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Title: SUSTAINABLE BUILDING DESIGN FRAMEWORK: AN INTERGRATED APPROACH

Abstract approved:

Irem Y. Tumer Christopher J. Hoyle

This paper combines two research publications working toward the development of an integrated framework for commercial sustainable building design. Current methodologies utilize a traditional architectural top-down approach to sustainable building design practices that consumes financial and temporal resources early in the design process. By identifying the array mechanical subsystems required to meet modern building standards such as net-zero energy and water, and recognizing the importance of these interactions, designers can mitigate this resource consumption. The first paper presents an anthropological case study of the schematic design process of the Oregon Sustainability Center, a net-zero building slated for construction in Portland, Oregon. This research outlines the complexity of mechanical subsystems required to achieve net-zero standards and how project stakeholders affect the design process. The second paper further explores this concept by analyzing building subsystems in the context of a traditional complex system (airplane, automobile, etc.), and uses optimization techniques to understand significant system interactions. A computer model is created that optimizes lighting availability for a commercial workspace incorporating cost, building standards, and user environment. By considering post construction building usage, each subsystem can be designed for maximum user productivity, reducing costs associated with sustainable design practices.

Sustainable Building Design Framework: An Integrated Approach

by
Joseph R. Piacenza III

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APPROVED:

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Co-Major Professor representing, Mechanical Engineering

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Co-Major Professor representing, Mechanical Engineering

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Head of the School of Mechanical, Industrial, and Manufacturing Engineering

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Joseph R. Piacenza III, Author

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

SUSTAINABLE BUILDING DESIGN FRAMEWORK:
AN INTERGRATED APPROACH

INTRODUCTION

Incorporating sustainable building design practices into modern commercial and residential buildings is an essential step toward reducing global energy consumption. In the United States, 30% of the total annual energy consumed is from building usage [1]. Current building standards such as Leadership in Energy and Environmental Design (LEED), a mandate for modern sustainable building standards such as energy efficiency, water saving, materials selection, and indoor environmental quality, are contributing to the proliferation of sustainable design practices [2]. More robust standards like the Living Building Challenge (LBC), a guideline for net-zero energy and water consumption, demand more sophisticated building designs and use of modern technologies, with 12 consecutive months of zero energy use required to achieve the certification [3]. As expected, the primary barrier to these types of mandates is additional costs associated with both design and implementation practices [4]. By diverging from a typical top down architectural design approach, to an integrated design framework considering post construction occupancy, additional financial and temporal resources associated with sustainable design techniques can be reduced.

A consideration often neglected when developing commercial buildings, specifically under modern standards (LEED, LBC), is post construction user interaction, and how that can affect energy usage. Designing a building as a snapshot in time, without understanding how design decisions will affect the building occupants, ignores the potential for user's interactions to be factored into energy use estimates. This concept, known as behavior modification, considers the building user as a component of a quantitative energy usage estimate [5]. For example, by installing passive systems such as stairs, instead of elevators, and encouraging occupant usage with aesthetic design appeal, a measurable energy savings could be achieved. It should be noted that sustainable building mandates are in addition to current building standards such as ASHRAE 90.1-2010 [6].

In addition to behavior modification, user productivity is another way to mitigate the additional costs of sustainable building techniques. By understanding how the user will respond to his or her environment, a designer can optimize a workspace for maximum productivity while still achieving an energy efficient solution that meets sustainable building standards. Previous literature suggests these two principles are not mutually exclusive in that an energy efficient workspace can also be the most productive. For example, indoor environmental factors such as lighting, temperature, and physical geometries can have a positive effect on an individual's productivity [7, 8]. By incorporating architectural features such as high ceilings, large window-to-wall ratios, and reflective surfaces, a workspace can be extremely energy efficient, while maximizing user productivity. It can then be inferred that if an individual is performing above his or her expected level, the employer will benefit financially by receiving a larger volume of work than that associated with a given pay rate.

In the first manuscript, a case study of the Oregon Sustainability Center (OSC) schematic design process was explored using the anthropological method [9]. The OSC is a 150,000 ft^2 commercial research facility designed under the LBC mandate, slated for construction in Portland, Oregon [10]. A unique opportunity was presented to passively observe various design teams during a four month timeline, where their goal was to produce a comprehensive schematic design that met the LBC's net-zero energy and water requirements. The intensive design process revealed the internal complexity of subsystems required to create a net-zero building of this magnitude, along with the diverse team of stakeholders involved. One primary barrier was the availability of energy generation techniques that could meet the needs of traditional ASHRAE building standards, which forced the designers to consider a wide breadth of passive solutions. For example, the addition of several photovoltaic (PV) arrays to the building's envelope did not meet the projected energy demands of the building. The OSC design team concluded a 75% reduction in energy usage would be required to utilize PVs as a viable energy source considering PV efficiency constraints [11]. These various design considerations allowed for the categorization of the various building subsystems required to satisfy the net-zero energy mandate. In addition, this case study highlighted the need for an integrated design method, instead of the traditional top-down approach. It also became evident during the schematic design process that stakeholder interactions during the design process had a significant effect on the design outcome, consuming financial resources.

Based on observations of designs decisions made during the schematic design OSC case study, three primary questions emerged:

- Do stakeholder interactions inadvertently drive design decisions?
- Can incorporating an integrated approach to sustainable building design facilitate resource conservation?
- Will developing an integrated framework for sustainable building design lead to replicable and reliable designs?

These questions were the basis for subsequent research presented in the second manuscript, a follow-up to the OSC case study, working toward the optimization of the various mechanical subsystems present in net-zero energy buildings. While these questions came from anecdotal evidence in a single case study, they highlight important issues associated achieving modern building standards for sustainable building design.

Stakeholder interactions are a necessary part of any large-scale project, however their effects on the design may not always be positive as communication between project leaders, contractors, designers, etc. is often limited by communication, scheduling, or hierarchical constraints. One step toward an integrated design approach, helping to mitigate these barriers, is the use of computer simulation and modeling techniques during early design trades [12, 13]. The implementation of system models in early design allows dynamic changes to be made within system, producing an array of feasible design solutions. These design options can then selected, as appropriate, by design personnel, reducing the need for multiple project level meetings.

In addition to expanding the feasible design space, computer simulation models can produce replicable designs for similar applications. During the OSC case study, a diverse breadth of talented engineers, architects, and consultants were needed to produce a design to achieve the LBC mandate of net-zero energy and water. A vast selection of sustainable building design strategies and components were chosen, based on organization tribal knowledge, training, and experience. Instead of relying exclusively on experience for future designs, populating a database with the products and materials used during the OSC schematic design would allow subsequent net-zero building to be designed using common components and associated design strategies. The second manuscript presents an argument for coupling a sustainable building component repository with a computer model to produce a design for one subsystem of a sustainable building.

Based on question raised in the OSC case study, this paper presents the concept of shifting the traditional building design paradigm from an aesthetic based architectural approach, to an integrated mechanical engineering methodology of evaluating the building as a complex system. This approach, often found in automotive and aerospace applications, presents high-level analysis of various mechanical subsystems and their interaction with each other, as well as the system as a whole [14]. One advantage of treating a building as a complex system is the introduction of complex system analysis techniques into the design process such as risk assessment, failure, and system optimization [15].

In this paper, a lighting optimization methodology is presented that considers the post construction building occupant usage in the form of workplace productivity, while still meeting building standards, and minimizing total cost. A single criterion approach is proposed that captures the trade-offs between these three factors. To further understand these relationships, a model has been developed that simulates a proposed workplace, examining the trade-offs between electrical and passive lighting components, and how different configurations affect user productivity. This process began by functionally examining the various ways lighting can be achieved within a building, and creating a component repository, populated with a selection of products including electrical lighting, windows, and light shelves [16, 17]. This repository was used as the basis for a component selection model that optimized a workplace for minimum total cost, while maximizing user productivity and maintaining current building standards. The resultant output of the model was a discrete workplace lighting geometry that included specific component selections for both active and passive lighting systems. To create a more robust model, additional subsystems could be added that also affect user productivity such as indoor thermal environment, as well as interior floor plan geometry.

This research presents an argument for incorporating an integrated design approach to sustainable building design methods by optimizing workplace environments for maximum user productivity as a way to mitigate additional costs due to sustainable building practices. By designing building subsystems for the entire lifespan of a building, instead of a one-time snapshot, the payback period could be significantly lowered. The contributions to the field of sustainable design are as follows:

- *Anthropological case study of Oregon Sustainability Center*

  The passive participation in the four-month schematic design process of the OSC produced a chronography of design process, decision events, and project stakeholders. In addition, the series of mechanical subsystems, and their associated system interactions required to achieve the net-zero requirement imposed by the LBC mandate, were identified.
- *Critical analysis of OSC schematic design process*

  Based on anecdotal evidence and literature review, observations of the OSC schematic design process identified research questions that highlighted the need for further research in sustainable building design, specifically the development and implementation of computer-simulation models for subsystem optimization during early design.
- *Subsystem optimization methodology*

  An optimization methodology was developed for the lighting subsystem of a sustainable building. This single criterion objective methodology considers cost, building standards, and user productivity.
- *Building component repository*

  To achieve replicable designs, a building component repository was populated with components used in the lighting optimization methodology including electrical lighting, windows, and light shelves.
- *Proof of concept optimization model*

  A lighting optimization model was developed using Phoenix Integration's Model Center software. This model produces an optimal design, based on cost, for a commercial workspace by evaluating trade-offs between different types of lighting (active and passive), and how it affects user productivity. Component data is taken directly from the building component repository.

BACKGROUND

The following two manuscripts include a diverse breadth of existing engineering and architectural concepts and methodologies that contribute to the big picture understanding of sustainable building design research. A primary concept explored in this research is integrated engineering design, and how it could be directly applied to sustainable building techniques. As building mandates like LEED and LBC become more sophisticated, traditional top-down approaches to building design are not feasible to achieve mandate goals [12]. This is primarily due to the addition of various mechanical subsystems required to achieve these building standards. By adopting an integrated design methodology, financial and temporal resources can be conserved during early design, increasing an investors return on investment [18]. Korkmaz et al. propose a methodology for incorporating the use of visualization tools to increase the design process efficiency, and provide a case study utilizing a *decision-based design process model* (DBDPM) [13]. DBDPM identifies critical decisions, information, commitments, and competencies the design team encounters during the design process. In the first manuscript, the decision event outlined case study of the OSC exemplifies the need of this methodology. While techniques such as this create a more efficient process, it is difficult to quantify these benefits in the context of financial savings. Vaidya et al. explore a cost estimating effort that demonstrates the ability of a design team to achieve high performance building designs without significantly increasing cost beyond a standard building design [19]. This method helps combat barriers associated with sustainable design due to perception of excess cost. Another strategy proposed by Jaffal et al. is a statistical computer simulation focusing specifically on the heating system [20]. This fast modeling of dynamic simulations allows designer to make decision about subsystem requirements, such as heating, ventilation, and air-conditioning (HVAC), earlier in the design process. Wilde et al. have also explored this strategy of incorporating building simulation tools in sustainable building design, but have expanded it to actual component selection [21].

As previously mentioned, the primary need for an integrated design approach stems from the increasing complexity of modern building standards. The most recognized standard is Leadership in Energy and Environmental Design, or LEED. This standard is typically used as a benchmark for sustainable building projects, and many new construction buildings strive to meet this standard, not only for its environmental benefits, but also for its social perceptions. The LEED standard, first published in 1998 by the U.S. Green Building Council, has five primary categories buildings are rated on [2]. These include *sustainable sites, water efficiency, energy and atmosphere, material and resources*, and *indoor environmental quality.* Each category has an associated point value identifying various requirements that must be met to achieve full compliance. While the initial four categories are broken-down into quantifiable metrics, the concept of *indoor environmental quality* contains many subjective attributes such as interior lighting, presence of sunlight, and thermal comfort. The Living Building Challenge (LBC) includes a similar category call *health,* which outlines a building interior that "envisions a nourishing, highly productive and healthful indoor environment" [3]. These subjective requirements in otherwise highly quantitative building standards identified a need for additional research in sustainable building design, specifically addressing this concept of indoor environment effects on a building user. It is apparent both LEED and LBC recognized the importance of positive user interaction with the building, but do not explicitly identify how to quantify it.

One technique for quantifying a users response to his or her indoor environment is to evaluate productivity. Literature has shown factors such as lighting, temperature, and interior geometry can influence user productivity in the workplace [7, 22, 23]. In addition to productivity, these three factors are a common consideration in sustainable building design, particularly when it comes to energy efficiency. In a building design sensitivity analysis by Heiselberg et al., lighting and HVAC systems are the greatest consumers of energy in modern buildings [24]. The research presented in the second manuscript bridges the gap between these two concepts postulating that interior environment, specifically lighting, can affect user productivity. Subsequently, productivity is then quantified in terms of utility, reducing labor costs and overhead [25].

In addition to LEED certification is the Living Building Challenge (LBC), a net-zero energy and water mandate for sustainable building design. The LBC is a significantly more robust mandate, requiring the applicant to achieve 12 consecutive months of net-zero energy before the certification can be awarded. The LBC contains similar categories as LBC including *site, water, energy, health, materials, equity,* and *beauty*. The first manuscript presents an anthropological case study of the schematic design process of a building attempting to meet the LBC mandate. In this case study, several complex mechanical subsystems are identified as components of potential strategies for meeting the LBC's net-zero requirement. The required interaction between these building subsystems was analogous to complex system relationships found traditionally in automotive and aerospace applications [26]. By employing early design complex system strategies such as cost versus risk assessments to sustainable building design, significant savings in time and cost can be achieved [27]. As with any complex system, understanding critical interactions at the conceptual design level is allows designers to make educated system design decisions. Complex system methods like Integrated Systems Health Management (ISHM) and system optimization are applicable to sustainable building design as they can be used as early design tools to identify efficient subsystem interactions [15]. For example, Tuhus-Dubrow et al. use a genetic-algorithm simulation-optimization tool to determine energy efficiency of unique building envelope geometries [28].

Various software tools currently exist to perform computer simulation-optimizations. In the second manuscript, Phoenix Integration's Model Center was chosen based on its ability to incorporate multiple software programs into a single model and also allows the use of external data sets [29]. For this application, a building component database was created containing products with similar functionality, such as windows and electrical lighting. This concept of a functional design repository was outlined by Bohm et al. who presented a schema for component functional relationships [30, 31]. The primary goal of this Design Repository was to allow a user to query the database for component functions, and draw inspiration from other products with similar functionality. In the context of sustainable building design, a user working with the lighting subsystem could achieve the same functionality with both electrical lighting designs and passive components such as windows. These two components would be an example of potential subsystem trade-offs Model Center would be able to evaluate during system optimization.

TOWARDS A SYSTEM ANALYSIS AND INTEGRATION FRAMEWORK FOR EARLY DESIGN TRADES IN SUSTAINABLE BUILDING DESIGN

Authors

Joseph R. Piacenza III

349 Batcheller Hall

Email: piacenzj@engr.orst.edu

Irem Y. Tumer Ph.D

408 Rogers Hall

Email: irem.tumer@oregonstate.edu

Robert B. Stone Ph.D

406 Rogers Hall

Email: rob.stone@oregonstate.edu

Jeffrey Knighton

High Performance Environments Lab

Email: knighton@uoregon.edu

Ihad Elzeyadi Ph.D

High Performance Environments Lab

Email: ihab@uoregon.edu

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ABSTRACT

The design and implementation of net-zero energy and water commercial buildings is a high-performance alternative to traditional structures. The complexity of engineering and architectural design strategies required to achieve post-construction net-zero standing requires an integrated design approach, utilizing an array of novel sustainable building design technologies. Here, we document the schematic design timeline of the Oregon Sustainability Center (OSC), a 150,000 ft^2 net-zero energy commercial "smart" building slated for construction in Portland, Oregon. The design of the OSC is constrained around guidelines described in the Living Building Challenge (LBC), a building standard for sustainable, net-zero energy and water design in modern construction. This paper identifies the primary OSC design considerations, mechanical subsystems required to achieve these goals, as well the various stakeholders associated with the project. A correlation between stakeholder influences on design decisions is mapped demonstrating the relevance of peripheral effects on the design process. The intent of this case study documentation is to work toward an integrated approach to sustainable building design based on the goal of making critical design decisions strategically during the design process, conserving both financial and temporal resources. An integrated design framework for net-zero energy and water subsystems will assist in creating replicable sustainable building designs.

INTRODUCTION

As the global demand for commercial structures continues to increase, the need for sustainable building becomes more apparent. As of 2003, nearly 4.9 million office buildings exist in the U.S. alone, with 170,000 commercial buildings constructed annually. Of this 4.9 million, only 44,000 are being demolished each year [32]. One barrier to sustainable building is the perception of higher costs associated with both design and construction methods. This conservative way of thinking by stakeholders of modern building projects presents issues when determining current and long-term energy use requirements for a structure. Programs such as U.S. Green Building Council's LEED certification, developed in 2000, have taken initial steps to outline and promote sustainable construction [2]. While these certifications have increased awareness about sustainable building methods and quantify reduction in environmental footprint, high costs associated with these methods deter the majority of new construction from implementing these types of recommendations. Subsequently, the International Living Building Institute developed the Living Building Challenge, a guideline for net-zero energy and water usage in an attempt to mitigate higher costs of sustainable construction by eliminating all post build energy and water cost [3]. This certification is unique in that data regarding energy and water use must be provided for 12 consecutive months after the building is in operation. In order to achieve this net-zero energy status, the complexity of the building and its corresponding subsystems is increased significantly.

Because of limitations in today's photovoltaic (PV) efficiencies for solar energy collection, creating a net-zero energy structure is not as simple as adding a PV array to the exterior of a new construction building. Constraints specific to high-rise typologies such as micro-climate effects on building ventilation, geography, relative proximity to other structures, and future construction can affect or even compete with available daylight [33]. To create a net-zero energy building, the design team estimated the new structure be constructed with a 75% reduction in energy, compared against ASHRAE 90.1-2007 building standards [34]. In order to achieve this significant energy reduction, a multitude of active and passive energy saving solutions must be developed and implemented, while still maintaining federal commercial building codes, including those for safety. Developing an array of passive energy savings solutions creates a challenge when attempting new building design.

Implementing an integrated approach during the design process will assist in coordinating the necessary interaction between various stakeholders present during the building design stage. To achieve the goal of integrated design the definition of the building team needs to expand in order to overcome the lack of communication present in the traditional design process [35]. The available resources and constraints defined by the LBC further necessitate the need for integrated design. To achieve the desired 75% energy reduction, novel passive energy savings practices will need to be developed across building components to facilitate energy reduction. In addition to net-zero energy use, the LBC stipulates a “Red List” of building materials that cannot be used. The intent of the Red List is to induce a successful materials economy that is non-toxic, transparent, and socially equitable [3]. These material constraints create additional barriers to the traditional design process. This transformation from traditional discrete series of building components into a greater complex system elicits the development of a method for an integrated design process for sustainable building.

The primary goal for this paper is to compile, using the anthropological method, a set of criteria for design decisions made during the schematic design process of the OSC, and apply them to assemble a design framework applicable to future design projects [10]. The four-person team observing the OSC schematic design was an engineering graduate researcher, an architectural graduate researcher, and their corresponding advisors. Critically observing and documenting these decisions by third party participants assists in creating an unbiased interpretation of the events, barriers, and decisions that drive the design process. This observational process revealed an array of stakeholders linked with the OSC project that had a broad range of effects on design decisions at varying points in time during the process. The detailed identification of these stakeholders and their relationship to the project helped understand decision rationale and aided in tracking which groups had the greatest influence over design decisions. While the original intention of the OSC project was to incorporate a comprehensive integrated building design approach to facilitate the complexity of creating a net-zero energy building, a disconnect between participants appeared causing barriers that hindered progress.

The real-time observation of the OSC schematic design is the first step toward achieving the long-term research goal of developing a replicable framework for integrated sustainable building design. In this paper, a detailed outline has been created identifying the subsystems required to achieve net-zero energy and water use, along with the associated project stakeholders influencing critical decisions made during the OSC schematic design process. The dynamic relationships have been explored between these subsystems and the project stakeholders to correlate stakeholder influence on design decisions throughout the schematic design. Capturing this information will lead to determining the source of barriers created by specific design decisions observed within the OSC case study. Additionally, by identifying the cause of these barriers, steps toward creating a framework for future integrated building design projects will be taken by exposing the internal relationships that diminished project resources. This developing framework will ultimately serve as a tool to mitigate barriers associated with design decisions made due to systems complexity in sustainable buildings, as well as stakeholder influence, resulting in an optimized design solution for a particular building given the available resources, design criterion, and applicable constraints.

BACKGROUND

There are currently many different strategies that have been created to assist in the development of sustainable building design. Based on existing literature these strategies generally concentrate on specific subsystems such as passive solar, wind energy, façade geometry, or cost [19, 36-38]. In addition, many of these techniques apply to projects with smaller overall areas such as residential buildings and or discrete floors of an existing building [39, 40]. Conversely, at approximately 150,000 ft^2, the OSC is slated to be one of the largest net-zero energy buildings in the world [41]. Another barrier is that most case studies are evaluated to determine actual energy savings post construction, and do not account for costs incurred because of deficiencies in the building design [42].

A challenge of developing a methodology for integrated building design that would work with similar projects to the OSC is the large breadth of both subsystem and stakeholders associated with designing and construction of a net-zero energy building [13, 43]. Existing process modeling tools and performance indicators will only work on with projects of smaller scope since considerations such as meeting LBC requirements and stakeholder involvement aren't factored into the methods [43, 44].

The complexity of achieving net-zero energy and water has also lead to the need for multi-objective optimization of the required subsystems as they interact with the building as a whole. Techniques for building optimization have been explored, but they have only developed around a particular subsystem of sustainable building such as building orientation for maximum sunlight exposure to assist in natural lighting and energy collection [28, 45]. The complexity of designing a net-zero energy building requires each subsystem to be analyzed individually as a component within the building, and then after rigorous iterative testing, the system can be optimized based on desired objectives [46].

Numerous research efforts have highlighted the need for an integrated framework for sustainable design that is applicable for large-scale net-zero energy and water projects such as the OSC. By identifying the various subsystems and stakeholders participating during the schematic design process of the OSC, a better understanding of the requirements necessary for sustainable building design at the net-zero level can be achieved.

CASE STUDY – OREGON SUSTAINABILITY CENTER

Oregon Sustainability Center Vision

The idea for the OSC was conceptualized out of the vision of having a research hub for sustainability related projects that showcased current technologies relating to sustainable building and specifically design. This would be achieved by forming research partnerships with the Oregon University System, establishing a portal for Oregon's sustainability community, and occupancy by tenants who support the global green economy. Several institutions within the Oregon University System would occupy the OSC with dedicated sustainability directed research areas. In conjunction with the array of novel sustainable building technologies that will be required to achieve net-zero energy and water, the OSC would also be designed to meet the constraints of the LBC. In 2008, the City of Portland funded a feasibility study for the Oregon Sustainability Center, selecting the design team in January 2009 . Based on the results of this study, the state legislature authorized up to $80 million in Oregon University System bonds to fund the project . The schematic design began in fall 2010 using a selected group of consultants such as engineers, architects, building contractors, and systems management groups. Based on temporal restrictions given by the OSC Board of Directors, the initial schematic design had to be completed by March 2011, and fall within the prescribed timeline, while meeting the construction criteria of the LBC. Based on the focus of both the feasibility study and the resulting schematic design, the following individual subsystems were identified as pertinent to primary design considerations:

- *Active Energy Collection* Energy for the OSC will be primarily collected using a rooftop photovoltaic array, as well as from Bifacial photovoltaic panels incorporated into structure awnings.
- *Passive Energy Savings* A suite of varied passive energy saving designs will be incorporated into the building structure, which will account for an estimated 67% of total energy savings [41].
- *Water Collection* Rooftop water runoff will be collected, stored, and processed into potable water to be used on site.

- *Waste Treatment* Greywater and Blackwater will be treated on site using a Constructed Wetland.
- *Heating and Cooling* HVAC systems will take advantage of either geothermal energy or sewer mining technology.
- *Behavior Modification* Energy consumption of building tenants will be monitored and reduced by passive and interactive features incorporated into the building design.
- *Building System Controls* Real time energy usage will be monitored to ensure net-zero energy goals are achieved; a robust controls system of both hardware and software will be implemented.
- *Light Rail Re-Routing* Portland's TriMet Metropolitan Area Express (MAX) Light Rail will be re-routed to bisect the city block that contains the OSC [47].

The design of such a complex structure requires a host of variably skilled teams with expertise in the different building subsystems. In addition to technical challenges, dynamic financial constraints must also be considered as different subsystem components are explored and implemented. The impetus for writing this paper was the opportunity to observe the design process of the OSC, and view how the various stakeholders' interactions during the schematic design affected the overall design outcome.

Investigating the design of a net-zero facility is predicated on the assumption that a reduction or elimination in post constructions energy costs will become a predominant driver in reducing elevated costs associated with sustainable building. Additionally, there is a gap in research regarding integrated building design, specifically as it relates to constraints imposed by relatively new construction standards such as LEED Certification and LBC. The novel system design required for a building to reach a net-zero energy status also requires a smart building controls systems to manage subsystems such as individual tenant energy use, heating and cooling requirements for various occupational states, as well as fluctuating lighting needs governed by geographic and seasonal variation in available light [48]. While current state-of-the-art technologies will be integrated into the building design, a primary vision of the OSC is to become a flagship structure for sustainable building design practices, not a "snapshot" of today's technology that will rapidly fade to obsolescence. This will be achieved by having a "living laboratory" within the building, a principle that was conceptualized during the feasibility study and will be implemented by the occupancy of various members of the Oregon University System. Here, the tenants of the various labs will work to proliferate research pertaining to sustainable building techniques. The intended result is a building that, 50 years from now, will continue as a relevant contributor in the sustainable building timeline. This vision will be accomplished by focusing continuing research efforts towards topics such as passive energy saving techniques, occupant behavior modification, and materials research for efficient photovoltaics.

Oregon Sustainability Center Stakeholders

The vision to create a novel building with a high level of complexity requires an alignment of various stakeholders to propel the project from concept, through design, and finally to completion. The multi-dynamic interactions though the entire process have had a continual effect on an undertaking of this magnitude, specifically the design process. Making technology choices for a building development is a social and highly contextual process, hence very much affected by the perceptions of project stakeholders and unique project characteristics [43, 49]. Since the majority of the funding for the OSC is coming from Oregon University System bonds, a bureaucratic process must be implemented and abided by to ensure proper appropriation of funds. This process adds another layer of interaction to an already complex system of design constraints. It should be noted that interactions and decisions made by different stakeholders have the ability to influence the design and the design process with just as much vigor as a physical constraint such as geography. While observing the schematic design of the OSC, the following stakeholders were identified that actively participated or contributed to the design process, along with potential project benefits and barriers associated with each group:

State and Local Government Results from the City of Portland funded feasibility facilitated the contribution of $80 million in Oregon University System bonds [41]

Primary Benefits

- If successful, the OSC will be a flagship model of sustainable building design and energy efficient technology
- High profile project that supports the City of Portland's and Oregon in general position as a leader in sustainability
- Concurrent with the City of Portland's EcoDistrict vision [50]

Barriers and Constraints

- Budget cap must be enforced
- Bad publicity if project is unsuccessful

Oregon University System The OSC will house laboratories relating to sustainable technologies

Primary Benefits

- Sustainability research funding and high profile laboratory space for each contributing institution.
- 250-person auditorium integrated into primary building design exclusively for Portland State University (PSU)

Barriers and Constraints

- Must perform activities within the constraints of the OSC and the LBC (ex. Limited available electricity)
- Participation in experimental designs such as a DC loop power supply [51] and active behavior modification implementation

Board of Directors Comprised of members from the Oregon University System, City of Portland Bureau of Planning and Sustainability, Portland State University, Portland Development Commission, and the Oregon Living Building Institute

Primary Benefits

- Comprehensive objectives benefiting multiple parties
- Organizational participation in novel project

Barriers and Constraints

- Sole group in control of project budget
- Conservative perspective of innovative design methods or technologies

Public Perception Since the OSC is state funded, the public has a vested interest

Primary Benefits

- Promotion of sustainable building could promote growth in local economy

Barriers and Constraints

- Negative perception of OSC based on current financial climate in Portland, Oregon, specifically the 10% unemployment rate [52]

Building Contractors Contracting firms such as plumbers, electricians, and construction contractors

Primary Benefits

- Motivated to include project in personal and organizational portfolios

Barriers and Constraints

- Contractors are using designs from their current knowledge base and may be biased against novel practices

Technical Contractors Specialty contracting firms such as engineers and architects

Primary Benefits

- Progressive selection of technical designers aligns with project goal
- Motivated to include project in personal and organizational portfolios

Barriers and Constraints

- Loss of focus on "big picture" goal attempting to optimize assigned subsystem

Vendors Companies specializing in both hardware and software integrations for smart building applications

Primary Benefits

- State of the art system controls software and hardware being offered
- Venue to display implemented technology as form of advertising
- Potential cost reduction in exchange for product placement advertising

Barriers and Constraints

- Design decisions are being influenced by what technologies vendors are pushing
- Tendency to focus on using state of the art components for active energy saving instead of passive designs
- Must choose from within a company's product suite

Living Building Challenge Building standard the OSC is attempting to achieve

Primary Benefits

- Explicit building standard that removes ambiguity from project guidelines

Barriers and Constraints

- Restrictions such as building material uses may be difficult to comply to

Behavior Modification Measures

As previously noted, the concept of both passive and active tenant engagement as a quantifiable measure for energy savings was estimated at 12% of the overall typical energy use for a traditional building constructed to today's ASHRAE ISO 90.1-2007 standards [34, 41]. The topic of tenant behavior modification was prominent during various design meetings and multiple considerations were developed with lengthy discussions on how various practices could be implemented. The following is a selection of strategies developed as a method of energy reduction exclusively regulated by passive and active interactions imposed upon the building occupants:

- *Laptop Computers* Since typical desktop computers use almost four times as much energy (approximately 120 Watts vs. 30 Watts), laptop computers will be required [53].
- *Personal Energy Monitor* Each permanent tenant will have a daily allowable energy budget and an associated energy usage display at their workstation, allowing them to track personal energy usage. A rewards system was also considered for occupants who do not meet the maximum usage.
- *Occupant Empowerment* The ability to elicit behavior change by empowering occupants to make energy conscious choices such as taking the stairs instead of the

elevator. By citing personable and encouraging statistics about cumulative energy savings and personal heath benefits, an individual will feel he or she is making the active choice to conserve energy.

- *Temperature Differential* Typical climate set points within an office building are 66-72 degrees in heating season, and 74-78 degrees cooling season [54]. The OSC plans to deviate four degrees in each season to reduce energy. Occupants will be encouraged to dress accordingly to adapt to the inside climate. Additionally, based on temperature, the tenants will be cued when opening their workspace window will have a favorable effect on local climate comfort.
- *DC Power Loop* An experimental building floor, most likely to be located within the university research annex, will feature DC power only. Typical workstation devices such as laptops, LED task lighting, personal fans, and cellular phone chargers will operated by plugging directly into a DC system in an effort to reduce conversion losses associated with converting solar energy to AC, and then back to DC for device operation [51]. Building occupants in this floor will not have access to an AC power outlet and will have to complete all required task using only the available DC energy resource.

While the general consensus by the stakeholders was that the selected strategies could, in fact, produce a measurable impact on total energy use, several questions arose regarding implementation and enforcement of restrictions. As individuals can excerpt free will, introducing a radical paradigm change within a traditional workplace setting could prove difficult. Pre-occupancy training sessions were suggested as a method for mitigating pushback against the proposed behavior changing systems. Having occupants sign a written contract in advance of occupancy, outlining energy use expectations, was also identified as an effective method for control occupant engagement within the building. The mandate imposed by the LBC must also be considered when relying on tenant energy use during the first 12 months of data collection after the OSC has been built. If occupant energy use demands are exceeded, LBC certification may not be achieved.

METHOD OF APPROACH

In an effort to detail the concurrent interactions between the various stakeholders during the schematic design, a passive approach to data collection was taken. During the rigorous 16-week schematic design process of the OSC, a multitude of meetings were attended by the research team comprising of an engineering graduate researcher, an architectural graduate researcher, and their corresponding advisors, to capture a detailed understanding of the design timeline, along with a framework of the design decisions that were made along the way. Throughout the duration of the schematic design process, approximately 35 meetings, comprised of the following were attended by the research team based on relevance to the integrated design process of the OSC case study:

- *Consultants Design Coordination (CDC)* Primary architectural weekly meeting with engineering consultants and contractors as appropriate per agenda
- *Mechanical, Electrical, and Plumbing (MEP)* Weekly meeting series with contractors sighting detailed subsystem requirements
- *Public Presentation* Two formal public presentations were given with general information promoting the OSC along with schematic posters and architectural models
- *Project Managers Group* Weekly project coordination from team leads
- *OSC Business Board* Evaluation of design progress, requirements, and budget
- *Design Advice Committee (DAC)* Bi-monthly Project Managers Group presentation of current design to OSC Business Board

Having the opportunity to observe the real-time design methodology and complex dynamic interaction of the stakeholders was paramount in the attempt to understand the design process of the OSC. Considering the shear volume and breadth of novel ideas, stakeholder interactions, vendor presentations, and ultimately design decisions, the ability to passively engage in the design process allowed a detailed understanding of the project and the unique opportunity to document the decision process. As with any type of collaboration across groups who have to experience working with each other, there are many communication barriers that must be eclipsed in order to achieve a successful outcome. Observing these varied dynamics across multiple team settings helped navigate around communication issues and contributed to a comprehensive understanding of the OSC design process.

Coordination of the design process documentation by the research team was implemented using Google Sites, a wiki-based media that allows content to stored and accessed by selected members. This gave real-time access to schedules, meeting notes, and design images. The following actions were implemented by the research team to acquire and distribute relevant information from the presented case study:

- Passive interaction by at least one member of the research team during each meeting to observe and document design process
- Critical documentation and understanding of project stakeholders
- Posting of weekly design decisions and images to Google Sites
- Interpretation and assembly of comprehensive design timeline
- Detailed documentation of each design iteration to assist in project development understanding

OBSERVATIONS

Analysis of the OSC Schematic Design

Using the OSC feasibility study as a baseline vision for the expected outcome, the subsequent schematic design was a complex iterative process with an array of inputs and constraints from all actively participating stakeholders that attempted to replicate the initial parameters of the feasibility study. As with any integrated design process, communication between each participating team was paramount to optimizing each subsystem for maximum efficiency. In the OSC case study, the primary active constraints for overall building system optimization were the availability of electrical, financial, and temporal resources. There was a distinct ebb and flow during the design process that dictated the availability of these different resources as they related to each subsystem during the progression of the schematic design phase.

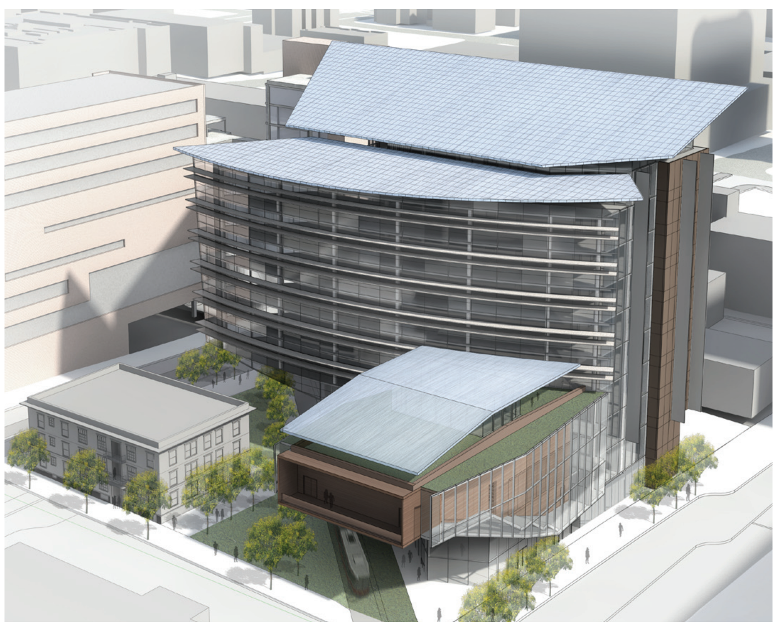

FIGURE 1: Initial schematic selected design option featuring a cantilevered auditorium with roof top PV array [10, 55]

For example, a 350-person occupancy cantilevered auditorium featured in Figure 1 was a primary architectural feature of the finalized design option selected between four potential design schemes [10, 55]. During the next 8 weeks, several variations were considered before the final 250-person occupancy geometry shown in Figure 2 was selected [10, 55]. Total system energy usage considerations such as heating and cooling of internal space, heat transfer within the auditorium envelope, and potential available area for PV array placement affected the decision to alter the building geometry with respect to the auditorium. Withdrawing the auditorium into the building reduced operations energy requirements for subsystems such as heating and lighting, but also sacrificed valuable rooftop space for additional PV arrays that generated electricity. The auditorium redesign did conserve financial resources, but diminished a unique architectural feature that contributed to the aesthetic value of the structure, a mandate governed by the LBC. In this case study, the auditorium was exclusively appropriated to a stakeholder group from the Oregon University System who also held a position as a representative on the Board of Directors. If, for example, this group had a vested interest regarding auditorium changes, they may be biased regarding schematic design changes, and may be unwilling to approve this particular change. This cascading interaction with various stakeholder groups demonstrates how significantly a design change can propagate through and affect the overall design process.

FIGURE 2: Final iteration of selected design showing auditorium geometry moved primarily within structure and significantly reduced rooftop PV array [10, 55]

Events Influencing the Design Process

Financial and Budgetary

In the referenced example of the auditorium geometry reduction, the impetus for this design change was a prescribed reduction in total project cost by the Board of Directors during a DAC meeting. This mandate by the Board was influenced by a rise in current median values over an estimated applicable timeline for interest rates and associated Federal taxes linked with the Oregon University System bonds, the primary source of funding [56]. The project cost per square foot was originally $430 and was suddenly reduced to $420, forcing the design team to rapidly make a decision that could reduce total building costs while still meeting all required constraints. In observing the case study, the distribution of the information significantly affected critical design decisions. The Project Managers Group was the first to receive information on the budget reduction and collectively made the decision to modify the auditorium, which the lead architectural firm impetuously reduced in their design rendering before the next CDC meeting. This new building geometry was then accepted as the current baseline from which all future architectural, engineering, and consultant decisions were derived from.

Design Decisions

The result of this informational disconnect between stakeholders began to form a "ringleader" paradigm throughout the remainder of the schematic design process as design decisions, significant to the entire system, were made predominantly by one stakeholder team with minimal input from others. The logic was that by implementing an executive design change decision with the interest of expediting the overall process, the decision making team would not sacrifice time often consumed by deliberating an issue tangential to the ultimately obvious choice for, in this example, cost savings. As a result, the disconnect between stakeholders increased, and gaps in the design process appeared as many consultants and contractors were unaware of the these design changes and continued to work under assumptions from what was, in many cases, a meeting held just days before. While the intent of the executive design decision was to conserve available resources, the lack of communication may have, in fact, had the opposite effect by diverging to a traditional top-down design process, instead of an integrated approach. Figure 3 displays design events relating to overall project budgetary changes, and their affect on various stakeholders and building subsystems.

Communication Barriers

It was observed that a disconnect in communication between project leaders and the associated teams during the design process did create a latency in information transfer. While this effect was inadvertent, it did consume limited financial and temporal resources available to complete the schematic design.

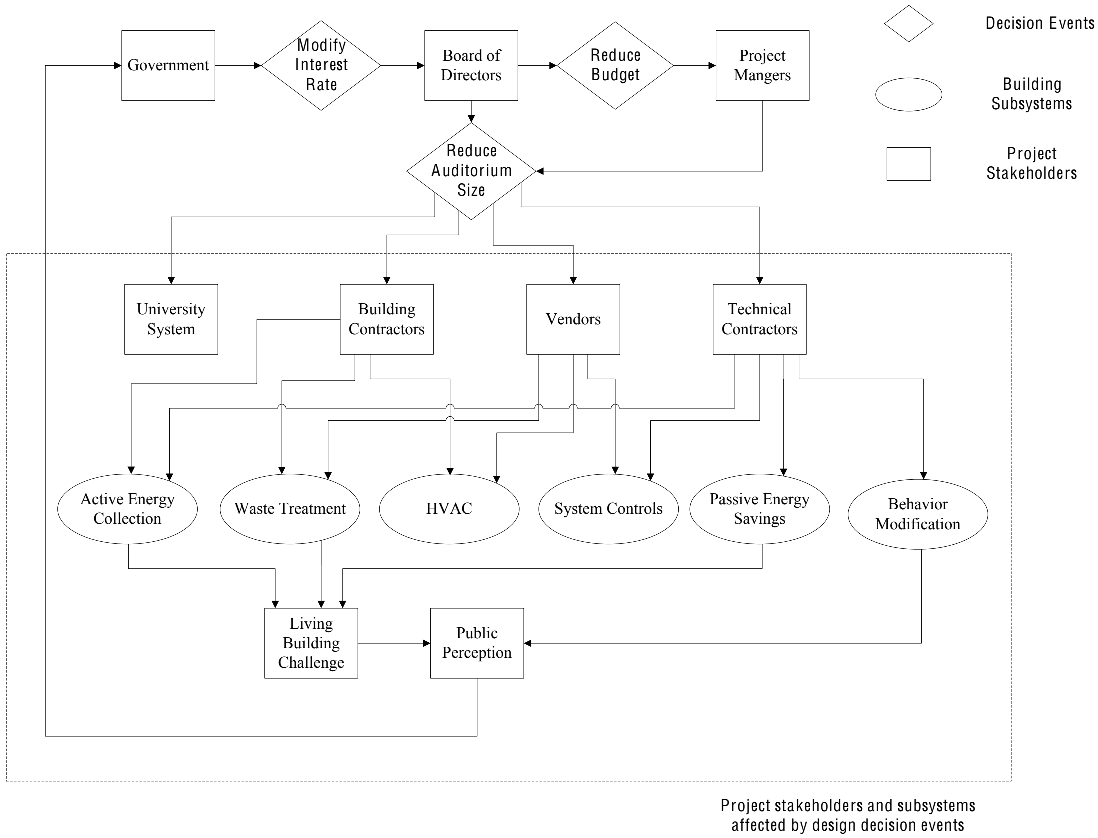

FIGURE 3: Decision map displaying the effect of decision events on various stakeholders and subsystems

As previously described, technical contractors such as engineers and architects found themselves in a reactionary design process situation, modifying their subsystem in response to a managerial decision. Additionally, this information was disbursed during the appropriate meeting schedule, which at times created a weeklong gap in information transfer. It has been predicted that engineers waste approximately 10% of their time waiting for management decisions, and this figure suggests an amount of acceleration that similar project might experience simply from going from a bottlenecked management hierarchy to a more efficient knowledge network [57]. Another example of a communication barrier was during a final energy analysis using the Department of Energy modeling tool eQUEST [58]. An engineering contracting firm performed an extensive building envelope energy analysis using an outdated building geometry because they didn't have the latest iteration of the rapidly cascading design versions. In the case of the OSC schematic design, the use of a traditional top-down approach to information distribution may have contributed to communication barriers.

DISCUSSION

Towards a Design Framework for Sustainable Building

By following the development of a unique project such as the OSC, the long-term intent of this research is to develop a framework for future sustainable building designs based on the actual interactions that took place during the design process. In an effort to dilute the overarching dynamic complexity encountered during sustainable building design, the decisions made by the stakeholders regarding the various subsystems necessary to achieve net-zero energy and water will be evaluated to help determine which had the greatest effect of the final schematic design. By incorporating the concept of integrated building design into what has now transformed into a complex system, energy, financial, and temporal resources can be conserved to further mitigate design and construction costs. While individual subsystem design teams can proficiently optimize their specific contribution, they can unknowingly affect other systems during the concurrent design process. When the availability of energy resources are scarce, this disconnect creates an inefficient design outline. Additionally, the various stakeholders outside of the primary OSC design group must also be accounted for as influencing contributors during schematic design. Their interactions concerning budgeting and public relations activities affected design decisions throughout the design process.

Building Design Optimization

A primary objective during the development of a framework for sustainable building design is the multi-variable optimization of subsystems that comprise a net-zero building. The best solutions will contain synergies between design disciplines to create an integrated design solution, where a single strategy will provide multiple benefits [35]. As there are many complex subsystems associated with net-zero building, developing an multi-variable objective function, which is representative of the whole system, is an arduous task when considering the multitude of interactions taking place during the design process [45, 59]. Each design team is able to use their knowledge and expertise to optimize one particular subsystem, however integrating all of these into the comprehensive building design can lead to an excessive use of resources [60]. Figure 4 outlines the desired objectives to be optimized along with the associated constraints affecting them. By optimizing the complete system, the expenditures of the available resources can be conserved in specific locations, allowing them to be re-appropriated elsewhere in the system.

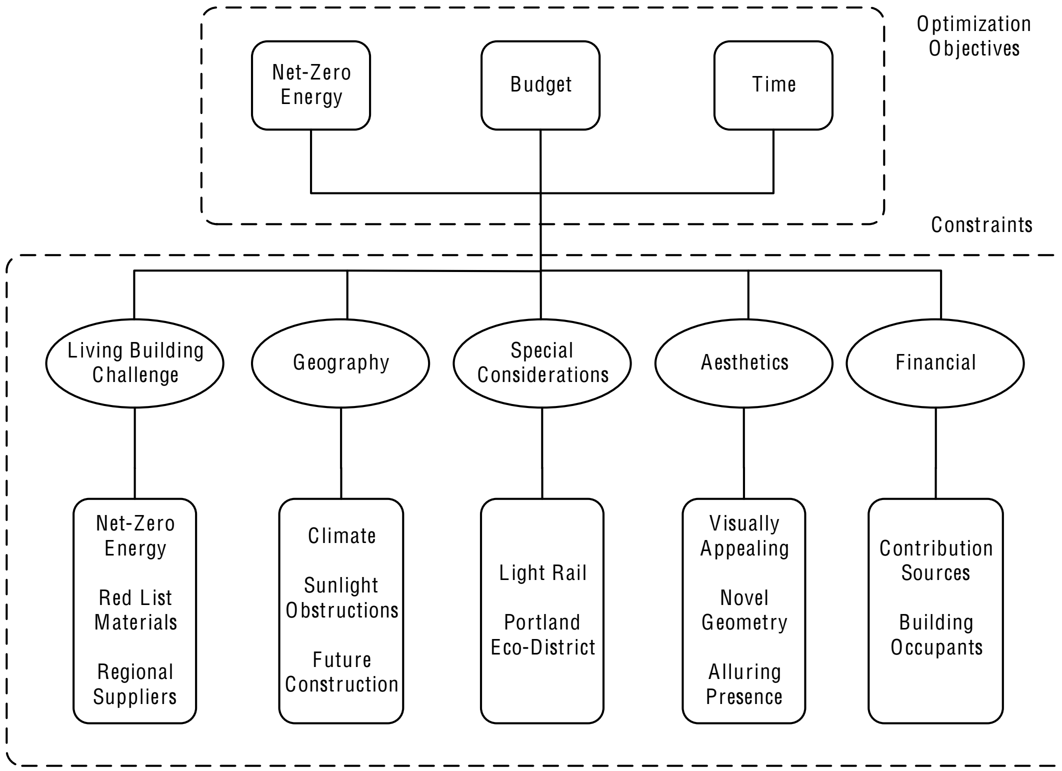

FIGURE 4: Optimization objectives and associated constraints

In order to further investigate the design drivers a sensitivity analysis should be performed regarding each of the associated variables in the objective function to determine which elements have the greatest effect of the system, given a specific amount of perturbance [28]. In the OSC case study, this would not only include the design parameters of the building, but also the decisions made along the way that affected these parameters. For example, the decision made to reduce auditorium size affected available PV area, heating and cooling requirements, as well as total cost. By associating the most sensitive design variables with a discrete decision, a relationship can be identified that links decisions to design changes during the process.

Relationship Identifiers

In an effort to establish a relationship value between the project stakeholders and the various subsystems contained within the building, a heat map (Figure 5) has been constructed to identify a correlation scale between the two groups [61]. Based on observations from the design team, the map has been shaded to indicate which stakeholders have the greatest influence on a specific subsystem. For example, it is possible to conclude that decisions made by state and local government have little or no affect on behavior modification strategies, while technical contractors such as engineers are relying on these strategies as a quantifiable means for reducing energy consumption in the building. Establishing these relationships from the OSC case study will assist in construction of the proposed integrated design framework by identifying the sensitivity of stakeholder input on project subsystems and facilitate understanding of design decisions that have the greatest effect on the overall design.

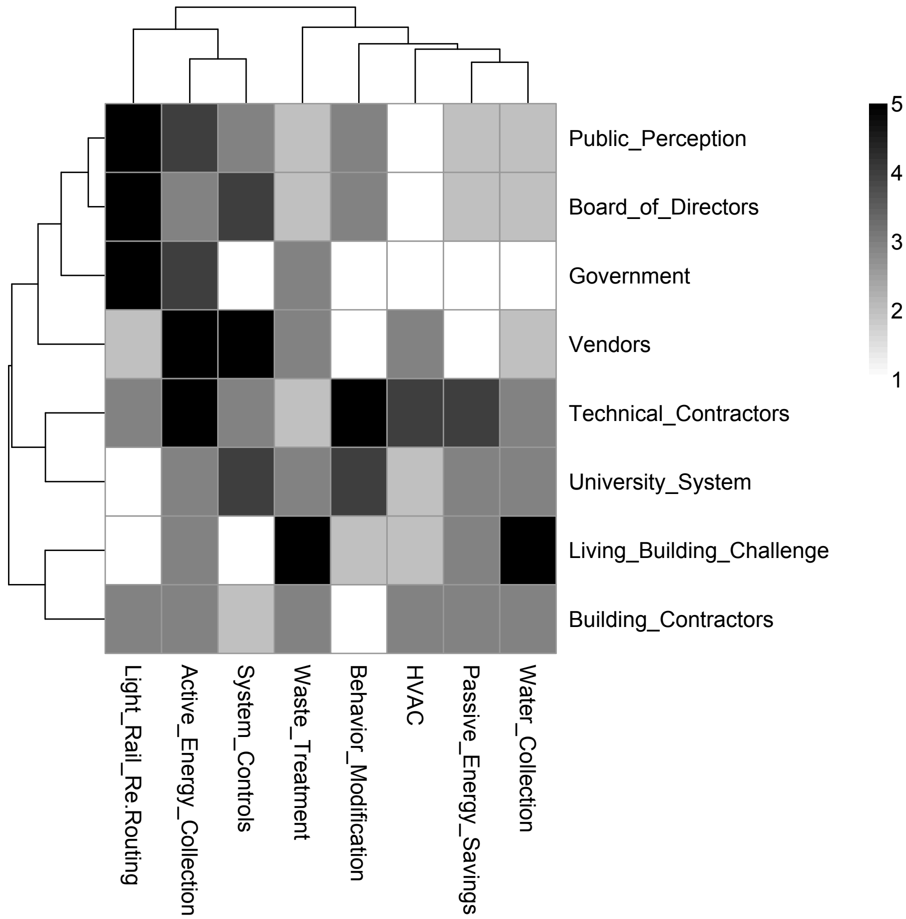

FIGURE 5: Optimization objectives and associated constraints

Behavior Modification

The goal of quantifying behavior modification as a replicable means of explicit energy reduction was not successful developed by the OSC design team. While many techniques were, in fact, incorporated into the schematic design, they were generally only applicable to the OSC project. Further development of this energy reduction technique will be needed for integration into higher-level sustainable design strategies.

CONCLUSION

This paper has presented a detailed outline of events, systems, and stakeholders involved in the schematic design case study of the OSC. Based on the unique opportunity given to the design team to passively observe the design process, a cursory relationship has been established between critical decisions made affecting the overall design, and the associated project stakeholders influencing these decisions. This correlation is the first step toward creating an integrated framework for sustainable building design. Subsequent work is still needed to explore a multi-objective optimization applicable to sustainable building design, specifically for net-zero specifications. Nevertheless, the work presented here will hopefully contribute to a greater understanding of the complex array of subsystems, participating stakeholders, and the significance of critical decisions required to achieve net-zero standing, and enforce the need for a integrated design approach.

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LIGHTING OPTIMIZATION FOR SUSTAINABLE BUILDING DESIGN CONSIDERING USER PRODUCTIVITY

Authors

Joseph R. Piacenza III

349 Batcheller Hall

Email: piacenzj@engr.orst.edu

Irem Y. Tumer Ph.D

408 Rogers Hall

Email: irem.tumer@oregonstate.edu

Christopher Hoyle Ph.D

418 Rogers Hall

Email: chris.hoyle@oregonstate.edu

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ABSTRACT

User productivity is a key component of an integrated sustainable building design framework, as a consideration in addition to operating and construction costs associated with sustainable building practices. Research has shown that employee productivity increases as visible light levels rise in the workplace. Incorporating efficient lighting systems into sustainable building techniques can potentially increase user productivity while reducing electricity costs. This paper presents a single criterion approach that captures the trade-offs between costs, users, and current building standards. A model has been created to explore the feasible design space of a commercial workspace by populating a repository of both active and passive lighting components that can be accessed to generate various lighting designs. A genetic algorithm is used to optimize potential lighting choices in a given workspace, and allows the designer to explore Pareto optimal productivity solutions that best fit the desired application. The result is an optimal solution for a given workspace lighting configuration that captures user productivity while minimizing operating costs.

INTRODUCTION

The growing global demand for energy usage in commercial buildings has precipitated the need for novel energy efficient design techniques in modern building construction. With 19% of the annual U.S. energy supply being consumed by commercial buildings alone in 2009, energy reduction strategies during new building design can assist in diminishing usage [1]. While construction mandates such as ASHRAE, LEED, and Living Building Challenge (LBC) outline building guidelines and standards for building efficiency, these have presented both architects and engineers with new challenges. For example, to obtain the Living Building Challenge certification, a building must show a cumulative net-zero energy value for 12 months of operation. Due to inefficiencies in current energy generation techniques suitable for discrete "off-grid" applications such as photovoltaic arrays, design engineers must explore alternative solutions to work in parallel with traditional energy generation techniques. To achieve net-zero status, a building must consume approximately 75% less energy based on ASHRAE 90.1-2007 building standards [34]. In addition, these mandates do not consider the influence of the standards on future building users [2, 3, 6].

The research presented in this paper shifts the traditional architectural design paradigm from a top-down, aesthetically driven approach, to an integrated engineering design approach commonly found in aerospace design and other complex systems [14, 15, 26]. A recent case study of the Oregon Sustainability Center (OSC), a net-zero energy and water smart building slated for construction in Portland, Oregon, revealed a diverse array of mechanical subsystems required to achieve the LBC's certification [10, 62]. These included on site energy generation, passive energy savings, water collection, waste treatment, HVAC, system controls, and behavior modification for energy savings. Ouyang and Hokao outline behavior modification techniques as the ability of a building's occupants to reduce total energy consumption by up to 10% [5].

The OSC case study identified the mechanical subsystems utilized in a net-zero energy building, however it did not address the consequences of the building design on user productivity. Building occupants' behavior, as a result of their working environment, should drive design decisions, as an increase in productivity will effectively lower fixed operating costs. The focus of this paper is the development of a design tool for selecting the optimal lighting configuration of a typical commercial building workspace that will consider user productivity in additional to typical considerations such as building and operating costs. By isolating the lighting sub-system from the overall sustainable building framework, the developed methodology will assist in creating lighting solutions, early in the design process, that will optimize user productivity while considering energy efficiency.

BACKGROUND

The presence of complex mechanical sub-systems required to achieve sustainable building design requirements, such as net-zero energy, allows the identification of quantifiable energy saving objectives during the early design stage, before aesthetically driven customer requirements are addressed. By addressing energy reduction techniques in early design, fixed costs can be reduced during the life of the building. In addition to following energy efficient mandates such as Living Building Challenge, designers must operate within project budgets, while still meeting customer requirements for usage and building aesthetics. Many sustainable building design techniques face opposition as they are generally perceived as costly, with a long term payback period [4]. Financial barriers such as this encourage designers to look toward building optimization techniques, as well as post construction, or usage strategies, for mitigating costs.

A cursory literature survey has shown the use of various techniques to achieve optimized solutions for complete building designs. Geyer proposed a methodology using multidisciplinary grammars to optimize building components by linking qualitative design characteristics with a quantitative analysis [63, 64]. Wang et al. use a genetic algorithm to determine floor shape or footprint in buildings for optimizing envelope-related design variables such as window-to-wall ratios and shading, which were then linked to life-cycle cost measures [28, 37]. Christensen et al. examine a component selection driven process where minimum required values are calculated to achieve net-zero energy such as insulation, glass type, and foundation insulation [65]. This type of multi-objective optimization approach can lead to a wide selection of feasible designs [59]. A sensitivity analysis by Heiselberg et al. showed that HVAC systems are the primary energy users in sustainable buildings, with lighting having the next greatest effect [24].

One drawback to these strategies is the high level comprehensive nature of the methodology. To achieve LEED certification, five categories for sustainable design are described including *sustainable sites, water efficiency, energy and atmosphere, material and resources,* and *indoor environmental quality*. These categories are highly quantifiable, with the exception of *indoor environmental quality,* which contains subjective attributes such as interior lighting, presence of sunlight, and thermal comfort

[66]. Reinhart et al. have examined differences in static versus dynamic daylight performance metrics using existing several daylight simulation programs, but do not arrive at a clear metric to quantify these effects [67]. Similar research using Sensor Placement Optimization Tool (SPOT) software was used to create discrete building geometries to achieve energy efficient building designs, although quality of daylight designs do not involve the building user [68].

One concern not addressed in both total building design methodologies and lighting design strategies is user productivity. In a commercial organization, employee performance is tied to various metrics, including their response to indoor environments such as temperature and lighting. For example, Juslén et al. indicate a relationship between lighting levels and productivity in the workplace (Fig. 1) [69, 70].

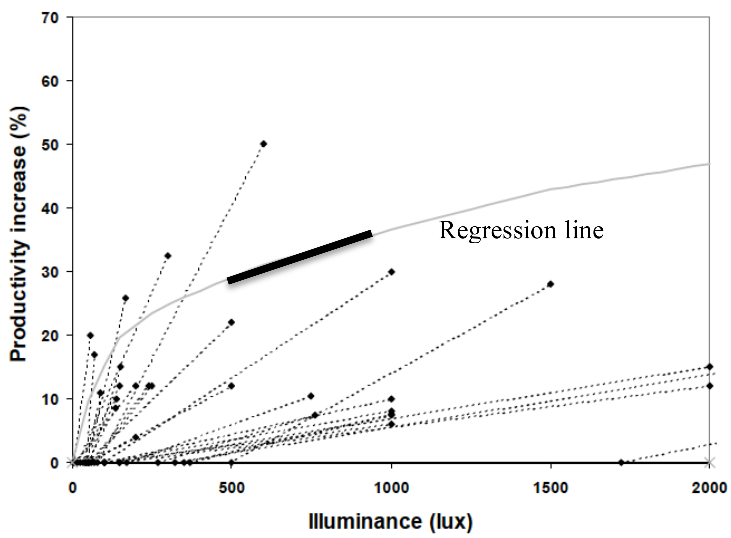


FIGURE 1: Productivity versus illuminance levels [70]

Jensen et al. examine a Bayesian Network approach to comparing various effects of thermal environment on the mental performance of office workers, suggesting employee performance is increased with thermal sensation, or how an individual feels with respect to his or her environment [71]. Positive effects of natural lighting in the workplace have also been linked to various performance metrics such as well-being, ability to perform, motivation, job satisfaction, and technical competence [72]. While this causation has been assumed for some time, Juslén has quantified these metrics by conducting field studies on lighting preferences in the industrial workplace and employee productivity [70]. This research outlined a productivity unit increase based on workplace metrics associated with lighting relationships including visual performance, visual comfort, visual ambience, and job satisfaction. In an effort to quantify productivity in terms of financial gain for an organization, Hunter and Schmidt identified a developed a utility function including reduced labor costs and overhead [25].

CONTRIBUTIONS

Current research in sustainable building design techniques and optimization, points to a need for a comprehensive approach that considers existing building standards, cost (implementation and post construction fixed), and building users. In this paper, a single criterion approach is proposed that captures the trade-off between these three concerns. For this work we consider the productivity of the users, and how they respond to presence of light, beyond traditional requirements, in the workplace. A model has been developed to select an array of potential lighting components that produce feasible combinations within a prescribed workplace geometry. A population of these components including electrical lighting, windows, and light shelves, were imputed into a design repository, from which the model can choose different options. The result is an optimization of lighting options that displays the trade-offs between operations costs and user productivity, while still maintaining building standards. Attempting to understand how building occupants will behave based on lighting choices and configurations will allow designers to consider alternative options early in the design process, contributing to an overall lower return on investment for a sustainable building.

OPTIMIZATION METHOD FOR USER PRODUCTIVITY

Based on the defined mechanical subsystems required to meet sustainable building mandates, interior lighting, and its effect on user productivity was selected as a means of quantifying *indoor environmental quality* within a prescribed workspace [62, 73]. Since lighting quality is a subjective characteristic, a users response to the lighting environment can be measured by productivity change [74]. Lighting was also selected as the second highest energy consuming building subsystem, behind HVAC. A sub-set of the total optimization framework is explored by choosing an optimal lighting configuration of active and passive options that maximize user productivity while considering energy efficiency. This began with examining the behavior of building users based on their lighting environment, and how a combination of both active and passive lighting options could be configured to conserve energy while maximizing user productivity. It was then inferred that increasing productivity effectively decreases the user's salary expense. A repository of lighting components was then created from current commercial lighting products used in modern construction, from which the optimization model could select components from based on desired objectives. Future work will include the addition on HVAC components into both the repository and optimization objective. This will add another parameter to *indoor environmental quality* while taking into account the two highest users of energy in buildings.

This method explores the possibility of incorporating the potential productivity increase of an employee, as a function of their environment, into a building subsystem optimization objective, such as reduced energy use through efficient lighting design. By expanding this optimization objective beyond the typical considerations of minimizing power while maximizing available light, the addition of a productivity function is expected to capture a more accurate estimate of the true cost of sustainable building design.

Optimization Objectives

To gain a complete understanding of the feasible design space, a multi-objective optimization framework was developed to model total system cost, based on hourly employee wage expenses and total workspace energy costs. For this model, initial lighting implementation costs were ignored, although these could be added in the future to calculate return on investment. Equation 1 describes this relationship:

$$C_T = \sum_i C_L + \sum_j C_{NE} \qquad (1)$$

where C_T is total workspace cost per hour (*\$/hr*), C_L is total light cost per node (*\$*), and C_{NE} is net employee cost (*\$/hr*). The optimization objective is as follows:

find $C_T, C_L, C_{NE}, PI, P_E, P_C, fc_{total}$

minimize $f = \sum_i C_L + \sum_j C_{NE}$

subject to

$h_1: -PI + P_E + (P_E * P_C) = 0$

$h_2: -C_{NE} + \frac{\frac{Salary}{hr}}{PI} = 0$

$h_3: -P_C + \frac{10}{46.5} * (\Delta fc_{total}) * 0.01 = 0$

$g_1 = PI - 1.10 \leq 0$

$g_2 = -PI + 1.10 \leq 0$

$g_3 = -fc_{total} + 46.5 \leq 0$

$g_4 = fc_{total} - 46.5 \leq 0$

Productivity Index

Assuming that an individual's salary per hour corresponds accurately with the job they are paid to do, their productivity, or *Productivity Index (PI)*, will have an expected value of one. The *PI* for an employee with higher expected performance (P_E) is defined in Equation 2. This represents the ideal situation where an individual is performing at exactly the anticipated level for his or her salary. It can then be inferred that there is an inverse relationship between employee productivity and salary per hour, postulating that if an employee on a fixed salary has a greater productivity than expected, he or she has a lower net cost (C_{NE}) to the organization, and vice versa as shown in Eqn. 3:

$$PI = P_E + (P_E * P_C) \tag{2}$$

$$C_{NE} = \frac{\frac{Salary}{hr}}{PI} \tag{3}$$

where *PI* is the Employee *Productivity Index*, P_E is the Ideal Productivity Value, P_C is the Change in Productivity, and C_{NE} is Net Employee Cost (*$/hr*). This method is similar to an approach by Hunter and Schmidt who developed a less conservative estimate accounting for both reduced labor costs and overhead [25].

In order to accurately estimate *PI,* a feasible range for productivity was estimated. Joarder et al. have shown that lighting levels beyond 95 foot-candles (1000 *lux*) produce a glare in the working environment that reduces lighting quality, and current building standards for office workspaces require a minimum of 46.5 foot-candles (500 *lux*) [75]. This gives an approximate efficient lighting range of 46.5-93 foot-candles. If 46.5 foot-candles is given as the expected productivity light level based on Fig. 1, productivity will increase up to 10% over a range of 46.5 foot-candles (500 *lux*) based on the regression analysis of Fig. 1 and shown in Equation 4:

$$P_C = \frac{10}{46.5} * (\Delta fc_{total}) * 0.01 \tag{4}$$

where P_C is the Change in Productivity and Δfc_{total} is the increase in total foot-candles for a given area.

Design Algorithm

For the lighting optimization model, a genetic algorithm (GA) was selected based on its ability to produce discrete solutions from discrete design inputs, such as light types and locations [76]. For example, total system cost can be compared relative to the productivity index and available light in the work plane, and a designer may be willing to compromise energy savings from lighting levels by an increase in employee productivity.

Literature survey showed a similar GA application by Ferentinos and Albright for selecting an optimum lighting configuration based on agricultural greenhouse needs, although it was not directed at energy efficiency [77]. Hutcheson et al. found GA to be an effective way to create a set of quality feasible design solutions using available component functions [78]. Although this method uses a single optimization objective, alternative solutions within the trade space can be examined by considering designs just outside the system constraints, along the Pareto Frontier. These solutions are considered Pareto optimal if they are not dominated by another solution in that performance space, but may be better for at least one of the chosen criteria [37].

NUMERICAL IMPLEMENTATION

In an effort to gain a clear understanding of the feasible design space, Phoenix Integration's Model Center was used to perform the proposed system optimization [79]. This software provides a graphical environment for automation, integration, and design optimization that enables users to create system models by integrating individual subsystem design modules [29]. It also allows the user to import data and coding from other software packages such as Microsoft Excel, where repository data was exported for this case study.

Creating a Component Repository

The first step toward optimizing workplace productivity as a function of environmental lighting was to explore the potential design space available in a typical commercial workplace. Typically, lighting design configurations are driven by customer requirements, and constrained by building standards such as ASHRAE 90.1-2010 [6]. Designers then begin to select lighting products based on training or past experience. To assist in this selection process and categorize potential lighting components, a database was created based on current lighting products available. To assist in capturing product functionality, a database or repository schema was developed as a way to organize various lighting attributes. This lighting repository schema was based on an existing database structure for consumer products, which was created as a way to identify and map product functionality [31]. For the purposes of this research, a subset of the original Design Repository schema was used, although future work could be expanded to include component attributes affecting other building subsystems (Fig. 2).

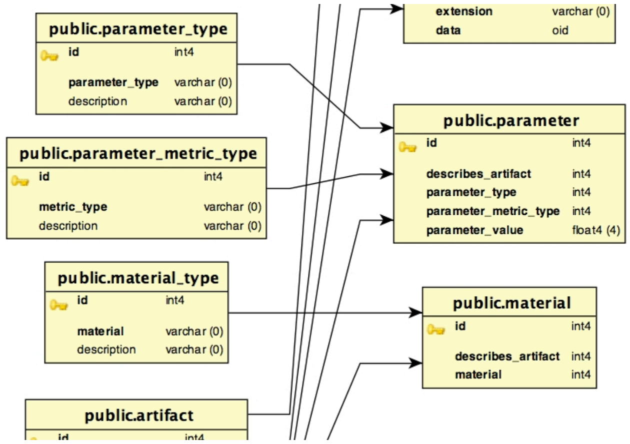


FIGURE 2: Repository schema sample [31]

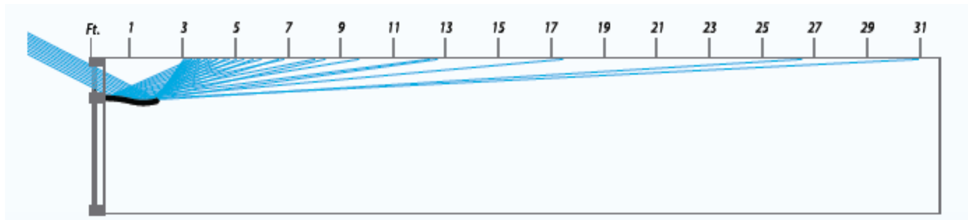
Lighting components are first entered as unique artifacts with a basic description and identification number. Each component is then assigned a set of parameters where additional attributes can be identified. These parameters include:

- *Parameter type* - physical characteristics of the components such as size, power requirements, light distribution properties, and illuminance.
- *Metric type* – type of units describing component features such as feet, watt, and lux.
- *Parameter value* – value of the parameter type based on the chosen component.

After the schema was established, three options for lighting were explored, as each item shares a common function of providing light.

- *Electrical Lighting* – Lighting options were chosen based on popular down-lighting options for commercial buildings. Ten types were selected with a significantly wide breadth of physical values such a size, wattage, and light produced. This information was taken from Acuity Brands Product Selection Guide for commercial lighting [17].
- *Windows* – Window selection was primarily based on the glazing type and light transmittance. The heat transfer coefficient was not considered, but would apply in a larger productivity model incorporating thermal environment [80].
- *Light shelves* – Light shelves are a way to passively bring light deep into a workspace (up to 30 ft.) by strategically reflecting incoming light onto the ceiling of the

workspace (Fig. 3). They are generally placed several feet above the work plane and can also simultaneously act as shading to reduce computer screen glare [16].



Length of room (ft.)

FIGURE 3: Light shelf lighting distribution [16]

Workspace Geometry

The objective of developing the lighting optimization model is to create a comprehensive design tool for selecting the preferred lighting design considering standards, costs, and users. This tool will allow designers to explore the array of feasible design solutions, bound by the constraints of requirements from customers, building standards, or specialty building mandates such as LEED and LBC, that could be scaled for more complex design requirements. The model presented for this research is constructed around a typical workspace configuration for a commercial office building. Here, a 2 by 3 lighting matrix is explored within a 600 ft^2 work plane as seen in Fig. 4. Each node within the design space represents a potential location for a specific lighting type (electrical, window, or light shelf), as selected from the available population of the previously constructed lighting repository. To increase geometry accuracy, it is assumed both windows and light shelves are located exclusively on the south-facing wall, so only nodes 2, 4, and 6 will have the option of selecting either of these components for lighting. As expected, a window and light shelf can be used together, however a light shelf cannot be used alone.

Once the basic workspace geometry was established, component parameter types were selected from the lighting repository data based on which attributes are needed to calculate values such as illuminance, power, and size. A cost-per-hour equation for each component was established to determine an hourly cost for each possible lighting configuration. The model will subsequently choose an appropriate light based on the users optimization objective, determining which configuration is optimized for preferences such as lowest cost or greatest amount of light. If the user chooses to minimize cost, the model will consider values for both hourly net employee cost as well as electrical lighting cost. The resultant configuration will be a solution where each node will contain a single discrete electrical light choice, and nodes along the southern wall can have the option of utilizing both an electrical light and multiple passive devices.

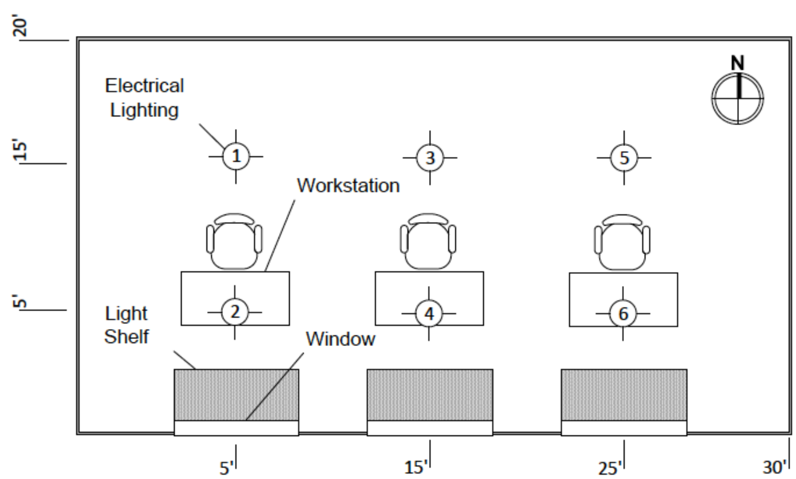


FIGURE 4: Proposed workspace geometry

In addition to electrical lighting, windows and light shelves are included as passive components to import light into the workspace. Light shelves are a low cost, efficient way of transporting light deep into a building, while simultaneously providing shading to workstations and eliminating computer monitor glare [81]. Fig. 4 displays the fixed location of these components. While daylight availability, solar incidence angle, window to wall ratio, interior surface reflectivity, and building orientation can vary, these will be assumed constant in an effort to simplify the model, however these attributes can be included in the future for a more extensive model [36]. Windows and light shelves are located along the south façade of the workspace for maximum exposure to available sunlight. Solar incidence angle, the angle between the solar rays and a line normal to the surface will be assumed constant at 45^{o} [82].

LIGHTING OPTIMIZATION STUDY

Model Configuration

This case study began with the development of seven modules contained within the lighting system shown in Fig. 5:

- Lighting Input – Raw manufacturer's data on electrical lighting, windows, and light shelves were exported from the lighting repository.
- Windows – Window specifications and calculations for available daylight.
- Position – Module that identifies the location of the nodes, and ensures a discrete lighting solution for each.
- Lighting Output – This module includes the resultant calculated lighting value based on the desired optimization lighting value.
- Lighting Cost – The electrical lighting cost module calculates a cost per hour for the lighting design, based on power usage requirements and estimated energy cost.
- Productivity – True employee cost calculated based on productivity index and salary rate.
- Total Cost – This module calculates the total resultant cost over a period of time for electrical light and employee salary costs.

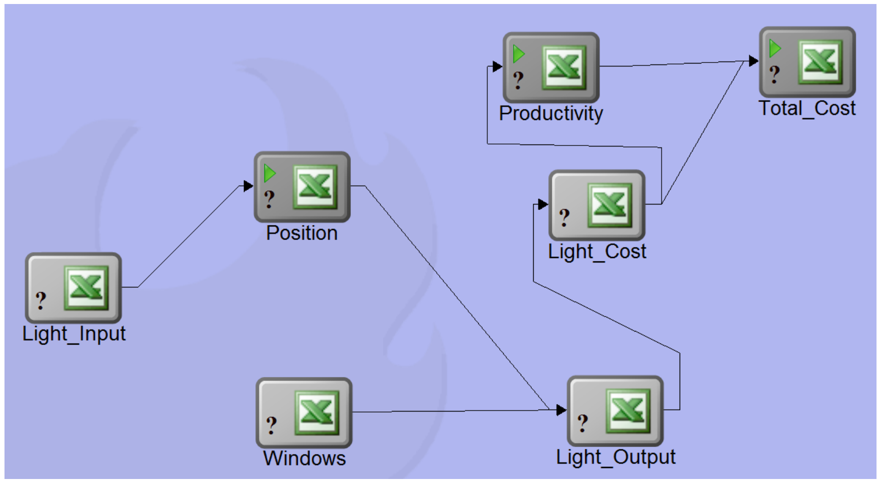


FIGURE 5: Model Center module relationships

Lighting Input Module

Manufacturer's product data was imported into the lighting input module from the design repository through Microsoft Excel, however future work will include a script wrapper so Model Center can access the data directly from the repository. Three different electrical lights, common to commercial workspace applications and one window type were chosen for this model. Light shelves were not included as part of the optimization case study, but will we included in future work as they have been added to the lighting repository. Table 1 displays applicable data collected from each component [16, 17, 80]. Incident angles for electrical lighting and the resulting values for *Candela* were assumed constant at 45^{o} based on manufacturer's photometry specifications. This relationship can be seen for the T5 Fluorescent lamp selected in Fig. 8 [83].

TABLE 1: Lighting component manufacturer's data

Name	2RT5	2ES8P	DOM8 LED	WS15	BS_STD
Description	T5 Fluor.	T8 Fluor.	8" LED	SG Window	Lightshelf
Housing Type	Recessed	Recessed	Downlight	Metal	N/A
Mounting Location	Ceiling	Ceiling	Ceiling	Wall	Wall
Brand	Lithonia	Lithonia	Lithonia	Jeld-Wen	HunterD
Quantity	2	2	1	1	2
Length (in.)	48	48	15	48	24
Width (in.)	24	24	13	48	18
Thickness (in.)	3.125	3.75	5.75	2.75	3
Initial (Lumans)	2600	2950	1200	N/A	N/A
Mean (Lumans)	2418	2800	1200	N/A	N/A
Avg. Life (hrs)	20000	20000	50000	N/A	N/A
Color Temp (K)	3000	3500	3500	N/A	N/A
Voltage (V)	347	347	120	N/A	N/A
Current (A)	0.5	0.47	0.1	N/A	N/A
Total Output (W)	56	64	27	0	0
Total Input (W)	60	55	27.5	0	0
Energy Star Qualified	No	No	Yes	No	Yes
Incident Angle	45	45	45	45	45
Candela	1280	1606	310	N/A	N/A
Power per bulb (W)	28	32	27	0	0

Position Module

Both active and passive lighting components were given discrete locations, or nodes, for use within the workspace. These nodes were assigned coordinate values based on their distance from the South West corner of the workspace. Each node was placed 5 ft. from the adjacent wall and 10 ft. from its nearest neighboring node (Fig. 4). Light placement height is assumed uniform at 8 ft. from the surface of the work plane; however, this model could be expanded to analyze multiple discrete light heights to simulate the implementation of task lighting at a particular workstation.

Window Module

To calculate average direct illuminance on the proposed work plane of the model, Equation 5 was used:

$$E_D = \frac{A_W * E_W * \tau * GBF * MF}{A_L} \qquad (5)$$

where A_W is the area of the window, E_W is the illuminance value from outside projecting onto the window, τ is the light transmittance of the window, GBF is the glazing bar factor, MF is the maintenance factor, and A_L is the area of the lower room surfaces below the mid-height of the window, excluding the window wall (Fig. 6) [84]. For this model, the outside environment is assumed to be sunny with no obstructions so E_W is estimated at 10,000 foot-candles [85].

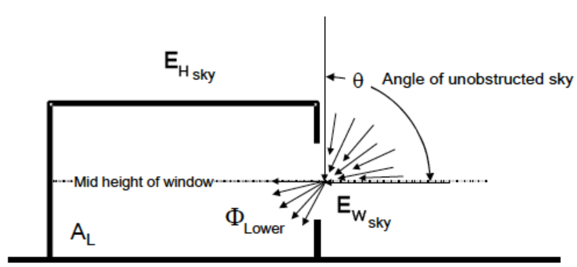


FIGURE 6: Average direct workspace illuminance from windows

Lighting Output Module

Since lighting incident angle (θ) is assumed at 45°, the lighting footprint radius is 8 ft. (Fig. 7) [86]. Figure 8 displays the relationship between incident angle and candlepower (*CP*), showing an increase in *CP* as the incident angle decreases.

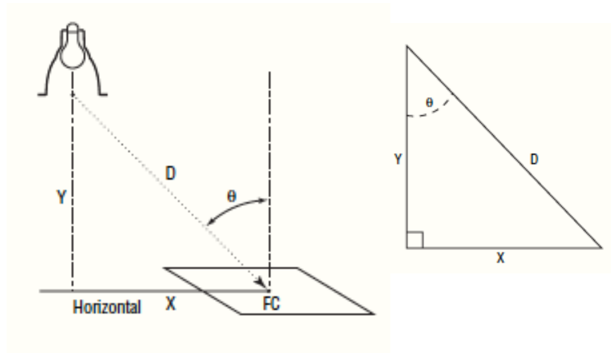
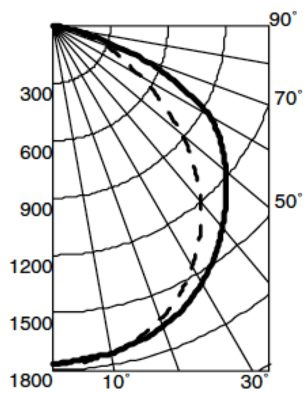


FIGURE 7: Lighting footprint calculation diagrams [86]



CP Summary

	0°	90
0°	1770	1770
5°	1766	1750
15°	1695	1707
25°	1555	1623
35°	1339	1473
45°	1044	1280
55°	695	1071
65°	393	715
75°	179	257
85°	30	21
90	0	0

FIGURE 8: Manufacturer's photometry table [83]

Point-to-point foot-candle values are calculated from Equation 6 and are assumed to be a minimum value within the lighting footprint:

$$FC = \frac{CP * cos\theta}{D^2} \qquad (6)$$

where *FC* is the foot-candle values at a location, *CP* is candle power in *Candela*, and *D* is the distance from the light to the point location. For nodes (15,5), (15,15), and (15,25), the model can select one light from the three available. Nodes (5,5), (5,15), and (5,25) can also select one of the three available light choices, but also have the option of choosing a window, or combination of both. This light source geometry simulates a typical configuration for a commercial workspace, and allows the model to select light sources based on user optimization objectives. The model configuration assumes that there are three employee workstations (Fig. 4), and each must receive a minimum lighting value of 500 *lux* or $lumans/ft^2$ based on current building standards [6].

Lighting Cost Module

A cost function calculates the total cost of a given lighting configuration by incorporating values for lighting input power, hours of operation, and employee salary. It is assumed that employees work for 8 consecutive hours during day, and any electrical lighting configurations chosen by the model will be on for the duration of the time. Electrical lighting cost per node is calculated as in Eqn. 7:

$$C_L = hr_E * c_U * p_L \qquad (7)$$

where C_L is total light cost per node (*$*), hr_E is employee operation hours, c_U electricity cost per unit *($/kWh)*, and p_L is input power of light (*kW*).

Productivity Module

This module was constructed from Equations 2, 3, and 4, where total employee cost was calculated based on three available workstations. Employees' salary was set at $20 / hr. and workday duration was set at 8 hours. The P_C (Change in Productivity) was limited to 10% to stay below the lighting threshold where increased illuminance presents a glare and decreases lighting quality.

Total Cost Module

Total cost for a prescribed workday was calculated from Equation 1 and was the basis for the optimization objective. By expressing all of the variables in terms of a single cost criterion, trade-offs between cost, user productivity, and building standards can be quantified.

Variable Relationships

In order to achieve the correct flow of information within Model Center, variables were linked between modules to establish functional relationships. Variables included electrical lighting component options, lighting component position, lighting state (on or off), window presence (yes or no), and light shelf presence (yes or no). This process began by linking the available electrical lights from the Light Input Module to each of the available nodes in the Position Module. Based on a user's objective, a discrete electrical lighting component is then chosen for one of the available locations. In addition to electrical lighting, the option to have a window or a light shelf is available for node 2, 4, or 6. To understand how lighting choices further affect the workspace, calculated values are linked between modules, producing feasible points within the design space. For example, Fig. 9 displays the transfer of the resultant value for total foot-candles in the *Lighting Cost* module to an input in the *Productivity* module.

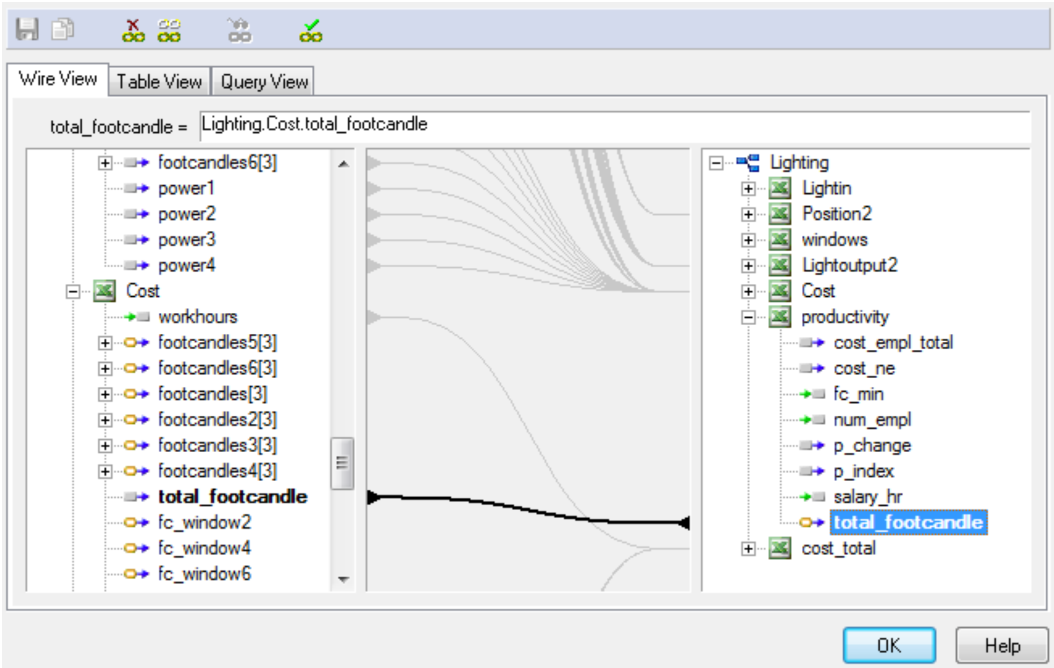


FIGURE 9: Variable relationship flow in Model Center

RESULTS OF MODEL OPTIMIZATION

A Darwin genetic algorithm was used in Model Center to optimize the objective of minimizing total cost, while still meeting current building standards, and increasing workspace user productivity. After 1000 iterations, the GA optimization model converged on a single optimal design solution (Fig. 10). Table 2 displays a summary of the position node's selected electrical lighting component choice, presence of window, average foot-candle value, productivity index, and total cost. Optimized values are outside objective constraints since this is a discrete choice model. As expected from the stated objective, windows were chosen for all available locations, as they do not consume electricity or incur any cost. The electrical lighting components selected were comprised of a mixture of the two lowest energy-consuming options. With an expanded model, a greater number of position nodes and electrical lighting components could be included to give a higher fidelity interaction significance of lighting selection and placement.

TABLE 2: Lighting component and position summary

Node	**Position**	**Light Type**	**Window**	**Avg. FC**	**PI**	**Total Cost**
1	{5,15}	DOM8	N/A	**98.9**	**1.11**	**$433**
2	{5,5}	2RT5	Yes			
3	{15,15}	2RT5	N/A			
4	{15,5}	2RT5	Yes			
5	{25,15}	DOM8	N/A			
6	{5,25}	DOM8	Yes			

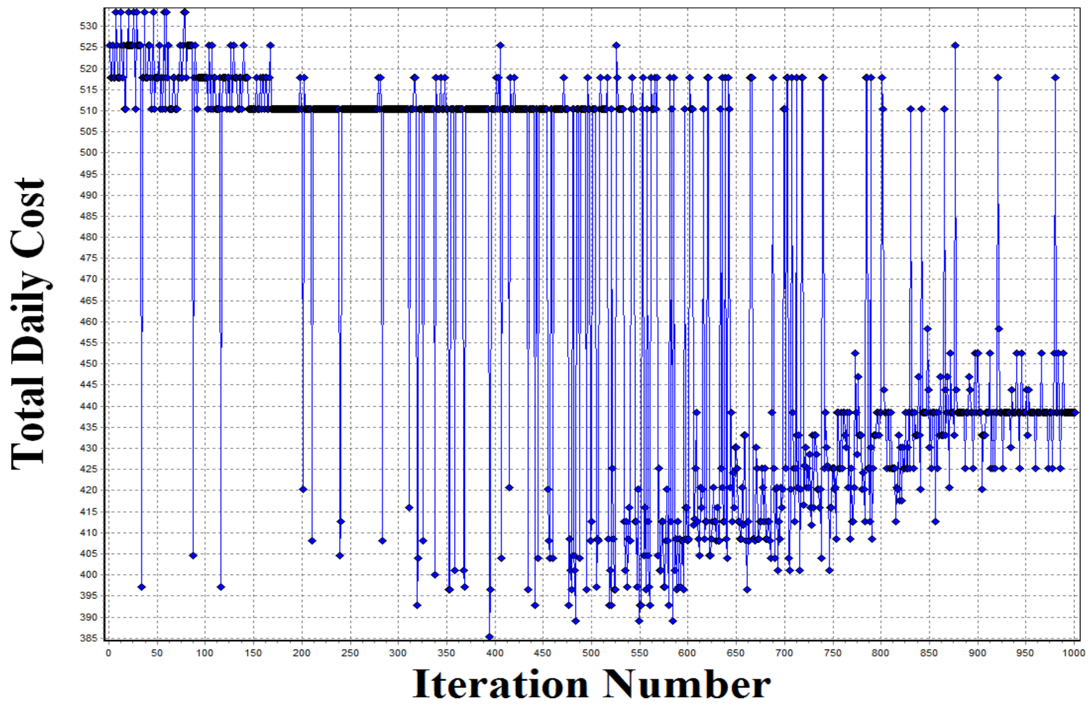


FIGURE 10: Cost optimization convergence after 1000 iterations

By relating all applicable relationships to a single criterion optimization, a picture of the feasible design space begins to form. Fig. 11 displays the relationship between total cost and average illuminance, showing feasible points along the Pareto Frontier. As illuminance increases, total cost decreases. Subsequently, Fig. 12 displays how an increase in user productivity also yields a reduction in total cost. A primary benefit of using Model Center is the ability for the user to visually explore all Pareto optimal solutions for a stated objective, assisting in understanding the variable interactions.

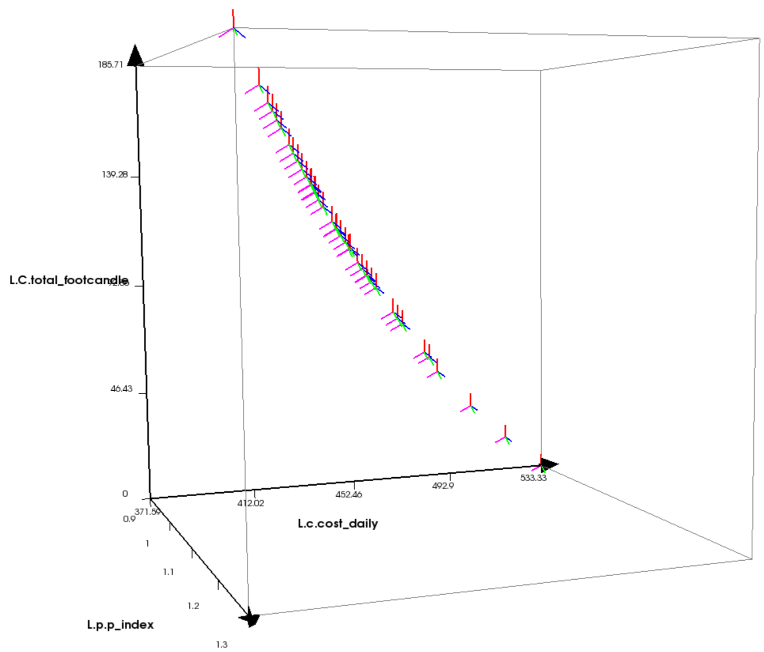


FIGURE 11: Feasible Pareto optimal designs displaying total cost versus total footcandles

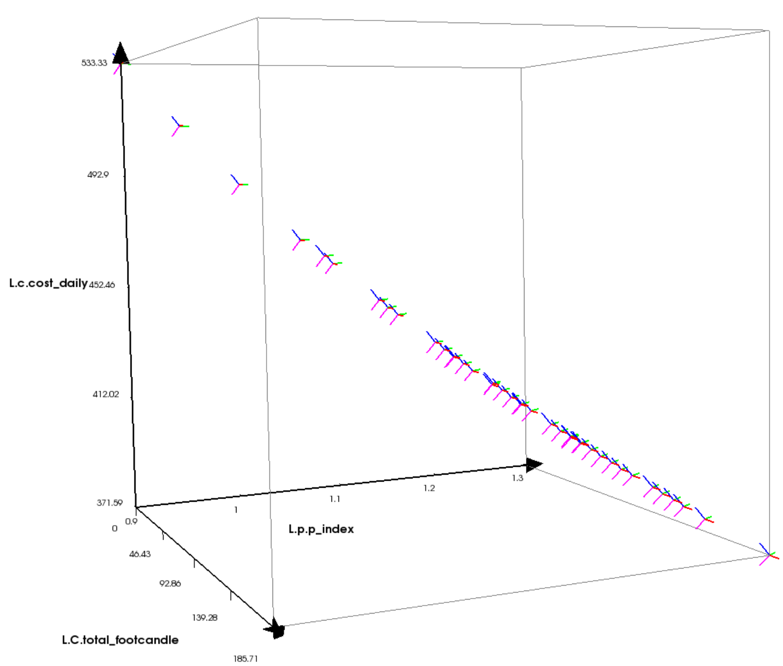


FIGURE 11: Feasible Pareto optimal designs displaying total cost versus total productivity index

While these results may have been expected based on stated variable interactions and applied constraints, this research provides continued insight into the need for an integrated approach during sustainable building design, that considers how the facility will be used. This initial model outlines a simplified relationship between lighting and user productivity, however it is applicable to other building subsystems and could be scaled accordingly to include other factors that affect workplace productivity such as temperature and building geometry. Considering post construction occupant productivity when designing mechanical subsystems required to achieve modern building requirements such as net-zero energy will assist in mitigating barriers associated with sustainable building techniques.

CONCLUSIONS AND FUTURE WORK

This paper presents an argument for examining workplace performance characteristics of employees, based on the availability of lighting, in early building design. By optimizing the component selection and placement of both electrical lighting options, as well as passive components such as window and light shelves, an energy efficient workspace can be created that maximizes occupant productivity while reducing energy costs and meeting modern building standards such as LEED and LBC. This post construction vision of workplace optimization can help mitigate additional building costs associated with sustainable design practices, and work toward eliminating barriers associated with cost concerns.

The model created for this research is a scalable representation of how a repository of building subsystem components could be used to create both productive and energy efficient workspaces, early in the design process, saving financial and temporal resources. Beyond lighting, other subsystems could be explored that have known benefits to improve occupant productivity such as indoor temperature, air quality, and interior geometry. These subsystem components could be added to the existing repository and incorporated into an expanded model increasing the accuracy of employee productivity estimates.

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CONCLUSION

Sustainable building design techniques are more prevalent as standards for modern buildings are becoming increasingly energy conscious. Currently, sustainable building design techniques utilize a top-down architectural approach that can consume financial and temporal resources during the early design stage. Design mandates such as net-zero energy and water make it difficult to utilize this top-down architectural approach to building design, as there are a diverse breadth of mechanical subsystems and associated complex system interactions required to achieve these requirements. In addition to mechanical subsystems, many commercial sustainable building projects require an extensive array of stakeholders to coordinate efforts, often constraining design decisions and inhibiting the use of an integrated design process. The implementation of an integrated framework for sustainable building design will shift the current architectural top-down design paradigm to a comprehensive approach similar to traditionally recognized complex systems.

In the first manuscript, a case study of the Oregon Sustainability Center (OSC) is presented that examines the schematic design timeline of a net-zero energy and water building. In this study, a detailed outline of the mechanical subsystems required to achieve net-zero status in a commercial building is presented. This outline details the similarity between the subsystems and associated interactions in a net-zero building and those in a traditional complex. By treating sustainable buildings as a complex system, interaction outcomes can be analyzed to achieve an overall more efficient design.

Additionally, project stakeholder contributions are detailed, along with their effect on the design process. The schematic design process of the OSC revealed stakeholder decisions during the design timeline inadvertently affected the overall design. By switching to an integrated design process, individual stakeholder decisions could be integrated with the entire design team.

This paper also addresses the need for subsystem optimization techniques to reduce energy usage levels. Efficiency limitations in energy generation techniques such as solar and wind require considerable energy conservation strategies to meeting net-zero mandates. By incorporating passive energy conservation techniques, individual subsystems can be optimized to minimize energy usage, while still meeting both customer and engineering requirements.

The second manuscript addresses the need for subsystem optimization, as a way to achieve sustainable building standards. Beyond energy efficiency, post construction user interaction is also considered, specifically user productivity. By addressing the potential for increased user productivity in the commercial workplace, additional costs associated with sustainable building design techniques can be mitigated. A single criterion optimization methodology has been developed to address subsystem costs while considering both building standards and user productivity.

This optimization model was created to produce feasible design concepts by selecting from a repository of components, specific to that subsystem. For this case study, the repository was populated with components applicable to a commercial workspace lighting design. As lighting levels rise to a maximum value of illuminance, user productivity increases accordingly. This increase in productivity contributes to minimizing overall costs, effectively reducing the payback period.

The treatment of modern sustainable buildings as complex systems allows the use of known techniques to produce replicable and robust building designs. Strategies such as system optimization continue working toward the goal of a comprehensive integrated framework for sustainable building design. By considering building users in the design process, additional costs can be mitigated, furthering the argument for net-zero energy and water buildings a viable option for global energy conservation strategies.

To further this research, several directions for future work have been considered. As an extension of the second manuscript, a design of experiment (DOE) is proposed using three existing LEED certified commercial buildings. In this experiment, real time data will be collected recording both building lighting levels, and corresponding user occupancy levels of a given workspace. The goal is to determine a relationship between changing lighting levels and user occupancy. While occupancy differs from productivity, it is another characteristic of *indoor environmental quality* as defined by LEED. In an effort to quantify this characteristic, a latent variable modeling approach will be considered, where user productivity and occupancy are indicators of the latent variable *indoor environmental quality* [87, 88]. In addition, a preference survey will be generated to determine others factors contributing to indoor environment [89]. This survey will include comparative choice information about various attributes present in each of the three buildings. Once a quantifiable relationship has been established for indoor environment, this information will be added to the existing optimization model from the second manuscript, increasing accuracy.

In addition to indoor environment, the current optimization model will be expanded by adding an additional module for heating, ventilation, and air-conditioning (HVAC). By incorporating HVAC considerations into the model, trade-offs between different subsystems will be observed. For example, window to wall ratio will affect both thermal conductivity of the building envelope and availability of natural light in a workspace. Expanding the inventory of building components will also increase the accuracy of the model. Adding additional lighting positions, multiple windows types and light shelves, as well as HVAC components will create a more diverse system optimization.

Finally, using the methodology established in the second manuscript, a high-level approach to global energy reduction will be considered by examining the U.S. power grid. Here, a cost driven single criterion optimization model will be created observing trade-offs between energy reduction strategies, future energy demands, and environmental impact of energy generation. Energy reduction strategies will include sustainable building design, industrial manufacturing energy audits, and residential energy reduction programs. Environmental impact will be quantified in terms of cost by evaluating historical expenses associated with both fossil fuel and renewable energy generation. For example, these would include the financial cost of environment strategies used to mitigate the negative effects of hydroelectric power on the local ecosystem. In an effort to address future energy demands, this model will incorporate future power plant construction based on regional feasibility, as well as power plants at the end of their life cycle that will go offline.

VITA

Joseph Piacenza earned his BS in mechanical engineering from the University of South Florida, and completed his MBA at USF in 2008 with a focus on entrepreneurship and management. While working toward the MBA, he founded an automotive-based small business, specializing in restoration and service of European vehicles. This business was sold in early 2010, and he is currently working toward a PhD in mechanical engineering at Oregon State University, performing research in the Complex Engineered Systems Design lab with a focus on sustainable building design for net-zero energy and water buildings. He is also involved with the OSU Industrial Assessment Center, a Department of Energy funded program developed to help conserve energy in industrial manufacturing applications.

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