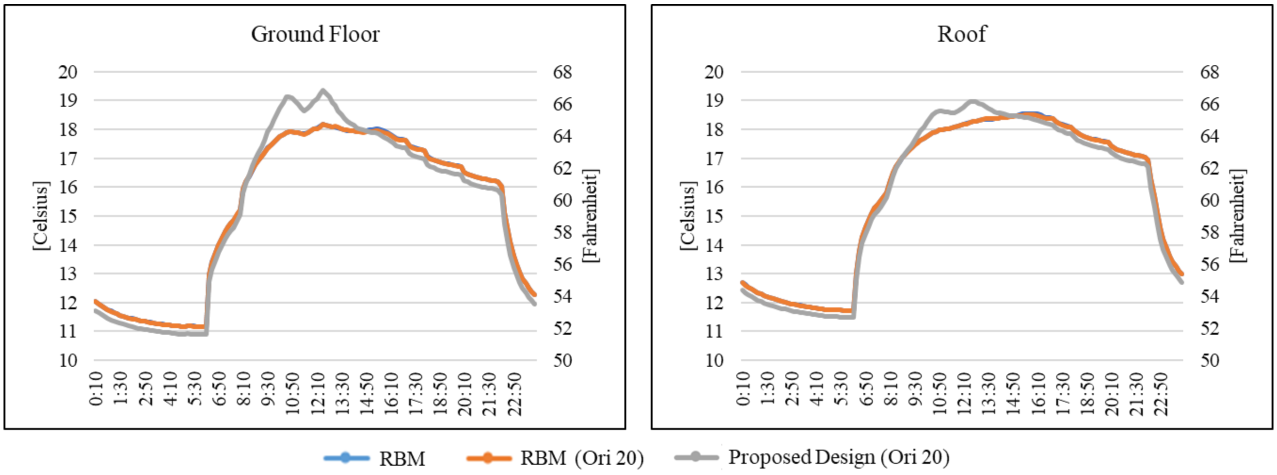


Figure 4.15 Ground floor and roof surface inside temperature (Meng & Zhang, 2016)

4.4.2. Heat flow prediction improvement

In order to reduce the heat flow prediction errors, the beam solar heat gain and ground floor reflected solar energy differences were analyzed. The beam solar heat gain ($\dot{Q}_{beam}$) is calculated according to Equation 4.6. It is a summation of beam solar introduced from all windows on that surface.

$$\dot{Q}_{beam} = \alpha \sum cos\theta_i * I_i * A_i \qquad \text{Equation 4.6}$$

Where,

α = solar absorbance of surface

θ_i = beam solar incidence angle, from the ith window

I_i = beam solar intensity transmitted though the ith window,

A_i = beam covered area on the ith window which it enters from (if shading is not used, it equals to window area).

The amount of ground floor unabsorbed beam solar equals to the total reflected solar that is redistributed among all interior surfaces. Although reflected solar will bounce a few times among surfaces, it is usually assumed in engineering calculation that reflection only happened once. Then reflected solar is evenly distributed onto all inside surfaces. The reflected heat gain of each surface is proportional to surface area (including the surface which reflected the beam).

The interior surfaces received solar energy differences (beam and ground reflected) between RMB and proposed design are normalized (to surface convective heat flow) and shown in Figure 4.16. For beam solar: a) ground floor difference is largest and matches the trend of prediction error, b) complying with the sun’s positions, differences of West and East walls appear in the morning and afternoon, respectively, c) as the proposed design has narrower floor plate than RMB, North and East walls received more direct beam in the morning and less in the afternoon, respectively so the spikes shown, d) no differences occur for surfaces like roof and south wall with no beam exposure. Comparing to beam solar, the intensity of ground floor reflected solar energy difference on each surface is much less. They reduce errors for surfaces with no exposure or during the time when surfaces are not covered by beam solar.

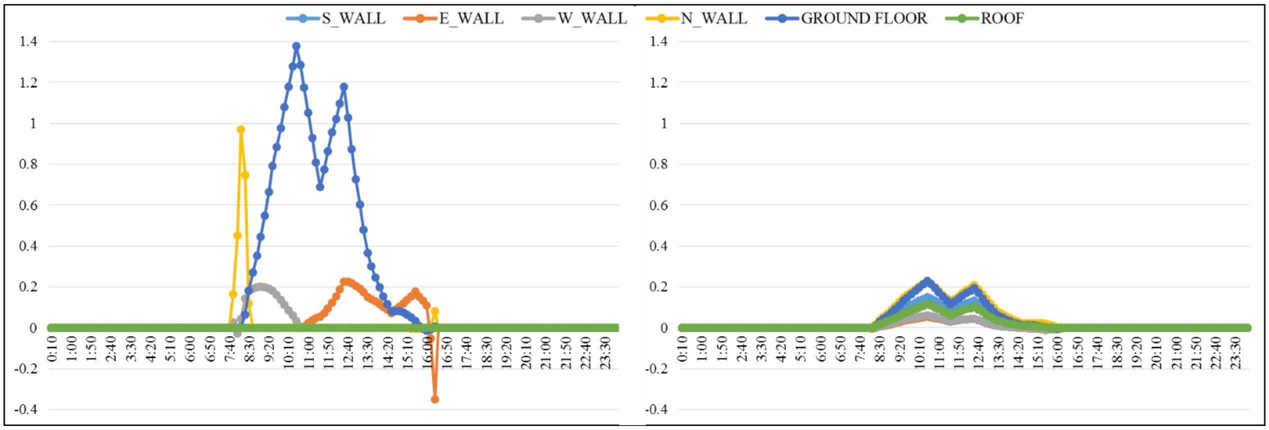


Figure 4.16 Beam (left) and ground floor reflected (right) solar energy differences (Meng & Zhang, 2016)

Heat flow prediction errors (Figure 4.6) were effectively mitigated by subtracting the above solar energy differences. Figure 4.17 shows that solar heat gain impact on interior surface energy balance caused by different window configurations and form design (aspect ratio) was effectively captured in the results. The average heat flow prediction error was reduced to -1.1%, -0.3%, -0.7%, -0.47% for walls (facing South, East, North, and West), -15% for the ground floor, and -1.7% for the roof. Ground floor error can be further mitigated when only the convective portion of received solar energy difference could be identified.

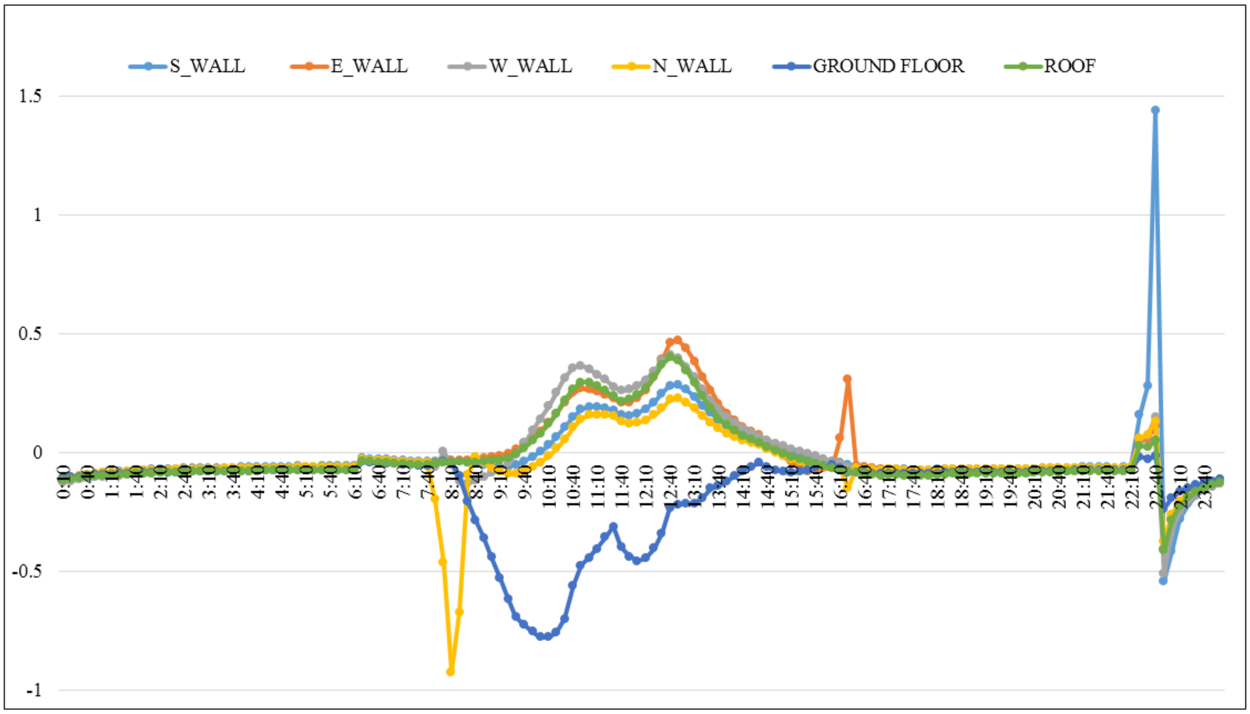


Figure 4.17 Heat flow prediction errors after correction (Meng & Zhang, 2016)

4.5. Conclusions

A simplified and scalable heat-flow based method was developed to support the early stage integration and optimization of multi-design factors. The model systematically classified the whole building enclosure systems based on their heat transfer characteristics and established correlations against the RBM to predict heat flows. Based on energy balance, it hierarchically aggregated predicted heat flow up to the whole building level to predict the energy performance. Both heat flow and energy performance prediction accuracies are sufficient for early stage analysis. Compared with conventional detailed energy simulation, this simplified scalable heat-flow prediction method enables effective design evaluations and fast iterations for the early stage HPB design optimization. For instance, in the conventional way, if the designer needs to evaluate 5 design options for each major parameters of form and massing (which include: orientation, aspect ratio, and WWR on all 4 facades facing different directions), it would need total of 15625 (= 5^6) simulations to be performed. Using the developed method, the required simulations can be significantly reduced to 6 (1 simulation for original RBM and 5 simulations for each orientation option). And the calculation time for the correlation model is negligible compared to the detailed whole building simulation time. Therefore, it can considerably reduce the computing time (by 2,500+ times for the design case analyzed above) and support the fast design iterations. Future models may be developed based on this method for more complex form and massing design and multi-design factor integrations.

CHAPTER 5. CONCLUSIONS

5.1. Summary and conclusions

A software framework VDS for the performance-based design of the green building has been established through this study. It has the capabilities of design task planning and coordination, performance simulation, results display and analysis, and performance evaluation. The framework provides a foundation for future research in integrated building system design informed by predicted performances from whole building simulation models.

The 3D design process module MC was developed as the core for the design integration and coordination in VDS. Using the "Input-Process-Output" pattern tasks with dependencies, it supports seamless transition among design stages, enhances multi-disciplinary coordination, and assist design factors integration through whole building performance analysis. A LEED Platinum rated medium-size office building was used as the case study to demonstrate how the MC method is applied to achieve a high-performance office building design. From early to the detailed design stage, the building design process and associated design parameters with heavy impacts on the building's performance were investigated, respectively. The design alternatives with optimal performance were recommended.

HPB design calls for integration, especially for early stage design that has fundamental impacts on building performance. Decisions made during the early design stage can significantly affect and limit later design choices. A simplified and scalable heat-flow based method was developed to support the early stage integration and optimization of multi-design factors. The model systematically classified the whole building enclosure systems based on their heat transfer characteristics and established correlations against the RBM to predict heat flows. Based on energy balance, it aggregated predicted heat flow up to the whole building level to predict the energy performance. Both heat flow and energy performance prediction accuracies are sufficient for early stage analysis. Compared to conventional energy simulation, this simplified scalable heat-flow prediction method is 2,500+ times faster, which enables effective and fast feedback for the early stage HPBs design evaluation and integration.

5.2. Recommendations for future research

While a VDS framework, its core design process integration module MC, and the simplified and scalable heat-flow based model have been developed and demonstrated for performance evaluation, much remains to be done to enhance and extend its capabilities for integrated building system design. Building upon the developed platform introduced in this dissertation, the following areas are recommended for future research:

- In certain critical design tasks defined in the MC module (at each design stage for given design factor), include an optimization engine to enable the recommendations of optimal design variables. It can automatically (in the background) evaluate the design alternative performances (near real-time) or provide their relative ranking for given design variable ranges. So the management/design team can make decisions with better supports.
- In this thesis, an office building was selected as the case study for the MC model template. Other templates for various types of building design processes can be developed. With

different building types, functionality, and performance considerations, the design process can vary significantly. These templates can be very beneficial for quick set up and streamlining the process, facilitating the key design integrations, and leading to the optimized design(s).

- The developed simplified and scalable heat-flow based approach for optimizing the form, massing and orientation for HPBs does not include the lighting energy. Develop a method that can predict both the HVAC systems and lighting energy can be helpful for the comprehensive evaluation of the building performance.
- Buildings have very long lifespan. This study mainly focused on the design phases. Extending the current study to incorporates the operational phase to complete the whole life-cycle performance analysis that reveals the "true success" of a building.
- "When the design of a building satisfies the emotional, cognitive, and cultural needs of the people who use it and the technical requisites of the programs it houses, the project is functionally successful" (National Institute of Building Sciences, 2020). Beyond the energy considerations, develop a performance evaluation model that incorporates these aspects.

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Professional Experience

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Publications

- Meng, Z., & Zhang, J. (2016). A Simplified and Scalable Heat-Flow Based Approach for Optimizing the Form, Massing and Orientation for High Performance Building Design. *2016 ASHRAE Winter Conference, Orlando, FL, USA: ASHRAE.*
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Honors and Awards

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