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Exploring Decision-Making Methods for Sustainable Design in Commercial Buildings

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EXPLORING DECISION-MAKING METHODS FOR SUSTAINABLE DESIGN IN COMMERCIAL BUILDINGS

by

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ABSTRACT

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During the building design process hundreds of decisions are made at different stages, and with multiple stakeholders. This includes choosing alternative materials, components, assemblies, systems, and buildings shapes. The design team faces many challenges in order to evaluate which alternative is more sustainable. The methods used in making those decisions must take the complexity of the design process into account and help the design team in understanding the trade-offs that must be made. This must be done based on context, and in a transparent and collaborative fashion. What is more, the design team may benefit from keeping decisions objective for as long as possible during the decision process to avoid unnecessary conflict and suboptimal decisions. Ultimately, the decision-making method used in those decisions will impact the final building design, and therefore, the building's social-, environmental -, and economic outcomes.

Much like designers and engineers benefit from relying on specific modeling-, analysis-, and evaluation methods to inform their judgment in the course of the design, the design team would also benefit from relying on decision-making methods. However, the architecture-, engineering-, and construction-management literature provides almost no guidance to internal stakeholders (owner, architect, design specialists, etc.) on how to choose a sustainable alternative (e.g., choosing materials, components, assemblies, systems, building layouts).

This research evaluates the ability of Multiple-Criteria Decision-Making (MCDM) methods to help design teams choose a sustainable alternative during commercial building design. The researcher identified several types of MCDM methods in the literature. Those with potential application for the 'choosing problem' studied in this research are (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods (including Analytical Hierarchy Process (AHP) and Weighting Rating and Calculating (WRC)), (3) Outranking methods, and (4) Choosing By Advantages (CBA).

The researcher compared these different types of methods and judged them on how they help in creating transparency, building consensus, and continuous learning for the problem of choosing a sustainable alternative in commercial building design. Thus far the literature contains no such comparison. The research method included interviews in the early exploratory phase and case-study research for testing the methods.

The researcher further compared AHP vs. CBA and WRC vs. CBA through case studies. The researcher selected AHP for its prevalence in AEC decision-making literature, WRC for its widespread use in AEC design practice, and CBA for its potential support in creating transparency, building consensus, and continuous learning, better than either one of these two methods do.

From the four types of methods studied the researcher found that:

(1) Goal-programming and multi-objective optimization methods are particularly suited to problems that require screening of a big or infinite number of alternatives according to ranked criteria. However, some multi-objective optimization methods avoid the use of explicit trade-offs by using a ranking of factors. This does not create transparency when comparing a small number of alternatives with known attributes.

(2) Value-based methods are widely used in building design practice and literature. However, such methods (e.g., AHP and WRC) may not help in creating transparency, building consensus, and continuous learning for group decision making. This is because they (a) may assume that factors have zero as a natural scale, (b) may assume that trade-offs between factors are linear functions, (c) may not differentiate between alternatives, (d) may be inconsistent when irrelevant factors are removed, (e) may mix 'value' and cost, (f) may require conflicting judgments for weighting factors, and (g) may lack support for context-based analysis.

(3) Outranking methods are hard to apply to this problem since they lack an aggregation function, which makes it impossible to rank alternatives and evaluate 'value' vs. cost. Even when these methods focus more on the differences between the alternatives than value-based methods do, they also require decision makers to weigh factors and attributes in order to build outranking relations.

(4) CBA focuses more on differentiating between alternatives, and better guides the design team to understand 'value' vs. cost compared to the other MCDM methods studied. In addition, CBA avoids assuming that every increment in performance is equally valuable or that trade-offs between factors are linear.

After comparing the methods, this research proposes the use of Choosing By Advantages (CBA) to overcome the deficiencies of the value-based methods in regards to creating transparency, building consensus, and continuous learning in the design process. The researcher further tested CBA in three case studies for different applications in architecture and engineering firms in the San Francisco Bay Area.

This work contributes to knowledge by providing: (1) A theoretical evaluation of the four types of MCDM methods being studied and illustrating relevant differences between them; (2) A practical evaluation of CBA vs. AHP and CBA vs. WRC presenting factors and criteria for evaluating their ability to assist practitioners in deciding which alternative is more sustainable in commercial building design; (3) A rationale for recommending the

CBA method in the research context; and (4) An analysis of the application of CBA for different types of decisions. In addition, this research discusses: (5) How sustainable rating systems (e.g., LEED) affect decisions; (6) How cognitive biases may apply to group decision making in this context and how they may be overcome; and (7) How rhetoric can support the CBA application. Through these seven areas of contribution, the presented research provides a basis for discussing MCDM method selection in commercial building design that may be expanded to other applications, and for advancing our understanding of the relationship between decision-making methods and building outcomes.

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ACKNOWLEDGMENTS

Obtaining a PhD was a transforming experience for me. I learned how to think critically and understand what it means to know the limits of knowledge in a field. While living in the US I also learned how to live in another culture and appreciate the synergies of the UC Berkeley community. Now I feel part of a big community, of people who have contributed to knowledge in a diverse range of topics. I feel proud of contributing knowledge in my field of interest. However, the process is not easy and requires dedication and perseverance.

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DEFINITIONS

Advantage	A benefit, gain, improvement, or betterment. Specifically, an advantage is a beneficial difference between the attributes of two alternatives (Suhr 1999).
Alternatives	Two or more people, things, or plans from which one is to be chosen (Suhr 1999). In building design, alternatives can pertain to materials, components, building systems, etc. In this research an 'alternative' can be at various different levels. It can be a material (e.g., choosing an insulation material), a component (e.g., choosing a ceiling tile), an assembly (e.g., choosing a wall assembly or window assembly), a system (e.g., choosing a structural, mechanical, or lighting system) or a building (e.g., choosing a building layout).
Analytical Hierarchy Process	It is a type of value-based method. This method measures relative importance of factors and preferences for alternatives through pairwise comparison matrices, which are recombined into an overall rating of alternatives by using the eigenvalue method (Saaty 1980).
Attribute	A characteristic, quality, or consequence of one alternative (Suhr 1999).
Choosing by Advantages	A decision-making system that supports sound decision making using specific comparisons of advantages of alternatives (Suhr 1999).
Criterion	A decision rule or a guideline. Usually, a 'must' criterion represents conditions that eliminate an alternative from consideration if that alternative does not meet them, or a 'want' criterion represents preferences of one or multiple decision makers. (Suhr 1999).
Design Process	A "systematic, intelligent generation and evaluation of specifications for artifacts (buildings) whose form and functions achieve stated objectives and satisfy stated constraints" (Dym and Levitt 1991).
Design Team	Architects, engineers (structural, mechanical, electric, mechanical, etc.), designers, managers, and contractors arranged to provide design services in a specific project (Parrish 2009).
External Stakeholders	Community, regulatory agencies.
Factor	An element, part, or component of a decision (Suhr 1999). Sustainability factors should represent social-, environmental-, and economic aspects of the alternatives.
Green Building	"The practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction" (Environmental Protection Agency 2012).
Internal Stakeholders	In this research, internal stakeholders are the design team plus the owner and users.
Lean Construction	Lean philosophy applied to construction (Koskela 1992).
Lean Management Philosophy	Production system management based on the integration and balancing of the transformation-, flow-, and value theory conceptualizations (Koskela 1992).
Lean Philosophy	Lean philosophy is about maximizing customer 'value' while minimizing waste.
Multiple-Criteria Decision-Making Method for choosing an alternative	In this research we look at a multiple-criteria decision-making method for choosing a desired alternative, not for sorting, ranking, or describing alternatives (Roy 1974). Several types of MCDM methods are available in the literature, those studied in this research are (1) goal-programming and multi-objective optimization methods, (2) value-based methods, (3) outranking methods, and (4) choosing by advantages.

Multiple-Criteria Decision-Making Methods	“A collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups to explore decisions that matter” (Belton and Stewart 2002). Also known as Multiple-Criteria Decision Analysis (MCDA).
Negative Iteration	“Iteration is essential for generating ‘value’ in design processes. However, not all iteration generates ‘value’. Iteration that can be eliminated without ‘value’ loss is waste (negative iteration)” Ballard (2000c). In other words, negative iterations do not add ‘value’.
Point-Based Design	Point-based design involves selecting a single feasible design alternative that meets the requirements at each step in the design process and then refining that single design (or point) while developing more details during the design process. This single design is then re-worked until a solution is found that is feasible (Parrish et al. 2007).
Set-Based Design	“Designers explicitly communicate and think about sets of design alternatives at both conceptual and parametric levels. They gradually narrow these sets by eliminating inferior alternatives until they come to a final solution” (Ward et al. 1995). In addition, set-based design produces fewer negative iterations when compared to point-based design.
Sustainability	Many sustainability definitions exist. The World Commission on Environment and Development (1987) defines it as, “Meet present needs without compromising the ability of future generations to meet their needs”. Osenbaum (1993) and the Environmental Protection Agency (2012) mention (1) respecting the limits of our natural resources, (2) understanding the interconnection of the three sustainability components (social-, environmental-, and economic system) and (3) providing an equitable distribution of resources and opportunities for this and future generations.
Sustainable Development	“Sustainable Development is positive change which does not undermine the environmental or social systems on which we depend. It requires a coordinated approach to planning and policy making that involves public participation. Its success depends on widespread understanding of the critical relationship between people and their environment and the will to make necessary changes.” (United Nations Educational, Scientific and Cultural Organization 2006)
Value-based Methods	These methods construct numerical scores for each factor, and then preferences are synthesized using an aggregation model based on the relevance (weights) of different factors. (Belton and Stewart 2002)
Weighting Rating Calculating	It is a simplified version of AHP in which factors are weighted, alternatives are ranked according their attributes and then the final score of each alternative is calculated.

ACRONYMS

A/C	Air Conditioning
AEC	Architecture Engineering and Construction
AHP	Analytical Hierarchy Process
AIA	The American Institute of Architects
ANP	Analytical Network Process
ASCE	American Society of Civil Engineering
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASSOHQE	Association pour la Haute Qualité Environnementale
ASTM	American Society for Testing and Materials
BART	Bay Area Rapid Transit
BAS	Building Automation System
BREEAM	Building Research Establishment Environmental Assessment Method
C&D	Construction and Demolition
CALGreen	California Green Building Standard
CASBEE	Comprehensive Assessment System for Build Environment Efficiency
CBA	Choosing By Advantages
CEE	Civil and Environmental Engineering
CFD	Computational Fluid Dynamics
CFL	Compact Fluorescent Lamp
CHPS	California Department of Health Services
CI	Consistency Index
CMU	Concrete Masonry Unit
CONICYT	Comisión Nacional de Investigación Científica y Tecnológica
CRI	Color Rendering Index
CSDEC	Conference for Sustainable Design, Engineering and Construction
DBB	Design Bid Build
DEA	Data Envelopment Analysis
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DOE	Department of Energy
ECC	Engineered Cementitious Composites
ELECTRE	Elimination et Choix Traduisant la Realité
EPA	Environmental Protection Agency
EPD	Environmental Product Declaration
EQ	Earthquake
EUI	Energy Use Intensity
EVAMIX	Evaluation of Mixed Data
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEQ	Haute Qualité Environnementale
HPD	Health Product Declaration

HQE	High Quality Environmental standard
HVAC	Heating, Ventilation and Air Conditioning
IEQ	Indoor Envromental Quality
IFOA	Integrated Form of Agreement
IGLC	International Group for Lean Construction
IofA	Importance of Advantages
IPD	Integrated Project Delivery
JCEM	Journal of Construction Engineering and Management
LBC	Living Building Challenge
LCA	Life Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCI	Lean Construction Institute
LED	Light-Emitting Diode
LEED	Leadership in Energy and Environmental Design
LPDS	Lean Project Delivery System
MAUT	Multi-Attribute Utility Theory
MAVT	Multi-Attribute Value Theory
MCDA	Multiple-Criteria Decision Analysis
MCDM	Multiple-Criteria Decision-Making
MEP	Mechanical, Electrical, and Plumbing
MOO	Multi-Objective Optimization
MR	Material Resources
NASA	National Aeronautics and Space Administration
NIBS	National Institute of Building Sciences
NRC	Noise Reduction Coefficient
NZE	Net Zero Energy
OC	On Center
OPL	One Planet Living
PC	Personal Computer
PDCA	Plan Do Check Act
PG&E	Pacific Gas and Electric Company
PROMETHEE	Preference Ranking Organisation Method for Enrichment Evaluations
PUC	Pontificia Universidad Católica de Chile
PV	Photovoltaics
SBD	Set-Based Design
SIP	Structural Insulated Panels
SMART	Simple Multi-Attribute Rating Technique
STC	Sound Transmission Class
TFV	Transformation Flow Value
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPS	Toyota Production System
TVD	Target Value Design

UC	University of California
UK	United Kingdom
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
US	United States
USDA	U.S. Department of Agriculture
USGBC	U.S. Green Building Council
UTA	Utility Theory Additive
VOC	Volatile Organic Compounds
WCED	World Commission on Environment and Development
WRC	Weighting Rating Calculating
WS	Weighted Sum
WWF	World Wildlife Fund
YWCA	Young Women's Christian Association

1. INTRODUCTION

This introductory chapter presents the problem that the researcher studied (Section 1.1); her motivation for doing this research (Section 1.2); the research questions she posed (Section 1.3); the background to understand the context of the study (Section 1.4); the scope of the research (Section 1.5); the research methodology used for answering the questions (Section 1.6), and the structure of the dissertation (Section 1.7).

1.1. Problem

Commercial buildings serve important functions in our society by providing spaces for work, education, and other public and private uses. Notwithstanding their importance, commercial buildings have a significant impact on the environment and occupants' health (Section 2.8). The Architecture Engineering and Construction (AEC) industry faces many challenges in designing more sustainable buildings, which not only serve the needs of people today, but also maintain resources and healthy conditions for future generations.

During the sustainable design of commercial buildings hundreds of decisions are made (e.g., choosing materials, structural systems, and space layout). These decisions have to consider social-, environmental-, and economic aspects, which involve multiple stakeholders, often with conflicting interests. Decisions may be complex involving multiple factors and dynamic relationships among multiple building systems. Accordingly, the design team may benefit from using a Multiple-Criteria Decision-Making (MCDM) method for creating transparency, for building consensus, and for continuous learning. Consequently, the design team may be able to provide a clear and shared rationale for arguing in favor of a sustainable alternative, and be able to evaluate 'value' vs. costs of different alternatives in order to improve the whole building design.

The problem is that the literature does not provide enough support for practitioners to select a MCDM method in this context. In addition, many decisions in practice are made without a formal method or discussion, which often generate conflicts and waste in the design process. Moreover, many practitioners are not even aware of the available MCDM methods. This research fills the literature gap and provides practical advice for practitioners.

1.2. Motivation

1.2.1. Current Practices

Decisions in the AEC industry are usually made without rigorous analysis (Mar 2012b, Fischer and Adams 2011). Through interviews and case studies this research also revealed that decisions are rarely documented. Often, when the design team chooses an alternative the rationale is not clear, and seldom is a formal decision-making method used. The decision-making process usually lacks transparency and does not help in building consensus or continuous learning. Moreover, in sustainable design of commercial buildings, multiple stakeholders are involved, who have different perspectives and often conflicting interests. The current practice for choosing among alternatives can be detrimental for sustainable design of commercial buildings (Ding 2005). This is because the lack of clear and shared rationale often requires decisions to be changed late in the design process, which results in the waste of time and resources if a solution can be found at all. This research focuses on three areas of the current decision-making process, each needing improvement:

- *Creating Transparency:* Often practitioners cannot explain the rationale of a decision, even when they were involved in the project at the time that it was made. Many decisions are based solely on cost or achieving points for a sustainable rating system (e.g., LEED), disregarding important differences between the alternatives. Creating transparency for choosing alternatives allows for understanding the rationale for a decision, clarifies the ‘value’ vs. the cost of the alternatives, and allows for optimizing decisions across building systems. Section 3.1.1 expands on the issue of creating transparency and how MCDM methods may help.
- *Building Consensus*: when making decisions in commercial buildings design, practitioners appear to use ‘decide, present, and defend’ approaches resulting in decisions made without formal discussion. Such approaches are seldom collaborative and they may not seek to optimize the whole building design. Building consensus is desirable for avoiding conflicts and unnecessary iterations in the design phase. This is critical in the case of sustainable building design because multiple stakeholders with conflicting interests are involved. Section 3.1.2 expands on the issue of building consensus and how MCDM methods may help.
- *Continuous Learning:* Many decisions are not documented, or documented in a way that is not transparent, which does not allow for continuous learning. If the design team is able to clearly identify the rationale for a decision, future iterations, especially those adding information (e.g., new alternatives or new factors) to the design process, will be better understood and guided. This may save time, resources, and result in a better overall decision than made otherwise. Section 3.1.3 expands on the issue of continuous learning and how MCDM methods may help.

1.2.2. Gap in Knowledge

This research fills a gap in knowledge by comparing four types of MCDM methods and evaluating their ability to support design decisions in commercial building, particularly when decisions consider sustainability issues. These MCDM methods are (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods, (3) Outranking methods, and (4) Choosing By Advantages (CBA). Previous studies compare MCDM methods (Belton and Stewart 2002, Guitouni and Martel 1998, Triantaphyllou 2000), but not for the context of design decisions in commercial buildings and they did not include CBA in the comparison. Parrish (2009) compared CBA and Analytical Hierarchy Process (AHP), which is a value-based method, for choosing rebar design. However, this research provides greater detail in comparing them, in addition to expanding the comparison of CBA with other methods, and further testing CBA in this context.

1.3. Research Questions

The researcher seeks to advance knowledge by answering the following research question:

- What is the best available MCDM method for choosing between sustainable alternatives in commercial building design?

The available MCDM methods are limited to the scope of this research. In order to answer the research question, the following specific questions were answered:

- Which decision-making methods are being used for selecting sustainable alternatives in building design?
- Which methods are available for decision-making processes in other fields?
- What are relevant differences between MCDM methods?
- How do the relevant differences between MCDM methods help (or not) the design team in creating transparency, building consensus, and continuous learning?

Given that CBA was found to be the best available MCDM method, the researcher investigated the following questions:

- Is it feasible to use CBA for choosing a sustainable alternative in commercial building design?
- How does CBA help (or not) the design team in creating transparency, building consensus, and continuous learning?

1.4. Background

This section expands on the research context and provides insights on why it is important to create a transparent decision in order to build consensus and allow for continuous learning in sustainable design of commercial buildings.

1.4.1. 'Traditional' Project Delivery Systems

The 'traditional' project delivery system is based on a highly fragmented industry. Usually multiple stakeholders (e.g., design specialists, contractors, subcontractors, investors, and users) are involved in the design and construction process, and they have to deal with complex information flow, interrelated building systems and few economic incentives to collaborate.

The project delivery system is composed of the project's organization, commercial terms and 'operating system' (Thomsen et al. 2009). The project's organization will affect the timing of decisions, when each member joins the project, how they collaborate, and share information. The project's commercial terms will affect interrelated decisions across a project's participants (e.g., architect, general contractor, subcontractor) and their consequences for the whole project. For example, if a project contract does not interconnect project participants and does not align their interests, making decisions may result in many conflicts. According to Thomsen et al. (2009), lack of interconnecting participants may result in each participant promoting his own financial interests regardless of the interests of other participants or the project as a whole. The 'operating system' defines how the work is done and will also affect how the decisions are analyzed. Traditionally, an 'operating system' is based on activities and how to optimize those activities individually. If decisions involve only one activity or one design decision, the design team may obtain a suboptimal result compared to evaluating multiple design decisions and their impacts in multiple building systems.

A decision-making method cannot overcome all problems of 'traditional' project delivery systems in commercial building design, but it can help to evaluate alternatives when multiple stakeholders are involved and they want to build consensus. A decision-making method may also help to analyze alternatives from a whole building perspective.

1.4.2. Design Process in Commercial Buildings

The design process and development of a commercial building using Design Bid Build (DBB) delivery may be divided in 5 phases: (1) Planning and programming, (2) schematic design, (3) design development, (4) construction documents and (5) construction. Table 1.1 describes the purpose of each phase, and what is usually done in terms of the organizational, contractual dimensions in every phase.

Table 1.1 Development phases in commercial building.

	Planning and Programming	**Schematic Design**	**Design Development**	**Construction Documents**	**Construction**
Purpose / Decisions	Project scope, features, purpose, and functionality	Conceptual design including scale and relationships between building systems	Decisions are worked out in greater detail. Requires coordination of all aspects of the design	Drawings and specifications for construction bids and for obtaining permits	Construction to ensure conformity to drawings, specifications, and standards
Organization	Owner and Architect	Owner, Architect, Structural Engineer, etc.	Owner, Architect, Structural, Mechanical, Electrical, etc.	Owner, Architect, Structural, Mechanical, Electrical, etc.	Owner, Architect, Engineers, Construction Manager, Subcontractors, etc.
Commercial Terms	Owner-architect agreement	Owner-other specialist agreement	Owner-all specialists agreement	Bidding process	Construction agreement

The level of detail considered in design decisions increases throughout the design phases, as more specialists are involved. At the same time decisions made early in the design process may have more potential to impact the design and a lower cost of application than decisions made late in the design process. Lack of interaction among stakeholders early in the design phase often results in conflicts and more iteration in the design.

The scope of the design phases may change in different project delivery systems. Moreover, the project delivery system used will affect who is involved and at what stage of the design the decisions can be analyzed in detail.

In a DBB project delivery, the architect usually works with the owner during planning and programming. Then, during schematic design, some specialists, such as structural engineers, come into the project. During design development, more specialists (structural, mechanical, electrical, plumbing, fire protection, etc.) are involved and coordinate all aspects of the design, providing a basis for the preparation of construction documents. During the construction documents phase, the final drawings and building specifications are developed, allowing the project to go through the bidding process. During the construction phase, the general contractors and subcontractors join the project and build to the design. External stakeholders are also involved in commercial building design. These include members of the community and regulatory agencies (e.g., fire department).

Section 2.12 presents a discussion of the differences between DBB and Integrated Project Delivery (IPD) and how this may affect the decision-making process.

1.4.3. ‘Traditional’ Design Process

The ‘traditional’ design process is based on the assumption that by optimizing each individual part (design, construction, operation) and each component (structural, mechanical, electrical, interiors, etc.), the whole building will be optimized. Unfortunately, as demonstrated by the poor performance of commercial buildings, such as cost and schedule overruns, energy and water intensive buildings (DOE 2008), unsatisfied clients, and wasting legal conflicts, this model has not been successful.

In order to produce more sustainable buildings, designers may benefit from using a collaborative approach that accounts for the complexity of the design process including the decision-making process.

1.4.4. Collaborative Design Process and Lean Design

Many authors (e.g., Reed 2009, Phelps 2012, Buntrock 2001) have emphasized the need for collaboration in order to produce a high performance and sustainable building. Figure 1.1 shows different levels of interaction among design team members in an integrated design process and in a ‘traditional’ design process. Different boxes represent different building subsystems or specialties. In an integrated design process the entire design team is coordinated in order to understand the effects of one system on another and the whole building performance. Reed (2009) argues that an integrated design team is required to produce a sustainable design.

Interactions of relevant stakeholders in the integrated design team may avoid negative iterations. According to Ballard (2000c), “Iteration is essential for generating ‘value’ in design processes. However, not all iteration generates ‘value’. Iteration that can be eliminated without ‘value’ loss is waste (negative iteration).” Examples of negative iteration are late changes in the design process due to lack of agreement by the stakeholders, or failure to incorporate all relevant perspectives. Often, it may be preferable to delay a decision rather than to make it without the right people involved.

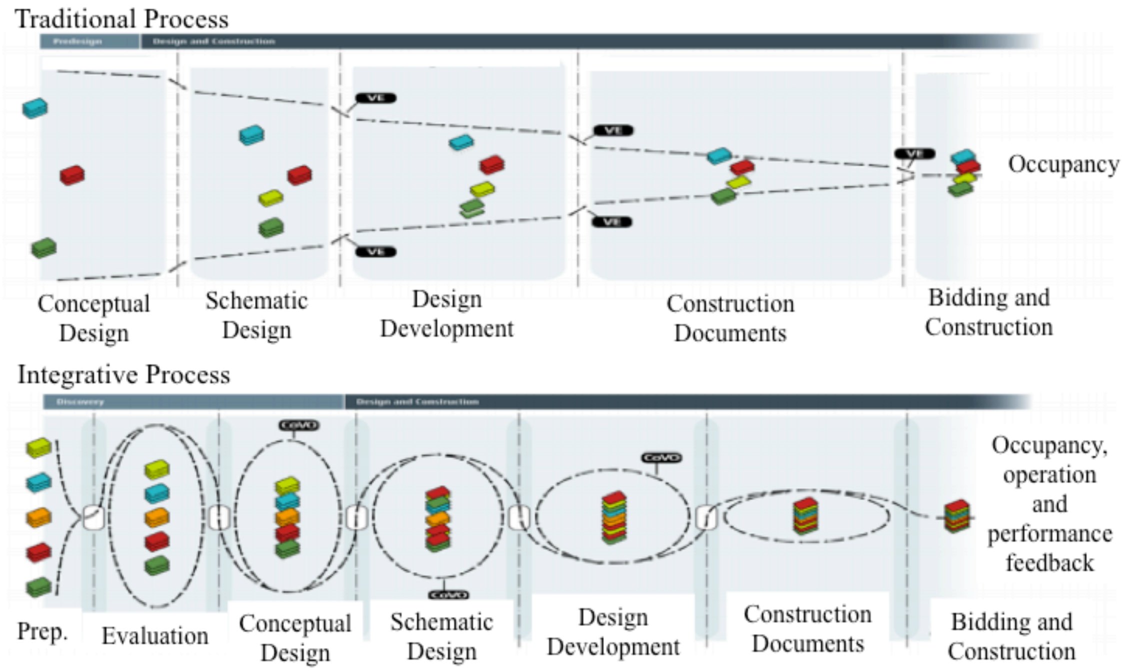


Figure 1.1 Integrative vs. 'traditional' design process (Reed 2009).

Lean design practices are well aligned with collaborative design, since they aim to optimize the whole project not just individual parts. Lean tools help the design team to increase 'value' for the customer and minimizing waste. Section 2.11 presents lean design and construction tools and how to apply them to the decision-making process.

A collaborative design team using lean tools can help to create an environment that supports the decision-making process by considering a whole building perspective and accounting for interactions among building systems. A whole building perspective is essential when analyzing sustainability in building design.

1.4.5. Decision-Making Process in Commercial Building Design

The decision-making process in commercial building design is characterized as group decision making, in which many internal stakeholders are involved (owner, architect, structural, mechanical, electrical, etc. and sometimes users). Hundreds of decisions are made in different phases of the design with different levels of detail, and multiple stakeholders' involvement (Hartmann 2011).

The decision-making problem in commercial building design can be separated into six stages (Figure 1.2):

(1) *Identify client needs:* The design team needs to identify the purpose of the decision.

(2) *Set design goals:* The design team needs to translate the client needs into design goals to guide the decision-making process.

(3) *Generate or identify alternatives:* The design team needs to generate or identify alternatives aligned with the design goals. This is the innovation or creative phase of the decision-making process.

(4) *Collect Data:* The design team needs to gather data in order to understand the attributes of the alternatives. This data can be quantitative (e.g., technical or environmental performance) or qualitative (e.g., opinions from experts).

(5) *Choose an alternative:* The design team needs to understand the differences between alternatives, considering the decision context, and choose the best one according to the available resources (e.g., cost and schedule constraints).

(6) *Reconsider:* The design team needs to evaluate if the alternative meets the goals of the whole building design, and analyze the interdependency with other decisions. Commercial building design is an iterative process, and decisions may be revised many times in the design as more data is obtained and more aspects of the design are developed.

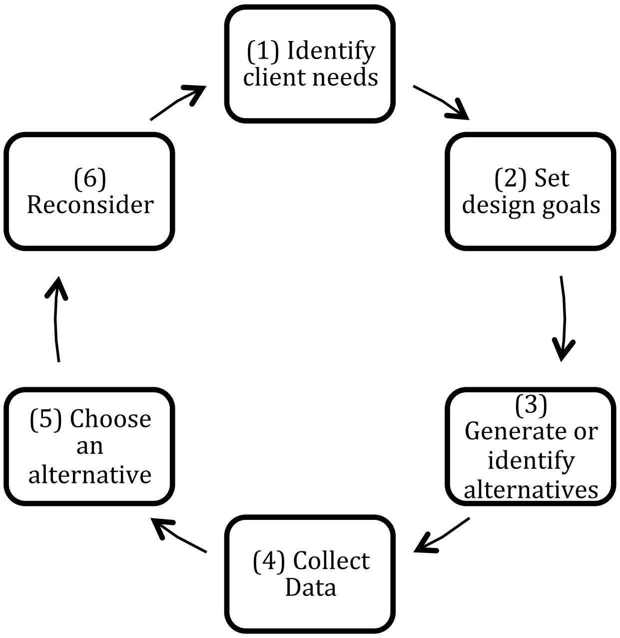


Figure 1.2 Decision-making stages in building design.

This process is usually iterative and does not occur linearly. Iterations are often necessary in order to understand client needs and generate valuable alternatives. Documenting decisions in a transparent manner can reduce negative iteration.

1.4.6. Decisions Considering Sustainability

Sustainability is not easy to measure or to define; multiple stakeholders will have different opinions about what sustainability is. In addition, the expectations about what is sustainable change over time in our society. For example, many building considerations that take into account people's health (e.g., emissions of volatile organic compounds) and safety (e.g., fireproofing requirements) were not common practices in the past. A decision-making method needs to deal with the subjectivity involved in people's perspectives.

The most widespread definition of sustainability can be traced to the Brundtland Report (World Commission on Environment and Development 1987), presented at the 1987 UN

Conference. It defined sustainable developments as those that "meet present needs without compromising the ability of future generations to meet their needs." An absolute truth about what is sustainable does not exist. How much of our resources should we expend in meeting our present needs? How do we even define meeting our present needs? These answers may vary based on stakeholders' points of view and on different contexts (geographic location, culture, etc.). The US Environmental Protection Agency (2012) provides another definition for sustainability: "Sustainability is based on a simple principle. Everything that we need for our survival and well being depends, either directly or indirectly, on our natural environment. Sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations." The US Environmental Protection Agency (2012) also states that sustainability is important in making sure that we have and will continue to have, the water, materials, and resources to protect human health and our environment. Several other definitions of sustainability and sustainable development are available. However, common themes between these definitions are: (1) respecting the limits of our natural resources, (2) understanding the interconnection of the three sustainability concepts (social-, environmental-, and economic system) and (3) providing an equitable distribution of resources and opportunities for this and future generations.

For many authors sustainability is seen as the only possible direction for the future (e.g., Constanza 2000 and Yohe et al. 2007). In particular, commercial building design, as in other engineering fields, is now required to account for sustainable outcomes. According to Oehlberg et al. (2009): "with significantly increased attention to both environmental and social issues today, engineers are faced with having to achieve the goals of sustainability in addition to traditional financial goals as they design new products." Traditionally the AEC Industry has focused on delivering a project on time, on budget and with a certain quality. Recently, concerns about impact on the environment and health have become more important and involve considering other types of information in the decision-making process.

This issue establishes an important challenge for the AEC industry. The efforts to confront this challenge in the AEC industry are related to efforts in producing 'green buildings'. What is a 'green building'? The Environmental Protection Agency (2010) states that, "green building is the practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle, from siting to design, construction, operation, maintenance, renovation and deconstruction. This practice expands and complements the traditional building design concerns of economy, utility, durability, and comfort." In other words, 'green' refers to the design and construction of buildings that have a minimal negative impact on the environment. Green buildings reduce environmental impacts in site planning, safeguarding water and water efficiency, energy efficiency and renewable energy, conservation of materials and resources, indoor environmental quality, user satisfaction, etc. (Lowe and Ponce 2008). This research distinguishes between 'green' and 'sustainable' buildings. A 'sustainable' building accounts for all the above and more. Building 'sustainably' ensures that future generations will be able to construct their buildings, and meet their future needs, including environmental, social and economic needs. However, note that not all AEC industry practitioners differentiate between ‘green’ and ‘sustainable’ building.

Sustainable buildings provide several advantages over less-sustainable buildings. From the environmental point of view, a sustainable building reduces the impact of natural resource consumption, and it decreases atmospheric greenhouse gas emissions, which are known to contribute to climate change. From the social point of view, a sustainable building enhances occupant comfort, benefits community health and improves overall quality of life. From the economic point of view, a sustainable building should save costs in the operation and maintenance phase (e.g., Blackhurst et al. 2010), and may also decrease costs in the construction and decommissioning phase.

The design of sustainable commercial buildings poses new challenges for decision-making. Design teams are now encouraged to include environmental and social factors in addition to economic factors when evaluating alternatives.

1.4.7. Complexities in Decision Making about Sustainability in Buildings

In order to account for sustainability in decision-making, designers have important challenges to overcome: (1) Uncertainty in the attributes of the alternatives. For example, lack of accurate data for measuring health and environmental impacts. Even though the AEC industry has been using Life Cycle Assessments (LCA) for building materials and components (e.g., Singh et al. 2011, and Marshall et al. 2012), it still has a long way to go. Other uncertainties include changes in the building use during the operation phase and changes in the environment (e.g., climate change). (2) Modeling capability within the design team. The design team needs to use an energy strategy and simulation tools in the early stages of the design process in order to generate a sustainable design (Horman et al. 2006). According to Papamichael (2000), sustainable building performance prediction and assessment requires use of complex tools, which can vary significantly with respect to their modeling capabilities and prediction accuracy. This poses challenges in both the modeler’s capability and the simulation tool’s capability. (3) Willingness to change business as usual practices. This requires early awareness of sustainable concepts in the project’s and owner’s commitment to sustainability (Lapinski et al. 2006). (4) Calculating life-cycle cost including social and environmental aspects. Many challenges exist in estimating the future costs of the alternatives (Section 2.10). For example, applying a discount rate to future costs may not provide an accurate manner to account for irreversible environmental damage done in the present. (5) A collaborative delivery model. In order to optimize the whole building design and not just the parts, extensive collaboration is required. Some authors point out the necessity of using a collaborative delivery process (Korkmaz et al. 2009, and 2010), an integrated design process (National Institute of Building Sciences 2005), and an early involvement of key project participants (Riley and Horman 2005). (6) Conflicting trade-offs. Many trade-offs are required to choose a building alternative, within a system, among different factors (e.g., comfort, esthetics, energy, environmental impact, etc.), and among different systems. This requires an understanding of complexities and interrelations among different building systems. (7) Accounting for factors that involve subjective considerations. Different stakeholders often have different opinions and they may also have conflicting interests.

A decision-making method cannot overcome all these challenges. Specifically, it cannot overcome the first four, (1) uncertainty, (2) modeling capability, (3) willingness to change, or (4) calculating life-cycle cost. However, it can help in overcoming the last three by (5) facilitating collaboration, (6) accounting for transparent trade-offs, and (7) accounting for subjectivity.

1.4.8. Sustainable Rating Systems

Currently in the US practice and increasingly in other parts of the world, the LEED (Leadership in Energy and Environmental Design) rating system plays an important role in decision-making. According to Cubbison et al. (2012) "In the AEC industry, owners often base decisions on first cost data due to construction budget constraints. When they are able to take a longer view, environmental impact becomes a key consideration. Through its various levels of certification, LEED is a tool that can be used for a spectrum of project types, ranging from those constrained by first costs to those able to invest in longer-term performance." LEED for commercial buildings evaluates five primary areas (US Green Building Council 2011c):

- Energy use, including energy efficient lighting and Heating Ventilation Air Conditioning (HVAC) systems
- Location of the building and sustainability of the immediate environment
- Indoor air quality and use of daylight to reduce lighting costs
- Water conservation and reduced-use mechanisms
- Use of sustainable materials during construction

Extra points toward certification may be awarded for innovative building designs or attention paid to compliance with regional environmental priorities.

Many other rating systems apart form LEED exist. One of the most stringent is the Living Building Challenge (LBC), which requires net zero energy and water usage among other performance areas for site, health, materials, equity, and beauty (International Living Future Institute 2012). While LBC uses a more holistic approach to sustainability than LEED does, it does not yet have many followers. Rating systems provide design guidelines or requirements, however they do not attempt to provide any methods for decision-making.

This research studies MCDM methods on how they support the design team to choose one among several alternatives. This includes using a wide variety of factors representing social-, environmental- and economic aspects, which include but are not limited to rating systems requirements or incentives. The use of MCDM methods for creating a clear and shared rationale can help the design team in arguing in favor of a sustainable alternative. A MCDM method may provide a broader analysis of the alternatives than the narrower set of factors and criteria established by most rating systems (e.g., LEED).

Section 2.9 presents a description of LEED and other rating systems used in the world. Most of the projects studied in this research were aiming for LEED certification at some level.

1.5. Scope

This section presents the scope of the research, providing a characterization of the types of decisions that were studied in this research.

1.5.1. Design in Commercial Building

This research focuses on decisions made during the design phase (e.g., schematic design, design development) or later when decisions require detailed analysis and multiple stakeholders are involved. The decisions considered (1) different types of alternatives, (2) finite numbers of alternatives, (3) known attributes, and (4) group decision making.

1.5.1.1. Types of Alternatives

The MCDM methods were analyzed for supporting the choosing problem of commercial building design at various levels of detail. It can be a material (e.g., choosing an insulation material), a component (e.g., choosing a ceiling tile), an assembly (e.g., choosing a wall assembly or window assembly), a system (e.g., choosing a structural, HVAC, or lighting system) or a building (e.g., choosing a building layout).

1.5.1.2. Finite Number of Alternatives

This research compared MCDM methods for choosing among a finite number of alternatives (from 2 to 15). Even when this range is applicable to many decisions in commercial building, the evaluation of the methods is not valid for an infinite number of alternatives.

1.5.1.3. Known Attributes

This research considers that the attributes of the alternatives are known or can be reasonably estimated. Therefore, this research does not consider uncertainty in the attributes of the alternatives.

1.5.1.4. Group Decision Making

This research presents decisions made by groups of people. These types of decisions include psychological aspects that affect human behavior. Section 2.13 presents group-decision-making issues, such as common cognitive biases and the use of rhetoric in the argumentation process. However, this research does not consider in depth the psychological perspectives of the decision-making process.

1.5.2. Decision-Making Process in Commercial Building Design

This research is focused on MCDM methods to support choosing an alternative (stage 5) and reconsider the decision (stage 6) in Figure 1.2. However, it also analyzes the interconnection between the choosing problem and the other decision stages, including the possible iterations.

This research did not consider methods for identify clients’ needs (stage 1), set design goals (stage 2), generate alternatives (stage 3), or collect data (stage 4) in Figure 1.2. However, it presents an analysis of how different MCDM methods can impact these other phases.

1.5.2.1. Identify Client Needs

This research is not focused on evaluating methods to help understand clients' needs. However, the MCDM methods are evaluated on how transparent they are in providing a rationale for the decision, which may help in the process of identifying clients' needs.

1.5.2.2. Set Design Goals

This research is not focused on evaluating methods to set design goals. Instead it focuses on decisions in which the purpose of the building and the design goals were identified by the design team. These design goals may influence factors used in evaluating the alternatives. The scope of this research is to evaluate MCDM methods on how transparent they are in integrating multiple factors.

1.5.2.3. Generate or Identifying Alternatives

Identifying alternatives is critical in obtaining a satisfactory decision result. Clearly, when an alternative is not considered, it cannot be selected. When measuring which alternative is more sustainable, decision makers have no guarantee that they are evaluating the best conceivable alternative. Therefore, a MCDM method should not be judged by the quality of the alternatives evaluated but by the MCDM method characteristics.

It is out of the scope of this research to help stakeholders to generate or identify new alternatives. Methods that help that process were not studied here. However, the evaluation of the existing alternatives may provide insights to the design team in creating new alternatives.

1.5.2.4. Collect Data

The research scope does not solve the problem of gathering reliable data, but suggests what to do with the data in order to make a transparent decision. If the data is not accurate, then the decision may not be accurate. Therefore, the available data should not be used to judge the MCDM method; instead, methods should be judged by the way in which they use the data.

The amount of time required for finding attributes of alternatives will depend on how much available information exists, the experience of the decision makers, and the types of alternatives.

The MCDM methods were evaluated for judging alternatives that were known, assuming that available data for making a decision existed. The researcher tested the MCDM methods through case studies using data that was available for the decision makers to compare the alternatives. The data gathered for analyzing the alternatives was specific to the context of each decision and may not be generalized.

1.5.3. Choosing Problem

This research focuses on the choosing problem, not sorting, ranking or describing problems (Roy 1974). Section 2.1 expands on the definitions of each type of decision problem. The choosing problem involves evaluating mutually exclusive alternatives, which means that only one alternative can be implemented.

1.5.4. Multiple-Criteria Decision-Making Methods

Multiple-Criteria Decision-Making (MCDM) methods, also known as Multiple-Criteria Decision Analysis (MCDA), are defined as "a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups to explore decisions that matter" (Belton and Stewart, 2002). Section 2.2 presents a description of the available MCDM methods and applications in the AEC industry and Section 2.4 presents MCDM methods used in other fields. The scope of this research is reduced to the following types of MCDM methods:

1. Goal-programming and multi-objective optimization methods (linear optimization)
2. Value-based methods (AHP and WRC)
3. Outranking methods (ELECTRE I)
4. Choosing by advantages (tabular method)

The first three methods are found in the literature about MCDM methods. The fourth method is mainly found in the lean community literature and is not part of the decision-making literature related to operation-research or MCDM methods publications. These methods were also found in the practice of building design.

A clear preference for using value-based methods in the AEC industry exists, especially the AHP method, which is often used and documented in the literature for choosing a sustainable alternative. Goal-programming and outranking methods are found less in the literature compared with AHP (Section 2.5). Applications of CBA are found only within the lean community and very few have the environmental perspective included in the analysis.

The researcher was not aware of other types of MCDM methods that were potentially applicable for the choosing problem in detail analysis of design alternatives. Decision-making methods that do not consider multiple-criteria were not considered in this research (e.g., voting). Variations of the MCDM methods that considered uncertainty (e.g., fuzzy set theory) were not considered in this research.

1.5.5. Decisions Considering Sustainability in Commercial Building Design

This research uses the context of sustainable design in commercial buildings because it makes richer the analysis of the MCDM methods. In this context multiple stakeholders are involved, and therefore, designers need to consider multiple factors in the decision-making process. In addition, A MCDM method that helps the design team in creating transparency, building consensus, and continuous learning will support decisions considering sustainability in commercial building design. Section 2.7 presents examples of MCDM methods applied in choosing a sustainable alternative in the AEC industry; Section 2.8 presents aspects to consider in sustainable building design; and Section 2.9. presents codes, standards and rating systems often used in sustainable commercial building design. Many of the differences between methods are relevant for other contexts in which multiple factors are analyzed, involving multiple stakeholders with conflicting interest.

In addition, this research provides examples of how to choose a sustainable alternative in building design. However, the focus is on comparing the MCDM methods and not on judging how sustainable the alternatives are. This research recognizes the challenges of calculating life-cycle costs (Section 2.10 discusses this issue). However, it is out of the scope of this research provide advice in order to calculate life-cycle cost.

This research considered objective and subjective data for evaluating which alternative is more sustainable. Such data is dependent on the project's context according to what was relevant for the decision makers for evaluating sustainability aspects of the alternatives.

1.5.6. Project Delivery and Involvement of Relevant Stakeholders

It is critical to gather all relevant stakeholders together for the decision-making process in order to obtain the best decision and one that will be accepted in the future. The type of MCDM method used is independent of the problem of gathering stakeholders. Therefore, a MCDM method should not be judged by having the right stakeholders or not. The MCDM method will play an important role in how it would help (or not) in integrating multiple stakeholder perspectives.

Section 2.12 presents a comparison of the characteristics of DBB vs. IPD according to the literature reviewed. However, it is out of the scope of this research to evaluate the impact of the project delivery system on the decision. The decisions evaluated in this research are in projects using a Design Bid Build (DBB) delivery, and involving multiple stakeholders.

1.5.7. Rating Systems

This research uses case studies in which the design team was pursuing a LEED certification. The researcher analyzed and evaluated the impact of LEED systems on the studied decisions in the pertaining case studies. However, it is out of the scope of this research to present a more extensive evaluation or criticism of sustainable rating systems such as LEED or others.

1.6. Methodology

Due to the nature of the research questions, which asks why one MCDM method is better than other, the researcher selected a qualitative approach. Qualitative research is a method of inquiry employed in many different academic disciplines, traditionally in the social sciences, but also where the context plays an important role in the solving of problems (Flyvbjerg 2004, 2006b, and 2011). Qualitative researchers aim to gather an in-depth understanding of human behavior and the causes of that behavior. In this case, interviews, observations, and case studies allowed the researcher to gain a thorough understanding of the differences between MCDM methods for choosing a sustainable alternative in building design.

Qualitative methods investigate the why and how of the problem, not just what, where, when. Hence, smaller but focused samples are more often needed than large samples. The analysis of the MCDM methods was based on case studies using a design research approach. Therefore, the knowledge generated is based on induction, moving from specific observations to broader generalizations and theories. This contrasts with deduction, which works from the more general to the more specific, using large amounts of data points.

1.6.1. Case-Study Research

This research follows the case-study design and tactics recommended by Yin (1994). The researcher developed case-study protocols for demonstrating that the operation of the study, such as data collection procedures, can be repeated with similar results. In addition, the researcher used replication logic in multiple-case studies, in order to establish the domain to which a study's findings can be generalized. Case study is understood as "an empirical inquiry that investigates a contemporary phenomenon within real-life context, especially when the boundaries between the phenomenon and context are not clearly evident" (Yin 1994). This definition is fully aligned with the scope of this research, because the evaluation of MCDM methods depends on the context in which they are used, and sustainability decisions are tightly linked to the project's context.

In the conventional view, qualitative methods produce information only for the particular cases studied, and any more general conclusions are only propositions (informed assertions). Quantitative methods can then be used to seek empirical support for research hypotheses. This view has been disputed by Oxford University professor Bent Flyvbjerg, who argues that qualitative methods and case-study research may be used both for hypotheses testing and for generalizing beyond the particular cases studied (Flyvbjerg 2006a). In this research, the conclusions can be generalized by understanding the impacts of the MCDM methods assumptions in case-study applications.

Case studies were chosen to cover a wide range of alternative levels such as materials, components, assembly and systems (Table 1.2). All case-study decisions had to have environmental, social and economic impacts. Some case studies were developed with public data and other with real projects where research and project specific interests were aligned. All case studies have multiple stakeholders' perspectives.

Table 1.2 Case studies.

	CBA	**AHP**	**WRC**	**Academic**	**Real-Life**	**Supply Chain**
Comparative case 1: Wall assembly	x	x		x		
Comparative case 2: Insulation material	x	x		x	x	
Comparative case 3: Structural system	x		x		x	
Testing case 1: Ceiling tile component	x				x	x
Testing case 2: HVAC system	x				x	
Testing case 3: Building layout	x				x	

1.6.2. Design Research

Design research or design science consists of activities concerned with the construction and evaluation of technology artifacts to meet organizational needs as well as the development of their associated theories (Cole et al. 2005). Design science is concerned with "devising artifacts to attain goals" (Simon 1981). Many authors argue that it is well suited for the field of project management (e.g., Ahlemann et al. 2011, Aken 2004, Hevner et al. 2004, Holmström et al. 2009, Gregor 2009, Kasanen and Lukka 1993, Lukka 2003, Venable 2006, and Voordijk 2009).

According to March and Smith (1995) an artifact can be a construct, a model, a method or an instantiation. In this research the artifacts were instantiations in the form of case studies. An instantiation is the realization of an artifact in its environment. In this research the instantiations are applications of the different MCDM methods for choosing a sustainable alternative. Instantiations demonstrate the feasibility and effectiveness of the models and methods they contain. Those instantiations were evaluated and conclusions were derived from them.

Considering the practical nature of the problem studied and the necessity of interaction between practice and theory, a collaborative research approach was appropriate. The research experiments were done collaboratively with practitioners. In other words, the instantiations were discussed and applied in collaboration with AEC practitioners. This approach is similar to Action-Research developed in social psychology, which requires the researcher to be directly involved in the research project, often as a promoter of change (Susman and Evered 1978, and Järvinen 2007). The research investigated real project decisions, and promoted the use of MCDM methods in order to test them, and thereby, make a contribution to the theory.

1.6.3. Research Steps

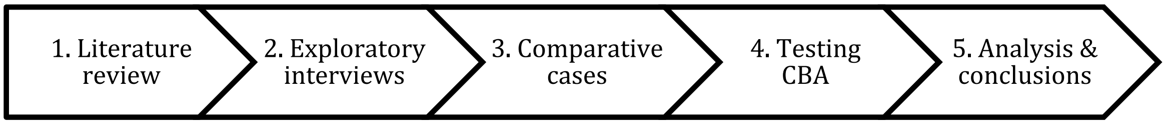


Figure 1.3 Research steps.

The research steps can be divided in the exploratory and the testing phase. In the exploratory phase, the researcher studied the literature and conducted interviews to understand which MCDM methods are used for choosing a sustainable alternative, and developed case studies to analyze the best method for this context. In the exploratory phase, CBA was tested in different applications.

In step 1, the researcher reviewed (1) which decision-making methods have been used in other fields, how those methods incorporated sustainability factors in their analysis, and what the differences were between them. In addition, the researcher reviewed (2) which methods have been applied for decision making in the AEC industry according to the literature. Later the researcher reviewed (3) different sustainable rating systems and how they affected decisions in commercial building design. The researcher reviewed (4) group decision making and cognitive biases that may occur when using MCDM methods.

In step 2, the researcher explored practices in the AEC industry. She conducted interviews with AEC practitioners, who explained how they chose materials, components, assemblies, building systems, or building layouts. The researcher collected information and data provided by the interviewees about decisions they made. The researcher conducted several preliminary interviews (e.g., Lesniewski 2012) and reviewed literature (e.g., BNIM 2012) in the search for case studies.

In step 3, the researcher applied two methods (CBA and AHP) for the first two comparative case studies and then she applied (CBA and WRC) to a third case study. In this step the researcher analyzed the differences between MCDM methods.

In step 4, the researcher tested CBA in three real-world case studies, and analyzed what worked, what did not, and why. One of the cases was done during an internship (June 2012 - December 2012) in Gensler, San Francisco, and involved choosing a ceiling tile component. The second case study refers to the Exploratorium building (March 2013 - June 2013) and involved choosing a mechanical system. The third case study refers to a Net Zero Energy (NZE) library in Berkeley and involved choosing a building layout (March 2013-June 2013). The researcher discussed the CBA applications with the practitioners.

Finally, in step 5, the researcher analyzed the results, drew conclusions about CBA and answered the research questions.

1.7. Dissertation Structure

Chapter 1 presents the Introduction.

Chapter 2 presents a synthesis of the literature reviewed, including available MCDM methods and its applications to the AEC Industry.

Chapter 3 presents a theoretical comparison of the 4 MCDM methods including (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods, (3) Outranking methods, and (4) Choosing by advantages.

Chapter 4 presents the first case study that compares and contrasts AHP and CBA for choosing a wall assembly using data in the public domain. Chapter 4 also presents the second case study that compares and contrasts AHP and CBA for choosing an insulation material (cotton vs. fiberglass), this time with greater detail and using data from a real project.

Chapter 5 presents the third case study that compares and contrast CBA and WRC for choosing a structural system (Chapter 6). This case expands the comparison of CBA and AHP including WRC.

Chapter 6 presents the fourth case study that applies the CBA method for choosing ceiling tiles. This was done in a real-life project during an internship with an architectural design firm.

Chapter 7 presents the fifth case study that applies CBA for choosing an HVAC system for a NZE museum

Chapter 8 presents the sixth case study that applies CBA for choosing a building layout for a NZE library.

Chapter 9 presents a cross-case analysis of AHP vs. CBA vs. WRC, and a cross-case analysis of CBA testing case studies.

Chapter 10 presents the conclusions including contributions to knowledge and future work proposals.

Chapter 11 presents the relevant references.

2. LITERATURE REVIEW

Chapter 2 presents the reviewed literature, including an overview of the following:

Section 2.1: the types of problems associated with decision making applicable to the design.

Section 2.2: the available Multiple-Criteria Decision-Making (MCDM) methods that may be valid to solve the choosing problem by the design team, and their applications in the Architecture Engineering and Construction (AEC) industry,

Section 2.3: the belief that MCDM methods are the equal.

Section 2.4: the MCDM methods used in other fields, such as in public policy for decisions considering sustainability issues.

Section 2.5: the most common MCDM methods applied to the AEC industry.

Section 2.7: the AHP method shortcomings.

Section 2.7: the use of MCDM methods applied to make sustainability decisions in the AEC industry.

Section 2.8: the sustainable design practices in commercial buildings.

Section 2.9: the codes, standards and rating systems for sustainable building design.

Section 2.10: the issues on calculating life-cycle cost on commercial buildings.

Section 2.11: the lean design practices and their relevance to decision-making process.

Section 2.12: the differences between Design Bid Build (DBB) and Integrated Project Delivery (IPD).

Section 2.13: the cognitive biases and techniques to avoid them in group decision making.

The detail on these sections follows.

2.1. Decision-Making Problem Characterization

The characterization of a decision problem is important in order to define what types of decision-making methods are relevant to this research. Different problems call for different decision methods, as will be illustrated in the next paragraph. In the AEC industry, a decision-making process is more likely to be embedded in a wider process of problem structuring and resolution (aka. design), rather than be found as a stand-alone problem. Usually the problem of defining alternatives, factors, and criteria is as hard as deciding which alternative to select.

In the process of formulating a problem, Roy (1974) identified four types of decisions:

(1) *Describing Problem:* To explain or describe each alternative provided together with its main consequences by reference to the decision-making problem being dealt with.

(2) *Sorting Problem:* To classify or sort all the alternatives into classes or categories. Each of these is graded on the basis of predetermined requirements established by the decision maker.

(3) *Ranking Problem:* To construct a ranking of all alternatives. The options are compared against one another and grouped into classes of equivalent rank, which in turn are sorted partially or fully in accordance with models of preferences.

(4) *Choosing Problem:* To select or choose one and only one action or alternative (or a combination of these). The problem consists in choosing the best of all. Optimization problems fall into this category.

Belton and Stewart (2002) added two more types:

(5) *Selecting a Portfolio Problem:* To choose a subset of alternatives from a larger set of possibilities, taking into account not only the characteristics of the individual alternatives, but also the manner in which they interact and produce positive and negative synergies.

(6) *Designing Problem:* To research for, identify or create new decision alternatives to meet the goals and aspirations revealed though the decision-making process.

Each one of these types of problems occurs in the AEC industry. This research will focus on the choice problem (4), in which alternatives are mutually exclusive and only one alternative can be implemented in the design of the building (e.g., two insulation materials cannot be used in the same space at the same time). In this research we consider the choice problem (4) as part of the design problem (6), in which goals and aspirations to define and judge alternatives are revealed through the process. Therefore, before the choosing problem the design teams need to research, identify or create decision alternatives. Even when the generation of alternatives is outside of the scope of this research, decision-making methods being studied need to allow design teams flexibility to add new alternatives along the way and provide support to differentiate between alternatives. In addition, we are considering methods that require the direct interrogation of the decision makers to represent their preferences as opposed to automated methods based on historical data.

2.2. Available Multiple-Criteria Decision-Making Methods and their Application in the AEC Industry

The reviewed literature presents many groups of MCDA, used in the fields of operations research, economics, and public policy (e.g., Belton and Stewart 2002, Guitouni and Martel 1998, Köksalan et al. 2012, Morris and Oren 1979, Roy 1976 and 1993, Roy and Vanderpooten 1997, Roy and Vincke1981, Stewart 1992, and Zavadskas and Turskis 2011). Belton and Stewart (2002) classify MCDA methods in the following three broad categories: (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods, and (3) Outranking methods. In addition, a fourth category (4) Choosing By Advantages (CBA) is found in Suhr's book (1999) and in the lean construction literature. The following sections present the particular characteristics of different methods used for addressing choosing multiple-criteria decision problems.

2.2.1. Goal-Programming and Multi-Objective Optimization Methods

Goal-programming and multi-objective optimization methods are known as 'aspiration' or 'reference-point' models. They are characterized by establishing a desirable or satisfactory level of achievement for each of the criteria and the decision-making process then seeks to discover options that are closest to achieving them. Belton and Stewart (2002) view these methods as the operationalization of Simon's 'satisficing' concept (Simon 1976), which requires improving the most important goal, until some satisfactory level of performance is achieved, and then shifting attention to the next most important goal, and so on. Further explanation of these methods is presented in Section 3.2.1. Table 2.1 shows examples of goal-programming applications in the AEC industry.

Table 2.1 Applications of goal-programming methods in the AEC industry.

Method	**Application**	**Authors and date**
Goal Programming	For choosing an aggregate blend in asphalt.	Lee and Olson 1983
Multi-Objective Optimization	For choosing an operation mode for reservoir systems.	Eschenbach et al. 2001
Goal Programming	For selecting a portfolio of BOT/PPP (build-operate-transfer/public-private-partnership) infrastructure projects for the Indonesian government.	Wibowo and Kochendoerfer 2011
Multi-Objective Optimization	For choosing strategies for greenhouse gas emissions reduction from transportation construction projects.	Avetisyan et al. 2012

2.2.2. Value-based Methods

Value-based methods are known as part of the American school, and they are based on multi-attribute value functions and multi-attribute utility theory (MAUT) (Keeny and Raiffa 1976, and Keeny 1996).

Value-based methods, also known as utility-based methods, are based on either total or partial compensation (i.e., where a good performance on an environmental factor can compensate for a bad performance with respect to a social factor). These methods construct numerical scores for each factor, and then decision makers synthesize their preferences using an aggregation model based on the relevance (weights) of different factors.

According to Guitouni and Martel (1998), other methods that are part of this category are: Multi-Attribute Value Theory (MAVT), Weighted Sum (WS), Technique for Order by Similarity to Ideal Solution (TOPSIS), Simple Multi-Attribute Rating Technique (SMART), Utility Theory Additive (UTA), and EVAMIX. Further explanation of these methods is presented in Section 3.2.2. Table 2.2 shows applications of value-based methods in the AEC industry.

2.2.1. Outranking Methods

Outranking methods, known as the French school (Roy 1968), use pairwise comparisons to assess preferences, indifferences, and incomparabilities between alternatives. This method first compares alternatives in terms of each factor, and after aggregating the preferences, seeks to establish the strength of evidence favoring the selection of one alternative over another. Table 2.3 shows applications of outranking methods in the AEC industry.

Table 2.2 Applications of value-based methods in the AEC industry.

Method	**Application**	**Authors and date**
Analytical Hierarchy Process (AHP)	For choosing contractors in a bidding process.	Seydel and Olson 1990
MAUT	For choosing a dispute resolution model.	Chan et al. 2006
Fuzzy TOPSIS	For choosing a project delivery system.	Mostafavi and Karamouz 2010
Analytical Hierarchy Process (AHP)	For choosing concrete structures within the Spanish structural concrete code.	Aguado et al. 2012
Analytical Hierarchy Process (AHP)	For choosing structural materials.	Bakhoum and Brown 2012
Weighted Sum (WS)	For choosing building systems in housing construction.	Pan et al. 2012
Analytical Hierarchy Process (AHP)	For choosing haul road layout in large earth movement projects.	Kang and Seo 2012
Analytical Hierarchy Process (AHP)	For choosing sustainable materials for building projects.	Akadiri et al. 2013
SMART	For choosing building design.	Green 1994

Table 2.3 Applications of outranking methods in the AEC industry.

Method	**Application**	**Authors and date**
ELECTRE	For choosing hydropower operation modes.	Duckstein et al. 1989
Superiority and Inferiority Ranking Method	For choosing a concrete pump.	Tam et al.2004
ELECTRE III	For choosing a construction process in housing.	Rogers 2000
ELECTRE III	For choosing a contractor.	Marzouk 2010
ELECTRE III	For choosing thin-film photovoltaic production processes.	Cavallaro 2009
ELECTRE III and PROMETHEE II	For choosing structural systems.	Balali et al. 2012

Outranking method helps decision makers to construct their preferences by recognizing the fact that preferences and values are often not pre-existing but are formed within a particular decision-making context. One sees this in multiple decision-making situations, such as sustainable building design. Even though this method requires the weighting of factors, these weights do not represent trade-offs. They have a poorly defined psychological interpretation (Belton and Stewart 2002). Further explanation of this method is presented in Section 3.2.3.

2.2.2. Choosing By Advantages (CBA) Methods

Choosing By Advantages (CBA) was developed by Jim Suhr, while he was working in the US Forest Service. In CBA, decisions are based on advantages of alternatives, not advantages and disadvantages; this avoids the double counting of factors. Once the advantages of each alternative are found, CBA assesses the importance of these advantages making comparisons among them. In this system, it is important to identify factors that will reveal significant differences between alternatives, not factor that will be 'important' in the decision based on preconceptions (Suhr 1999). Further explanation of this method is presented in Section 3.2.4. Table 2.4 presents applications of CBA methods in the AEC industry.

Table 2.4 Applications of CBA methods in the AEC industry.

Method	**Application**	**Authors and date**
Choosing By Advantages (CBA)	For choosing a green roof.	Grant 2007 and 2009
Choosing By Advantages (CBA)	For choosing a rebar design.	Parrish and Tommelein 2009
Choosing By Advantages (CBA)	For choosing a viscous damping wall system.	Nguyen et al. 2009
Choosing By Advantages (CBA)	For choosing a superstructure design for a guideway infrastructure project in public sector.	Lee et al. 2010
Choosing By Advantages (CBA)	For choosing building systems (Telecommunication, Lighting, and HVAC systems).	Thanopoulos 2012
Choosing By Advantages (CBA)	For choosing an insulation material.	Arroyo et al. 2012b

2.3. Discussion of Equality of Multiple-Criteria Decision-Making Methods

In some of the literature reviewed (Azapagic and Perdan 2005b, Akadiri et al. 2005), the authors suggest that all MCDM methods are equally effective, that the differences between them do not have an effect on the outcomes, and that a user may select any method according to his or her previous experience. In fact, Azapagic and Perdan (2005b) states:

"In practice, probably the most influencing factor in choosing a particular MCDA method is the *specialism of decision analysts and their experience in dealing with similar problems*. However, while some methods naturally lend themselves for particular types of problem, *perhaps the MCDA technique itself is not that important*; what is important is that it provides a structure and a guide to decision makers to explore their priorities in a meaningful way and choose an alternative that satisfies their needs" Azapagic and Perdan (2005b p. 127).

In other words, this quote states that a decision-making method is (1) chosen because of its familiarity with previous decisions, (2) requires specialists to decide what is better for them, and (3) doesn't matter which method is used. This quote assumes that the decision outcome will not change due to the decision method used. Finally, is it reasonable to place our 'trust' on the intuition and experience of the decision-making specialist only?

This research proves that the selection of decision-making method for selecting a sustainable alternative does matter, and should not be left to the user without guideline. Moreover, the selection of the method and the decision itself should not be left to one specialist. It is imperative to have a holistic approach to decision making, especially when trying to produce a sustainable design. As stated in lean practices, the design team should strive to improve the whole project, not its individual pieces. Therefore, specialists in the various construction disciplines should simultaneously review the project and participate in the design decisions. The timing of the decision and the participants involved are related with the work-structuring process.

The researcher agrees with Suhr (1999), who states that decision-making methods produce decisions, decisions trigger actions, and finally, actions cause outcomes. Consequently, if the outcomes matter, then the selection of decision-making methods should also matter.

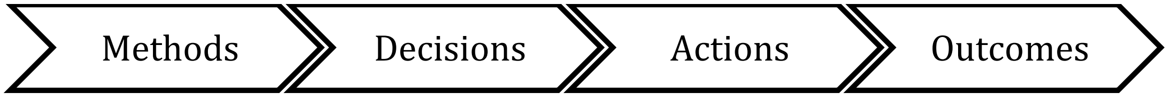


Figure 2.1 Cause-effect model of decision making (Suhr 1999).

This research demonstrates that not all MCDM methods are the same, and identifies characteristics that make a method viable for choosing a sustainable alternative in building design.

2.4. MCDM Methods Used for Choosing a Sustainable Alternative in Other Fields

Decision-making literature for sustainability refers to various frameworks and methods (e.g., Azapagic and Perdan 2005, Boulanger and Brechet 2005, Hofstetter et al 2002, Moffat and Hanley 2001, Grossardt et al. 2003, and Todorov and Marinova 2011). For example, Azapagic and Perdan (2005) present a sustainable decision-support framework (Figure 2.2).

Azapagic and Perdan (2005) claim that their framework is applicable for both corporate- and public-policy decision making in the context of sustainable development. It divides the decision-making process into three steps: (1) problem structuring, which includes identification of stakeholders, problem definition, identification of sustainability issues, identification of decision criteria, identification of alternatives, and elicitation of preferences; (2) problem analysis, which comprises preference modeling, comparing and evaluating alternatives, and conducting robustness-, sensitivity-, and uncertainty analyses; and (3) finally, problem resolution which involves choosing the most sustainable alternative, implementing the chosen alternative, and evaluation of the result.

Focusing on step (2) problem analysis, Azapagic and Perdan (2005b) ask decision makers to articulate their preferences for different decision criteria. They then use a MCDM method to model these preferences. Several different MCDM methods exist. However, they appear to assume that either all MCDM methods are equal or that the differences between them do not matter, because they do not provide a rationale for using one MCDM method or another under different conditions.

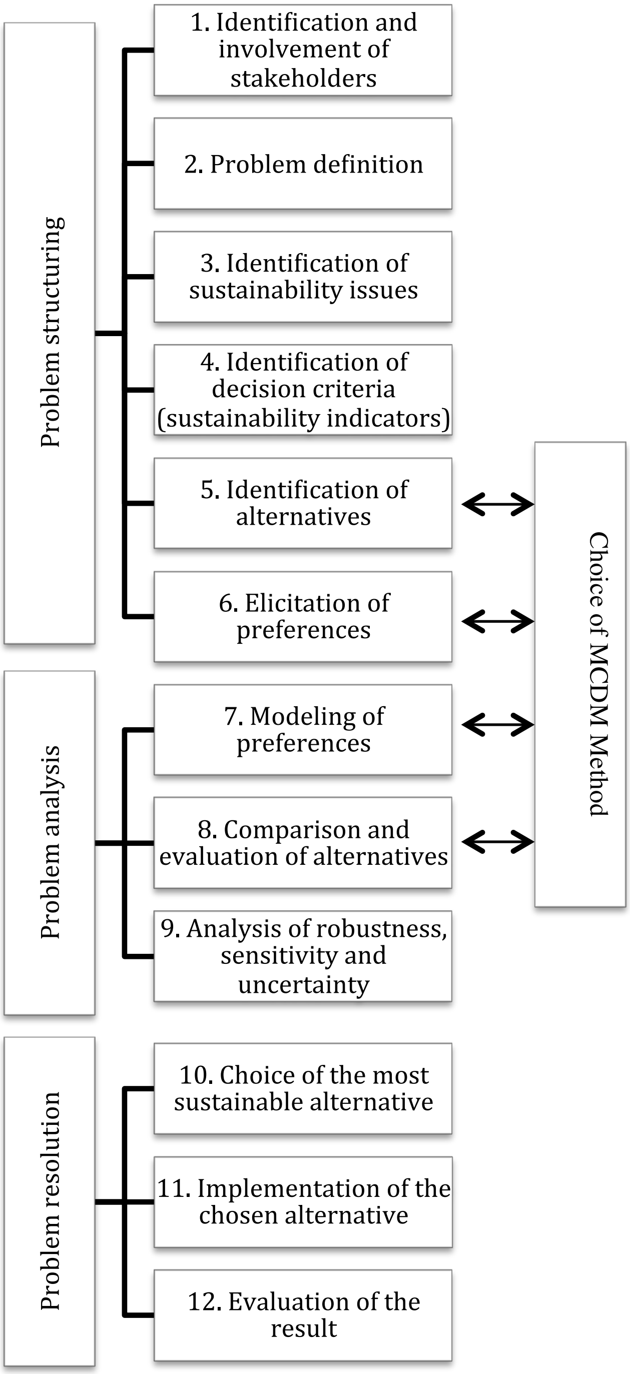


Figure 2.2 Decision-making framework for sustainability (Azapagic and Perdan 2005a). Adapted to make terminology consistent.

One important critique of this framework is that it requires finding sustainability factors and criteria (steps 3 and 4 in **Error! Reference source not found.**) before identifying alternatives. This seems unwise for choosing a sustainable alternative in building design since the identification of the alternatives may reveal what are relevant sustainability factors and criteria to analyze. Factors and criteria should be based on the relevant context and in consideration of available alternatives.

2.5. Prevalence of Various MCDM Methods Applied to the AEC Industry

In order to have a sense of documented current practices in the AEC industry for MCDM methods, the researcher investigated the Journal of Construction Engineering and Management (JCEM) by ASCE for all available online articles (from Vol. 109 Issue 1 1983 until Vol. 2013 Issue 2 2013). The reason for selecting the JCEM was for its high impact factor (0.927 SCImago Journal Rank Indicator 2012), which was the highest journal in construction management in the category of Building and Construction. The researcher looked for the following words: ‘Multiple-criteria decision’, ‘MCDM’, ‘MCDA’, ‘AHP’, ‘MAUT’, ‘Weighted Sum’, ‘TOPSIS’ ‘Simple Multi-Attribute Rating Technique’ (SMART), ‘Multi-objective optimization’, ‘Goal programming’, ‘ELECTRE’ and ‘PROMETHEE’. She found 142 papers, representing a wide range of applications in the AEC industry (Figure 2.3). The oldest publication is from 1983. It uses goal programming for asphalt aggregate mixing decisions. In total 127 papers mentioned value-based methods (MAUT, AHP, Weighted Sum, TOPSIS and SMART). By far the most used MCDM method was AHP, 90 papers mentioned the term, and at least 41 of them used AHP explicitly for different decisions. Looking at the whole ASCE civil engineering database AHP had 768 mentions in all online available years (1983-2013), while Outranking methods had only 52 mentions in the same database.

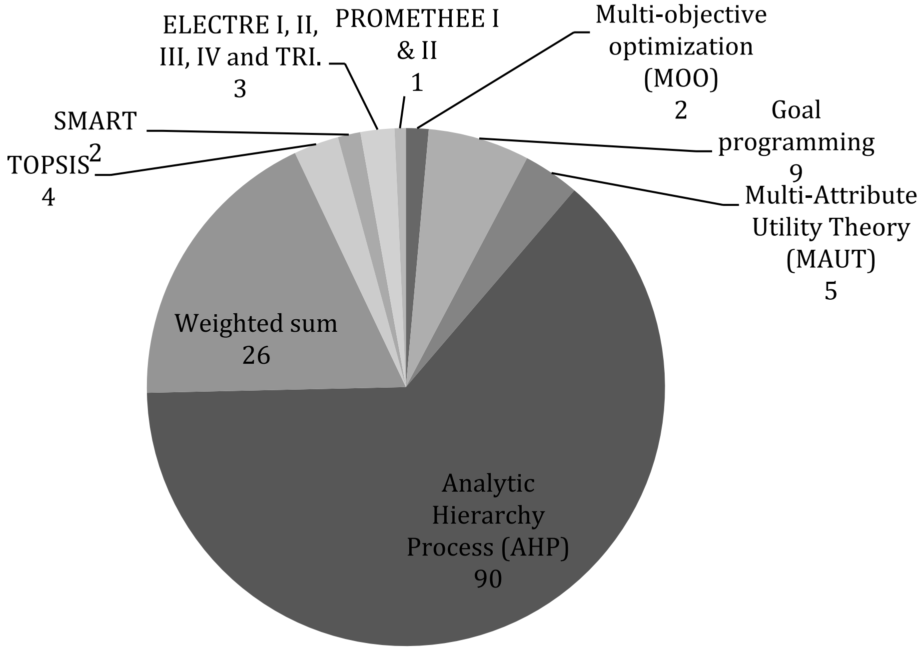


Figure 2.3 Number of papers using MCDM methods found in JCEM available online by February 2013.

This result shows that most of the academic papers in JCEM use the AHP method for multiple-criteria decisions, and very few states why they have selected AHP. A common explanation is: “The analytical hierarchy process (AHP) is used in this research to obtain the weights based on the pairwise comparison of objectives. Discussion of AHP is beyond the scope of this paper. The interested reader is referred to Saaty (1980).” (Cariaga et al. 2007). AHP is also used in other fields such as in public policy decisions (e.g., Aragon and Dalnoki-Veress 2012, and Forman and Selly 2001). However, the researcher also founded AHP shortcomings in the literature that are presented in next section.

2.6. AHP Shortcomings

Despite the fact that AHP is widely used the researcher found literature that highlights AHP shortcomings, such as:

- de Azevedo et al. (2012) point out:
    - Rank order reversal (Sarkis 2003). When alternatives are judged against criteria, it is possible to rank alternatives from the most preferable to the least preferable or vice versa. It is logical to expect that when new alternatives are added to a decision problem, the relative ranking of the old alternatives must not change. In other words, “rank reversal” should not occur. However, the original formulation of AHP allows rank reversals.
    - Lack of explanations of the scales of measurements (Barzilai 2001)
    - Lack of reference level for pairwise comparison of criteria (Lacerda et al 2011)
- Belton and Steward (2002), when weighting factors AHP assumes that trade-offs between factors are lineal functions and that there is no dependency among the factors, which is hardly true in real life decision-making.
- AHP cannot measure all possible interrelations among indicators (Chen et al. 2008). They propose the use of the ANP (Analytical Network Process) method for choosing vendors for sustainable construction. However, ANP is also based on the weighting of factors.
- Singh and Tiong (2005) state 3 shortcomings of AHP in the context of contractor selection: (1) the method does not take into account the uncertainty associated with judgment; (2) the subjective judgment and preferences of decision makers have great influence on the final decision; and (3) the method is mainly used in nearly crisp decision applications (Including “Yes” or “No” types of probability events) and hence choosing a contractor is not a perfect case for its application. They propose the use of Fuzzy theory with the Shapley (1953) method to aggregate criteria.
- Yeung et al. (2012) states that AHP is not able to cope with fuzziness satisfactorily, so they propose the use of Reliability Interval Method (RIM), which allows handling imprecise information. RIM requires stakeholders to weigh a factor using a fuzzy range of numbers. For example, they can weigh a factor as a range of 3 to 5, [3, 5], instead of an exact value of [4]. In addition, Li and Zou (2011) an application of Fuzzy AHP for risk assessment.

Note that not all these shortcomings are relevant for this research since the decisions studied consider known attributes of the alternatives. Therefore, shortcomings relating to uncertainty, fuzziness, and crisp decision are not studied further in this research. Chapter 3 and 4 analyze the AHP method for this research context.

2.7. MCDM Methods Applied to Sustainability Decisions in the AEC Industry

The literature also revealed some decision-making frameworks and methods for choosing alternatives when considering sustainability issues (e.g., El-Alfy 2010, Li et al. 2011, Karakosta and Psarras 2009, Palaniappan et al. 2008, Plass and Kaltenegger 2007, Reza 2011, Shen et al. 2011, Wang et al. 2012, Xia et al. 2011, Yeung et al. 2012, and Zavadskas and Antucheviciene 2006). For example, Reza et al. (2011) present a framework for selecting flooring systems in Tehran. They list factors (Figure 2.4) that include environmental-, economic-, and social issues. They use LCA (Life Cycle Assessments) for measuring GHG (Green House Gas) emissions. Finally, they use AHP to recommend an alternative.

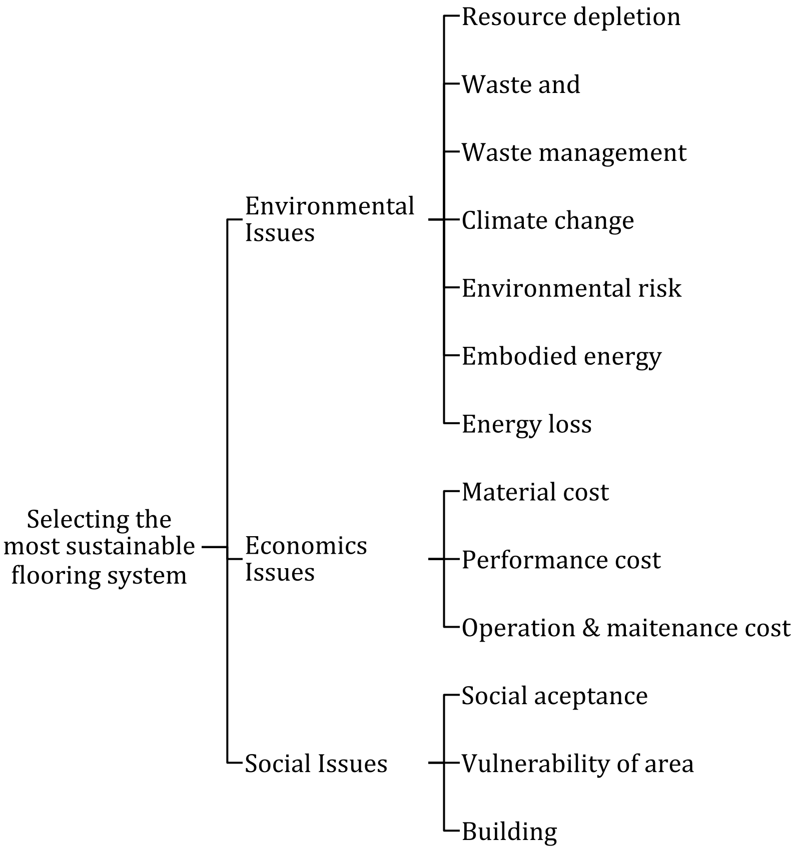


Figure 2.4 Framework for choosing sustainable floring system using AHP (Reza et al. 2011). Adapted to make terminology consistent.

The researcher has identified some deficiencies in the framework proposed by Reza et al. (2011) study:

- It does not say why they use AHP.
- It uses cost as one of the criteria for selection while the literature recommends treating cost as a resource, not as a characteristic of the material (Suhr 1999).
- It not clear how the authors treated interdependence between the factors. In AHP factor independence is a requirement for aggregation.
- It is not clear how social acceptance is measured. They treat it, as it if were something that can be measured regardless of the stakeholders involved or the type of construction in Tehran.
- It is not clear why they selected the factors that were used in the decision.
- It seems that they are not focused on differentiating between alternatives.

Akadiri et al. (2013) presents a similar approach in which they use LCA, and Fuzzy AHP for choosing a sustainable material. Akadiri et al. (2013) conclude "fuzzy methodology could also be extended with the other MCDM methods such as Analytical Network Process (ANP), TOPSIS, ELECTRE and DEA techniques (methods) in solving material selection (choosing) problems." This statement again leaves decision makers without a clear recommendation for MCDA selection in the context of sustainability.

2.8. Sustainable Design of Commercial Building

This section presents some of the issues and challenges of sustainable building design that are important to understand for the context of case studies presented in this research.

The Building industry plays an important role in the U.S. economy. Its contribution to GDP was 9 percent in 2005 (U.S. Department of Energy 2008), considering new construction, repairs and retrofits of residential and commercial building. The construction industry provides employment to 7.2 million wage- and salary workers in addition to 1.8 million self-employed workers in 2008 (Bureau of Labor Statistics 2011). However, buildings have a significant impact on the environment and people's health (Perez-Lombard et al. 2008, Horvath 2004, and McKinsey 2011).

Table 2.5 presents the environmental impacts of buildings in the US, divided between commercial and residential buildings according to the US Environmental Protection Agency (2009). The US Environmental Protection Agency (2009) also states that building-related Construction and Demolition (C&D) debris totals approximately 160 million tons per year, accounting for nearly 26 percent of total non-industrial waste generation in the US. In addition, According to the US Department of Agriculture (2002), the U.S. urban land area is 60 million acres (2.6 percent of the total 2.3 billion acres in U.S.) and it increased by 13 percent between 1990 and 2002.

Residential buildings are more numerous in quantity than commercial buildings. However, commercial buildings have a higher impact on the environment per unit with regard to primary energy use, electricity use, CO_2 emissions, and water use. Moreover, commercial buildings have shown a decrease in energy efficiency per unit of area, as opposed to residential buildings, which have improved in energy efficiency over the period 1985-2004. According to the US Department of Energy (2008), the US commercial building sector energy intensity increased by 12%, floor space grew more than 35 percent and the total primary energy usage grew 50 percent over the period 1985-2004 (Figure 2.5). This result shows that commercial building design has not improved, when judging based on energy use point of view. The same report indicates that the main usage of primary energy in commercial buildings are lighting (25%), cooling (13%), and heating (14%).

Table 2.5 Distribution of environmental impacts of buildings (US Environmental Protection Agency 2009).

	Residential and Commercial as part of US total (1)	**Residential (% of (1))**	**Commercial (% of (1))**
Units of existing buildings (Millions)		128 (in 2007)	4.9 (in 2003)
Primary energy used	39%	53.7%	46.3%
Electrical use	72%	51%	49%
CO2 emissions	39%	54%	46%
Water use	13%	74.4%	25.6%

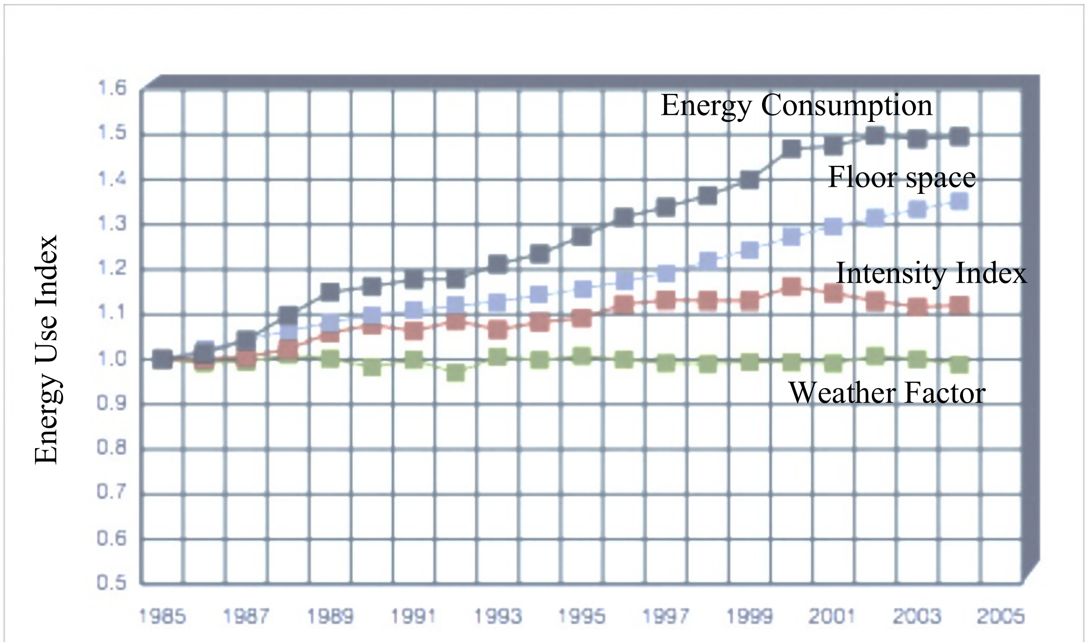


Figure 2.5 Commercial buildings, energy use, and intensity factors (US Department of Energy 2008, Figure 30).

In addition, conventional building design does not ensures stakeholders alignments. Many owners are developers, who are not directly affected by the future building performance (e.g., energy consumption). The United Nations Environment Programme (2007, 2008a, 2008b, and 2008c) developed a series of publications regarding this issue.

Conventional building design and construction practices have a great impact in the environment and human health, such as contribution to climate change, pollution of the urban air, water use, waste generation and destruction of wild-life habitat. Therefore, sustainable building design is needed to reduce the impact of buildings on the environment and human health. Sustainable building design accounts for:

1. Sustainable site planning
2. Safeguarding water and water efficiency
3. Energy efficiency and renewable energy
4. Conservation of materials and resources
5. Better indoor environmental quality
6. User and stakeholder satisfaction

In this research many factors are used for evaluating alternatives. The factors used in the case studies consider most of the sustainable design practices (American Institute of Architects 2012). All these practices should be considered together. No single practice should dominate the others. The importance of the factors will depend on the context of the decision and the differences between alternatives. For example when evaluating two materials, if they have the same embodied energy but different emitting properties that affect the indoor air quality, then the factor indoor air quality will have a greater impact in the decision than the embodied energy. The following sections expand more in the specific sustainable design strategies that are relevant for the context of the case studies developed in this research.

2.8.1. Sustainable Site Planning

In sustainable building design, the design team needs to consider the site planning. For example, the building orientation and account for a climate-responsive architecture. Figure 2.6 (Milne and Givoni 1979) presents design strategies (e.g., high thermal mass, evaporative cooling, humidification, night ventilation) that conform best to the bioclimatic chart for a specific location. In addition, different design strategies need to be used according to the dominated loads of a building.

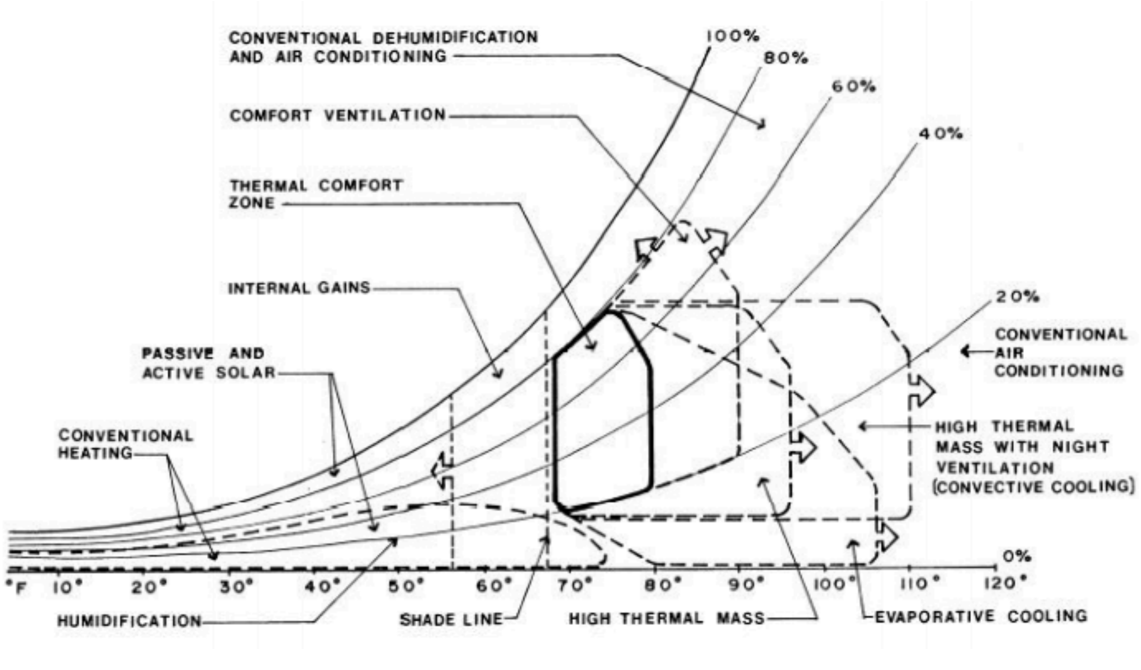


Figure 2.6 Bioclimatic chart (Milne and Givoni 1979).

Usually residential buildings (houses) are dominated by the exterior climate. In contrast, internal loads dominate commercial buildings, which means that the exterior climate does not affect the thermal comfort of occupants as much as the quantity of people or equipment been used inside the building (internal loads).

2.8.2. Safeguarding Water and Water Efficiency

In sustainable building design, the design team needs to consider the future water usage during building operation and reduce the amount of potable water used by the building while meeting the needs of the system (e.g., heating and cooling) and occupants. Usually commercial building water uses includes indoor water for restrooms and kitchen, outdoor water for landscape, and process water for industrial purposes and building systems.

Reducing water is important to avoid overwhelming of treatments facilities, which causes multiple social-, environmental-, and economic impacts such as, contamination of rivers, lakes, ocean, and soil by the untreated overflow of wastewater, and the construction requirement of new treatment plats at public cost.

Finally, the design team must evaluate the interactions of water related system with the other building systems design when making decisions.

2.8.3. Energy Use and Renewable Energy

Some authors propose that saving energy should be the number one design strategy for sustainable buildings. Wilson and Malin (1995) states, "The ongoing energy use is probably the single greatest environmental impact of a building, and so designing buildings for low energy use should be our number one priority." However, as we have discussed no one strategy or factor is always more important when choosing a design alternative. The importance of any factor will depend on the context. For example, in the case of hospitals energy usage may not the number one strategy and its importance, as a factor, will depend on the available alternatives for any decision.

Energy use in commercial buildings refers to the operation phase; the embodied energy of materials will be discussed in Section 2.8.4 conservation of materials and resources. Commercial buildings in the US use about 3.6% of world energy (US Department of Energy 2011). The end use of US commercial buildings in 2010 is distributed in 37% for space heating and cooling, 14% for lighting and 41% for ventilation, office equipment, refrigeration, cooking, water heating, and other uses. Figure 2.7 shows the US building energy end use for commercial buildings according to the US Department of Energy 2011.

The source of energy for commercial buildings is mainly electricity for all purposes and natural gas for space heating (US Energy Information Administration 2003). Since the US electricity generation comes mainly form coal, which produces a high amount of CO_2 emissions per kWh, the US commercial buildings adds significantly to global warming.

Figure 2.8 presents the US electricity generation (US Energy Information Administration 2009).

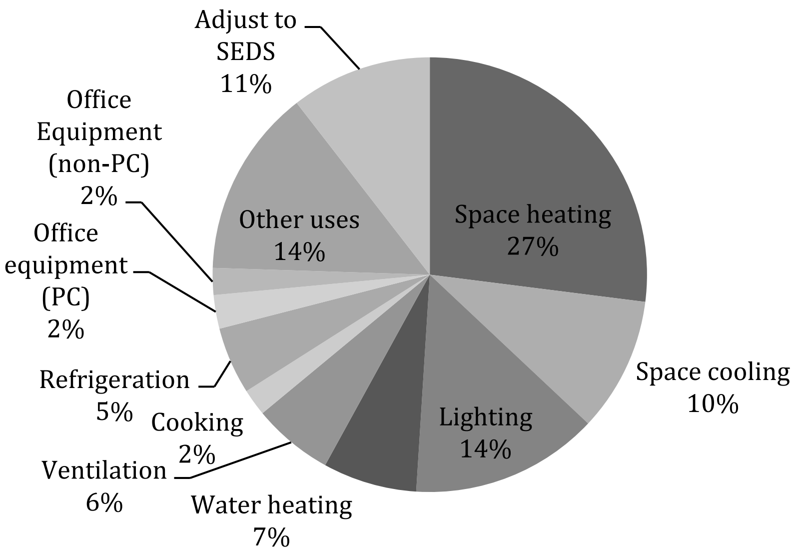


Figure 2.7 Total energy consumption by end use of US commercial buildings (US Department of Energy 2011).

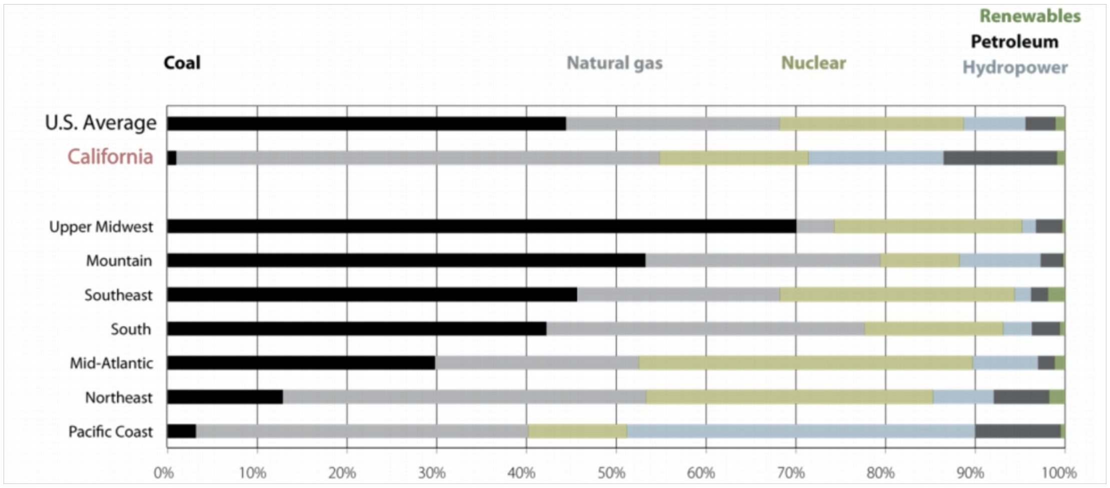


Figure 2.8 US electricity generation (US Energy Information Administration 2009).

Not all sources of energy produce the same CO_2 emissions per kWh. For example, Table 2.6 shows the CO_2 released for one kWh produced by major power generation methods measured in grams of CO_2 (BlueSkyModel.org 2009). What is more, in order to use 1 kWh of electricity available for use in a building, approximately 3.15 kWh must be generated at the source, mainly due to energy losses in transmission. Therefore, the use of renewable energy (e.g., solar and wind) on site provides opportunities for energy efficiency and reduces CO_2 emissions for kWh.

In sustainable building design, the design team needs to consider the energy requirements, given the purpose of the building (e.g., lighting, cooling, and heating requirements) and climate, as well as the sources of energy used in the building. In addition, the design teams needs to integrate building systems (e.g., structural and mechanical systems).

Table 2.6 Primary energy required (BlueSkyModel.org 2009).

Source	**Coal**	**Natural Gas**	**Oil and Diesel**	**Nuclear**	**Hydro-electric**	**Geo-thermal**	**Solar / PV**	**Wind Power**	**Wood / biomass**
Average CO_2 (g/kWh)	909	465	821	6	4	-	105	13	1,500

2.8.4. Conservation of Materials and Resources

Buildings generate a large amount of waste through their life cycles, from construction to building operations to demolition. In sustainable building design, the design team needs to consider the materials' embodied energy, as well as material selection to reduce waste during the demolition phase. Material selection should also consider its impact for building occupants, and the long-term social-, environmental- and economic consequences of materials used in design and construction of the building.

Conservation of resources also accounts for design for flexibility, so buildings can be reused at the end of their lifecycle instead of being demolished. The design team should also design resilient buildings, including for example potential earthquake losses when choosing structural systems.

2.8.5. Better Indoor Environmental Quality

Sustainable building design should be aim for improving the Indoor Environmental Quality (IEQ). According to the US Environmental Protection Agency (2009) Americans spend 90% of their time indoor. Therefore, the indoor environment affects people's health, well being and productivity. IEQ include:

- Indoor air quality
- Acoustical quality
- Thermal comfort
- Lighting quality

Consider for example indoor air quality and the impact of the ventilation and A/C systems have on that. Sickness and absenteeism due to poor indoor air quality may impact worker productivity. Hanssen (1997) study shows that the cost of ventilation and air conditioning are irrelevant compared to the cost of wages in a commercial building (Figure 2.9). Therefore, it is wise that companies spend more time and cost in the design and construction of indoor climate related systems to obtain a better working environment.

2.8.6. User and Stakeholder Satisfaction

When designing sustainable buildings, many different perspectives must be taken into consideration depending on the stakeholders' interests.

- End users may care about usability, maintenance, durability, aesthetics, safety, IEQ, and operation and maintenance cost.
- Design teams may consider different materials, systems, how they come together, how they look, and how much they cost.
- Owners may be concerned about market value, first cost, life cycle cost, and achieving a certain levels of environmental performance.

Among the challenges in the design of sustainable buildings are understanding and translating customer 'values', and achieving a joint understanding of each other's goals (Phelps 2012). During the design process the goals and aspiration of the project are usually revealed. Collaboration among stakeholders is needed in order to achieve a sustainable design. These suggest several questions regarding decision-making methods for sustainable design. How are trade-offs made in building design? How are factors defined in sustainable building design? Is there any decision-making method that supports collaborative decision making?

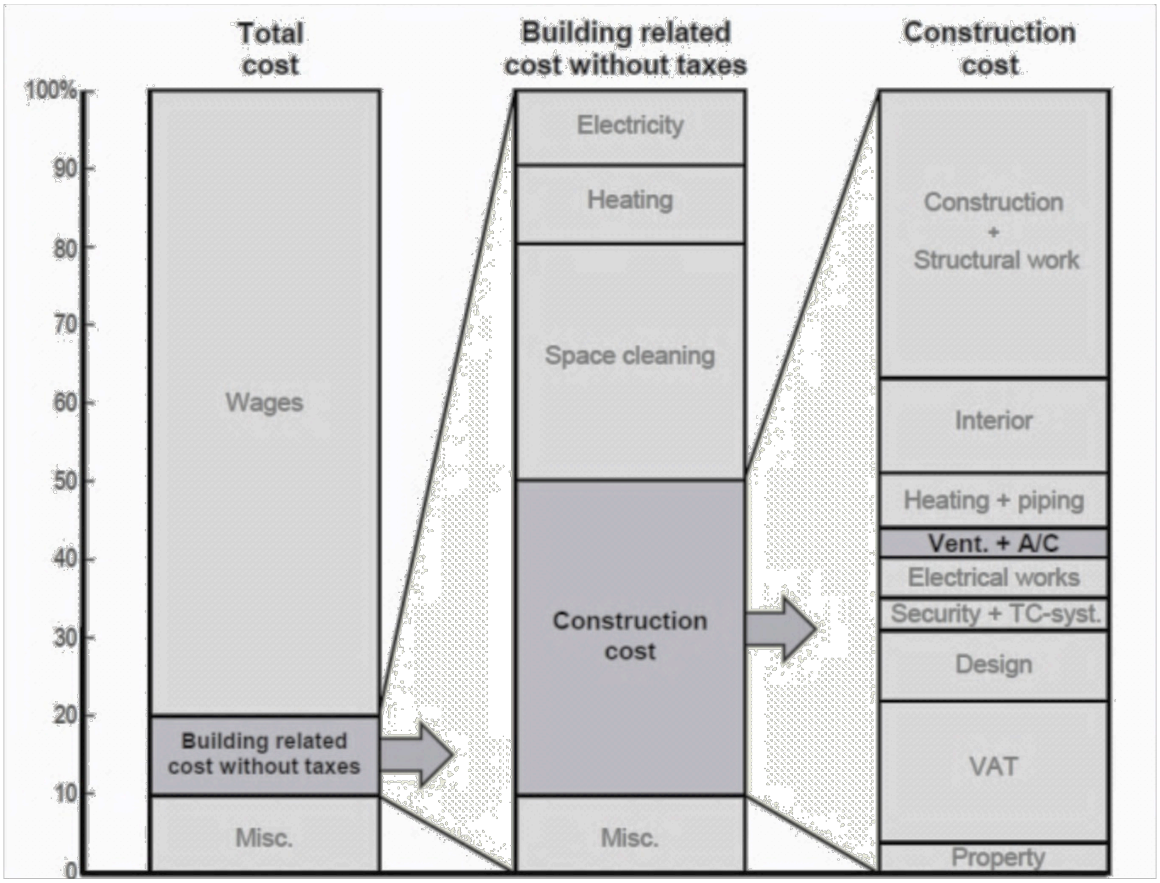


Figure 2.9 Economics vs. indoor climate (Hanssen 1997).

2.9. Codes, Standards, and Rating Systems for Sustainable Building Design

Codes and standards set the minimum requirements for building design and construction. In addition, rating systems encourage design teams to accomplish higher performance buildings, recognizing this through a certification program. The following sections present relevant codes, standards, and rating systems for sustainable building design.

2.9.1. Codes and Standards in California and the US

Codes and standards for energy efficiency, relevant to this research, are California Title 24, and American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.4. These two will be considered when choosing HVAC systems or material for insulation.

In addition, ASHRAE 189.1 requires specific performance for air quality, regulating:

- 8.4.2.1: Adhesives & Sealants
- 8.4.2.2: Paints & Coatings
- 8.4.2.3: Floor Covering Materials
- 8.4.2.4: Composite Wood, Wood Structural Panel & Agrifiber Products
- 8.4.2.5: Office Furniture Systems & Seating
- 8.4.2.6: Ceiling & Wall Systems

ASHRAE 189.1 will be considered in a case study in this dissertation when choosing interior design materials, specifically for ceiling tiles. This is also relevant when choosing carpets, furniture, paints, etc.

Since most of the case studies in this research are in California, some of the Californian requirements for building design are explained here. California is known as the leading state in the US for pushing sustainable buildings codes. In fact, California was the first to institute a state-wide green building code. The California Green Building Standards Code (CALGreen) became effective in January 2011 and was updated in July 2012. This new code establishes minimum green building standards for most new construction projects in California. According to Berkeley Analytical (2013), it is having a significant impact on product manufacturers, the design- and construction industry, and local jurisdictions that are charged with implementing the code.

CALGreen requires specific performance for non-residential buildings, such as:

- 5.504.4.4 Carpet systems
- 5.504.4.6 Resilient flooring systems

It also suggests voluntary standards for non-residential buildings, such as:

- A5.504.4.7: Resilient flooring systems, Tier 1
- A5.504.4.7.1: Resilient flooring systems, Tier 2
- A5.504.4.8: Thermal insulation, Tier 1
- A5.504.4.8.1: Thermal insulation, Tier 2
- A5.504.4.9: Acoustical ceilings and wall panels
- A5.504.8.4: Carpet systems

These standards will impact the design team decisions when choosing interior design products, especially flooring systems.

The following sections 2.9.2 and **Error! Reference source not found.** present the LEED rating system and other rating systems in the world.

2.9.2. LEED Rating System

2.9.2. LEED Rating System

The US Green Building Council (2011a) launched the Leadership in Energy and Environmental Design (LEED) in 1998, which promotes sustainable building and development practices through a suite of rating systems that recognize projects that implement strategies for better environmental and health performance (Bayraktar and Owens 2010). The LEED rating system is developed through an open, consensus-based process led by LEED committees, and diverse groups of volunteers representing a cross-section of the building and construction industry. LEED versions change on regular basis as result of this participative process. Currently LEED is the number one rating system in the US, and it is growing in the world.). Table 2.7 shows how the points can be awarded for new construction (US Green Building Council 2009).

Table 2.7 LEED 2009 for building design and construction point categories (US Green Building Council 2009).

Category	Description / Purpose	Points
Sustainable Sites	To discourage development on previously undeveloped land; seeks to minimize the impact of a building on ecosystems and waterways; encourages regionally appropriate landscaping; rewards smart transportation choices; controls storm water runoff; and promotes reduction of erosion, light pollution, heat-island effect and construction-related pollution.	26
Water Efficiency	To encourage smarter use of water, inside and out. Water reduction is typically achieved through more efficient appliances, fixtures and fittings inside and water-conscious landscaping outside.	10
Energy & Atmosphere	To encourage a wide variety of energy-wise strategies: commissioning; energy use monitoring; efficient design and construction; efficient appliances, systems and lighting; the use of renewable and clean sources of energy, generated on-site or off-site; and other innovative measures.	35
Materials & Resources	To encourage the selection of sustainably grown, harvested, produced and transported products and materials. It promotes waste reduction as well as reuse and recycling, and it particularly rewards the reduction of waste at a product's source.	14
Indoor Environmental Quality	To promote strategies that improves indoor air, as well as those that provide access to natural daylight and views, and improve acoustics.	15
Innovation in Design	To reward projects that use innovative technologies and strategies to improve a building's performance well beyond what is required by other LEED credits, or to account for green building considerations that are not specifically addressed elsewhere in LEED. This category also rewards projects for including a LEED Accredited Professional on the team to ensure a holistic, integrated approach to the design and construction process.	6
Regional Priority	These are selected for each region of the country by USGBC's regional councils, chapters, and affiliates to address local priorities.	4

LEED 2009 for building design and construction gives a maximum of 110 points distributed in 8 categories. Different levels of certification exist. For example, a new LEED construction project requires at least 40 points to attain the certification level, 50 points for silver, 60 points for gold, and 80 or more points for platinum (US Green

Building Council 2011b). LEED 2009 has also some critiques regarding to the effectiveness of energy savings (Scofield 2009).

The new LEED v4 (US Green Building Council 2013) incorporates LCA in the analysis of Materials & Resources (MR) credits. This LEED version added the option of obtaining credits for demonstrating a building life-cycle impact reduction by performing a whole building LCA of the project's structure and enclosure.

2.9.3. Other Green Building Rating Systems

Many rating systems other than LEED exist in the world. This section presents some of their main features. Even when most of the case studies presented in this research were pursuing LEED certification, reviewing other rating systems is important for understanding different perspectives in measuring sustainable design and how that may affect the decision-making process.

Building Research Establishment Environmental Assessment Method (BREEAM): BREEAM was the first national rating system, developed in 1990 in the UK. BREEAM has since expanded, going from a 19-page report with 27 credits available, to a massive 350-page technical guide (for the office version) with 105 credits. LEED is similar to BREEAM with regards to the structure. BREEAM covers the following aspects of a building and the construction process: management, energy, transport, water, materials, waste, land and ecology and pollution.

Haute Qualité Environnementale (HEQ) or High Quality Environmental standard (HQE): HEQ was created in France, based on the principles of sustainable development first set out at the 1992 Earth Summit. The standard is controlled by the Paris based Association pour la Haute Qualité Environnementale (ASSOHQE). It is similar to BREEAM and has 14 criteria for evaluation in the following 4 categories: eco-construction, eco-management, comfort, and health.

Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB): DGNB was developed in Germany in 2008. It goes beyond LEED because it uses a life cycle perspective for assessing environmental building performance. It also adds the economic and social perspectives into the building analysis. The DGNB system has 5 categories: environmental quality, economic quality, sociocultural- and functional quality (e.g., accessibility and social mixing), technical quality, and process quality. Using 51 criteria distributed in these 5 categories, DGNB uses a weighting system to score the overall performance of a building. Site quality is also assessed, but is not included in the numerical certification scores, which are gold, silver and bronze.

Other rating systems across the world use structures similar to LEED, BREEAM and HEQ, such as 3 Star from China, Perl (Estidama) from Middle East, Green Star from Australia and Comprehensive Assessment System for Build Environment Efficiency (CASBEE) from Japan. More stringent rating systems have been also developed such as the Living Building Challenge and One Planet Living.

Living Building Challenge (LBC): LBC is an international sustainable building certification program created in 2006 by the non-profit International Living Future Institute (Living Building Challenge 2010). LBC uses a more holistic approach to sustainability than LEED or BREEAM does. However, it does not yet have many followers. LBC differs from LEED in that it does not focus on rules, but offers a performance-based approach with very high targets. In addition, LBC certification is based on actual, rather than modeled or anticipated performance. It requires net zero energy and water usage among other performance areas for site, health, materials, equity, and beauty. In addition, it does not permit the use of any 'red list' chemicals in any area of the building. The red list approach is more stringent than current US Environmental Protection Agency regulations in the US. It was originally developed for Google projects that were seeking excellent air quality standards.

One Planet Living (OPL): OPL was created in the UK after the construction of a community project called BedZED, which was completed in 2002 (BioRegional 2013). It is not just a rating system for buildings, but also provides guidelines for business and individuals' life style. One of its main supporters is the World Wide Fund For Nature (Formerly World Wildlife Fund or WWF). The idea behind it is to create stringent targets in all human activities. As One Planet Living (2013) states, if everyone in the world lives like an average North American we will need 5 planets to live on (or 3 planets for an average European). The ten One Planet principles provide a framework that allows us to examine the sustainability challenges we face and develop action plans to live and work within a fair share of the earth's resources. The ten challenges are: (1) zero carbon, (2) zero waste (to landfill), (3) sustainable transport, (4) sustainable materials, (5) local and sustainable food, (6) sustainable water, (7) land use and wildlife use, (8) culture and community, (9) equity and local economy, and (10) health and happiness.

Rating systems provide guidelines for design and construction. However, they do not provide a method for decision making or for making trade-offs, other than achieving points. LBC and OPL provide stringent targets that force decisions to ensure a sustainable outcome such as net zero energy in the case of LBC or net zero carbon in the case of OPL.

2.10. Calculating Life-Cycle Cost of Commercial Building Alternatives

This research refers only to the economic aspects of a building's life-cycle cost. Given a specific design, it estimates the total cost of the resulting building, which includes planning, design, construction, operation and maintenance, and end-of-life through the lifetime of the building. The purpose of calculating life-cycle cost is to evaluate the initial monetary investment with the long-term expense of owning and operating the building.

The literature uses the term Life-Cycle Cost Analysis (LCCA), which is the process of evaluating the social-, environmental-, and economic performance of a building over its entire life. This analysis includes social costs such as healthcare costs for people, and environmental costs such as the price per ton of carbon emissions. Santero et al. (2011) present an LCCA for different alternatives of pavement design. According to Reidy et al. (2005) "By comparing the life cycle costs of various design configurations, LCCA can explore trade-offs between low initial costs and long-term cost savings, identify the most cost-effective system for a given use, and determine how long it will take for a specific system to 'pay back' its incremental cost."

Many challenges exist in calculating the life-cycle cost of design alternatives in commercial building. Some of them are:

- Discount rates may not represent the desires of future generations, and may not provide an accurate way of accounting for irreversible environmental or social damage. The discounting of future benefits has long been controversial. The greatest concern, according to Quiggin (1997) is, "The high rates of discount typically used, even large benefits and costs are treated as insignificant if they arise more than, say, thirty years in the future. … Environmentalists have argued that discounting procedures, particularly as they have applied to environmental benefits, represent unfair treatment of future generations."
- Uncertainty in the performance of the alternatives, especially during the operations of the building. This may add unforeseen costs to design alternatives.
- Market changes affect forecasting of prices, which is out of the control of the design team.

Designers may benefit for incorporating life-cycle cost in addition to first cost when making decisions. However, they deal with these and other challenges when calculating the life-cycle cost. This information complements the use of MDCM method, which provides a way of representing the 'value' of the alternatives. Then designers are able to compare 'value' vs. first cost and 'value' vs. life-cycle cost.

2.11. Lean Design and Construction

2.11.1.Lean Construction Origins

Lean philosophy originated in Japan in the 1950s and 60s. Taichi Ohno was a production engineer at the Toyota Corporation and is known as the father of the Toyota Production System (TPS), which is the basis of lean manufacturing. Ohno believed in the possibility of eliminating waste and increasing the 'value' for the customer. He defined 7 types of waste (Ohno 1988), lately Liker and Meier (2006) added waste type number 8.:

1. Overproduction
2. Waiting (time on hand)
3. Transportation or conveyance
4. Overprocessing or incorrect processing
5. Excess inventory
6. Unnecessary movement
7. Defects
8. Unused employee creativity

Lean philosophy has been applied to construction since 1992, when Koskela studied the implementation of TPS in construction. The term 'lean construction' was agreed in the first International Group for Lean Construction (IGLC) conference in 1993, adopting it from its use in the book "The Machine That Changed the World." Since 1997 the Lean Construction Institute (LCI) has spread the use of lean tools and methods. In addition, many lean communities have emerged in the US and around the world to improve the current industry practices by eliminating waste and creating 'value' (e.g., Leheman and Reiser 2000, and Howell and Lichtig 2008).

Koskela (1992) developed the Transformation Flow Value (TFV) theory, which is one of the basis of lean construction. TFV Theory adds the perspective of the flow and value generation views, to the traditional transformation view (Koskela 1992). Ballard (2000a) developed the Last Planner System^{TM}, which is a production planning system designed to produce predictable work flow and rapid learning in programming, design, construction and commissioning of projects. Tommelein (1998) provides an application to pull scheduling in the AEC industry. Uncertainty is also considered in scheduling and coordination among trades using lean techniques (Tommelein et al. 1999).

The application of lean principles across projects has led to development of the Lean Project Delivery System (LPDS) (Ballard 2000b), which consists of the following phases: (1) project definition, (2) design, (3) supply, (4) assembly and (5) use. Figure 2.10 represents how these phases overlap and influence each other, as opposed to understand each phase being independent (Koskela et al 2002).

According to LPDS, the phases of a project are interrelated; therefore, when making decisions the interrelations with the different phases should be analyzed. For example, a decision about what kind of partition wall to use for a commercial building is related to the design of the final product (how well it will fit the building purposes), the design of the process (the design of the wall's installation), the detail engineering (considering supply of materials and interactions with other building systems), the fabrication & logistics of the partition wall, the installation of the partition wall itself, and the commissioning of the building. The decision will also affect the operation maintenance and decommissioning of the building. In other words, decisions need to consider the impacts on buildings life cycle.

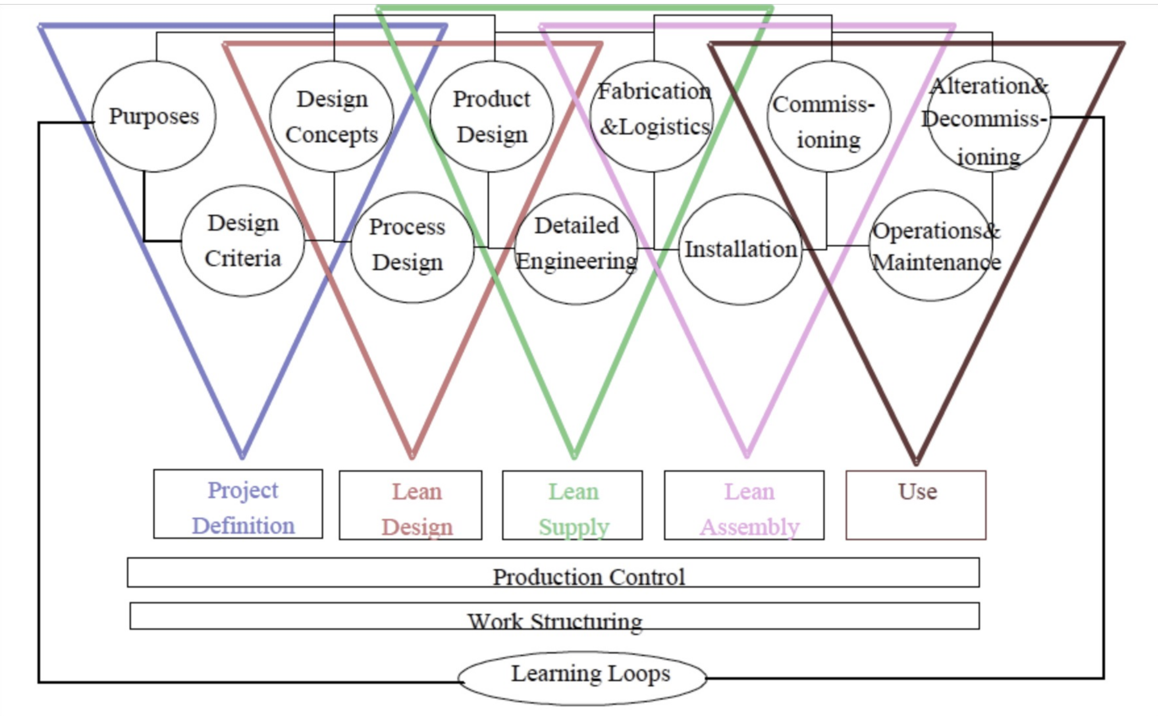


Figure 2.10 Lean project delivery system (Ballard 2000b).

2.11.2.Lean Design Tools and Methods

Several studies have analyzed Toyota design practices and applied it to other industries (e.g., Ward et al. 1995, Kennedy 2003, Kennedy et al. 2008, and Rother and Shook 2003). Lean provides tools and methods (e.g., A3 reports, Target Value Design (TVD), and Set-Based Design (SBD)) to design products and processes that can help in obtaining a more holistic sustainable perspective by focusing on improving the whole and not the pieces. Lean methods and tools seek to increase 'value' for the customer and reduce waste. Lean tools and methods can be more effective with the use of relational contracts, or Integrated Project Delivery (IPD) contracts, where collaboration is encouraged among stakeholders. The following sections describe lean tools and methods relevant to this research.

2.11.2.1. A3 Reports

A3 reports are extensively used in TPS to provide a communication tool in which a problem, its background, and possible solution are presented. This report is done on an A3 piece of paper (this was the biggest faxable size of paper), which allows for feedback among stakeholders. Documenting the decision-making process about which alternative is more sustainable supports the lean Plan Do Check Act (PDCA) approach, enhances transparency, and allows continuous improvement among the stakeholders. Documenting allows stakeholders to learn from previous decisions, generates better decisions and ultimately better outcomes in the future.

2.11.2.2. Target Value Design

Target Value Design (TVD) comes from Target Costing used in manufacturing (Nicolini et al. 2000). The main idea is to self-impose necessity as a means to innovation and continuous improvement. Ohno calls that "lowering the river to see the rocks." In TVD the design process is driven by achieving a target value, a desired performance for the whole building, under a certain cost set in agreement with the owner. This is in contrast to the traditional way, in which the design is made first and then the cost of the building is an outcome according to market conditions. **Error! Reference source not found.** presents the TVD phases.

TVD focuses on the need to understand the purpose of the building, and emphasizes design thinking that minimizes waste and increases the 'value' for the owner. TVD is a collaborative method in which stakeholders are introduced early in the design process, and together they define the ends, means, and purposes that will drive the design of the building.

Ballard (2005) presented a benchmark for TVD updated it in 2009 and 2011. The Project definition phase contains the business case produced by the owner's team. Ideally, the business case is revealed to the rest of the team in order to boost confidence and trust among the stakeholders. The design is done if the 'allowable cost' (the amount of cost that the owner is willing to expend in the project) is lower than the target cost. The feasibility study is where stakeholders identify ends, means, and constraints.

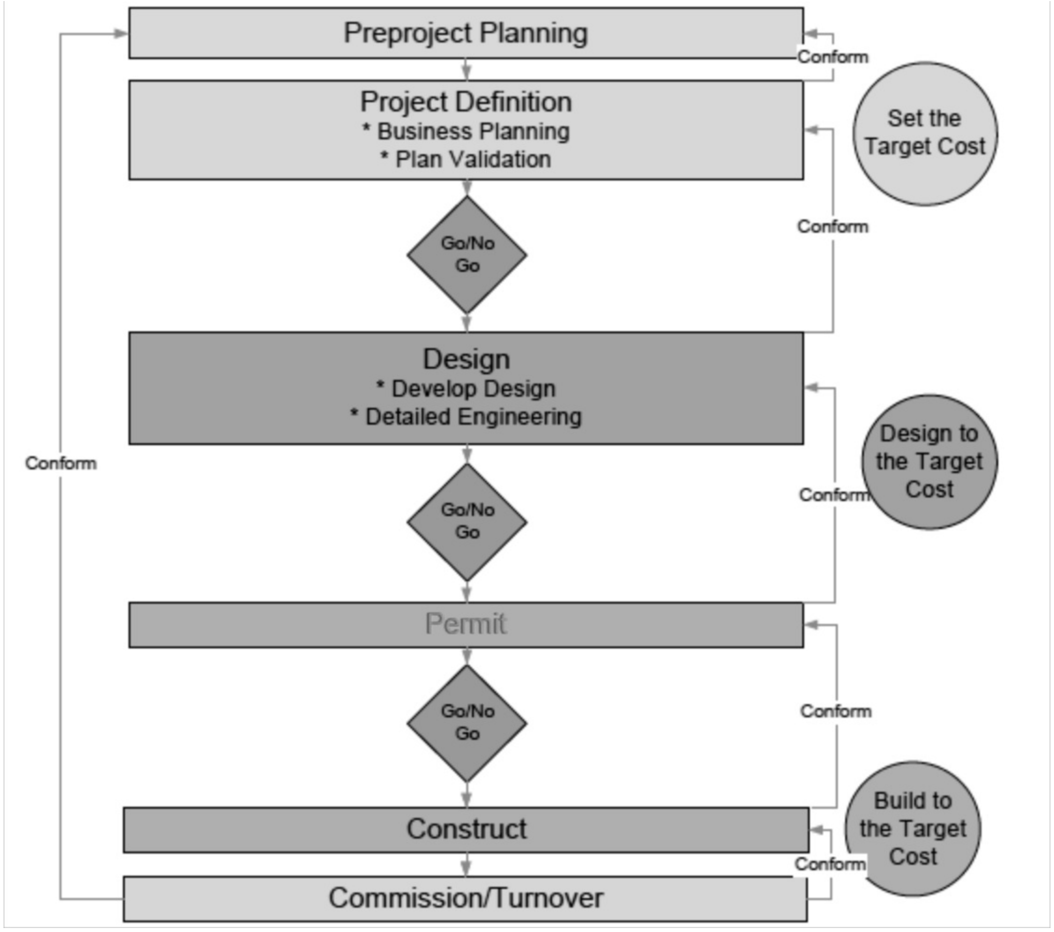


Figure 2.11 Project phases and target costing (Ballard 2008).

Ballard (2005, 2009, 2011) reported that positive anomalies are expected when using TVD. This includes the following: (1) Expected cost falls as design develops, and (2) The initial cost of the project is usually below market cost. Reasons why these positive anomalies happen are: (1) Scope control, the design is steered to targets; rework decreases due to more time and cost spent in the project definition phase. (2) Scope refinement, while the design is refined, contingencies decrease due to increase in certainty. (3) Proactive value engineering, engineers do not wait for problems, instead they think beforehand how to do the project in a better way.

The decision-making process when using TVD should be linked to the ‘value’ of the alternatives evaluated for the whole project and to the target cost. In TVD, the cost is assigned for the whole project; therefore, the design team can reassign and distribute the cost into different building systems in order to optimize the overall ‘value’. For example, the design team may decide to increase the cost on the insulation of exteriors walls and reduce the cost on the HVAC system if that provides a greater ‘value’ for the project.

2.11.2.3. Set-Based Design vs. Point-Based Design

Another lean tool that is closely related with the decision-making process is Set-Based Design (SBD) where designers are encouraged to explore alternatives collaboratively and keep them open until the last responsible moment, reducing negative design iteration. This is in contrast to Point Based Design, where one alternative is selected earlier in the design process and presented to the next design specialist.

In SBD, the design team should delay decisions in order to allow time to explore and evaluate as many feasible design solutions as possible (Singer et al. 2009), and also make sure that all factors and criteria are applied consistently to all alternatives (Figure 2.12).

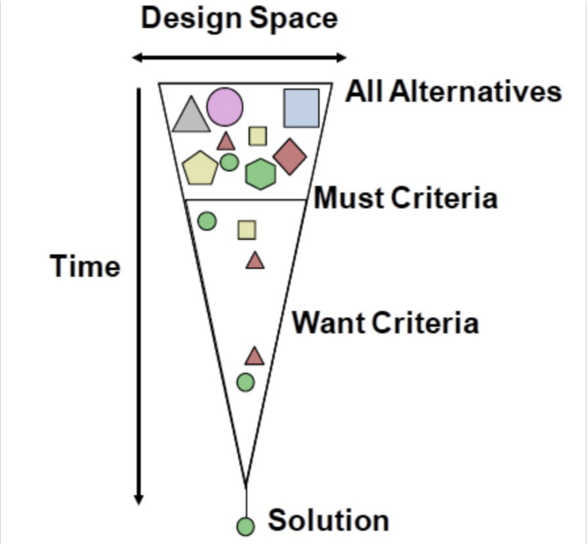


Figure 2.12 Set-based design process (Parrish 2009).

In SBD, the generation of alternatives, or exploration, starts from the owners need. Designers have a period in the design in which they need to keep all alternative paths open until the choice of an alternative path can be made with enough confidence. Designers need to understand the presumed outcomes of each alternative before making a decision (Figure 2.13). Then, the explorations of new alternatives begin again. Figure 2.13 shows also how decisions are interrelated, and how they impact future alternatives.

In contrast, Point-Based Design (PBD) (Figure 2.14) chooses a single, presumably best design (from one stakeholder perspective), which may later prove to be infeasible when other stakeholder views are considered (Ward et al. 1995). PBD results in repeating the process over and over again, generating negative (non-value-adding) design iteration, which is characterized by last-minute changes, lack of a systematic approach to promote innovative thinking, poor communication, and poor integration of design concepts (Ballard 2000c).

The characteristics of PBD are (2012a):

- Designers decompose the design into subsystems.
- Designers fix a concept based on their initial understanding.
- Designers decompose this overall concept into sub goals.
- Designers define or assume critical interfaces.
- Designers trade flexibility to avoid uncertainty.
- Designers constrain interactions long before trade-offs are revealed.
- Design will be feasible but sub-optimal.

- Designers allow very little iteration to optimize.
- Top-level concepts force a premature commitment.
- Designers cannot address requirements that emerge through the course of the design process.

This approach frequently strangles innovation.

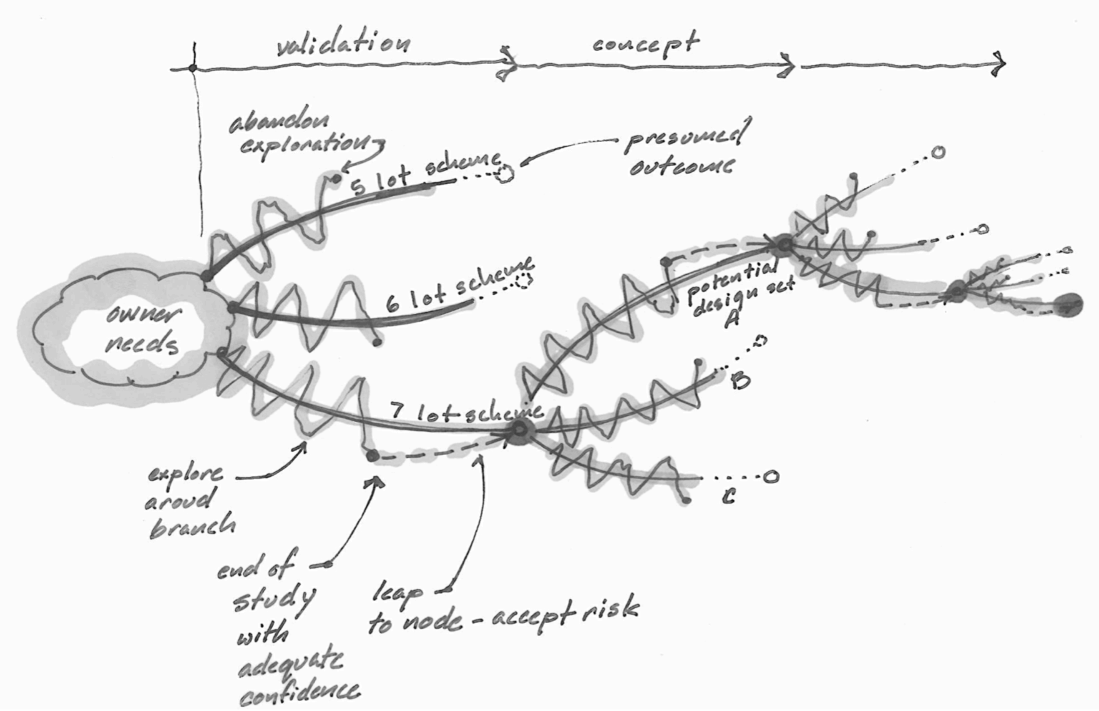


Figure 2.13 Set-based design and decision-making timing in design (Mar 2009).

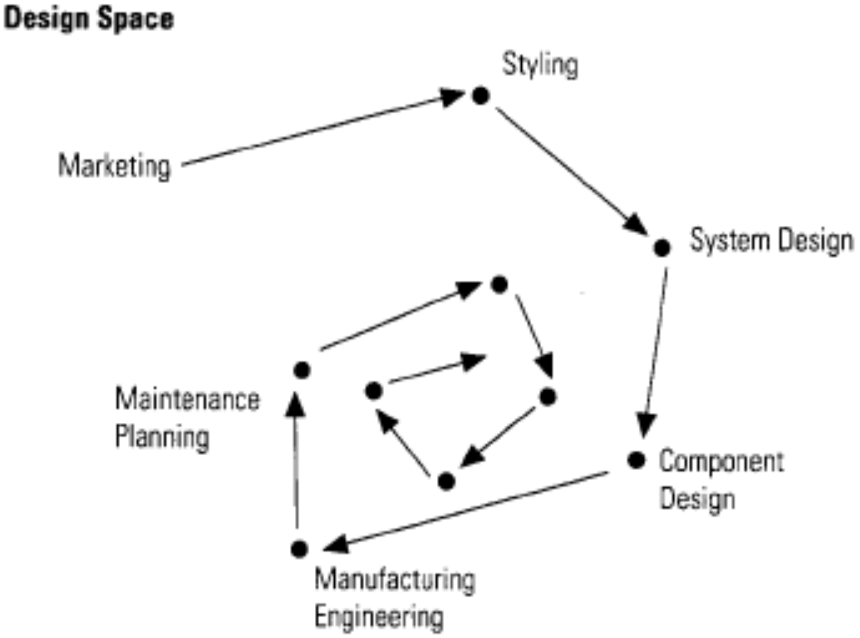


Figure 2.14 Point-based concurrent engineering (Ward et al. 1995).

A decision-making method aligned with SBD should allow for flexibility in the design, facilitating the incorporation of new design alternatives, and supporting the creation of new design alternatives based on design iterations.

2.11.3.Lean and Sustainability

Lean adds flow and value generation to the conversion view (Koskela 1992), which means that the focus on achieving sustainability should not be just in the product delivered, but also in the process to develop that product. An opportunity to use lean methods and tools exist to help in the transformation to more sustainable construction (Huovila and Koskela 1998, Koltz and Horman 2007, Koskela and Tommelein 2009, Nahmens and Ikuma 2012, and US Environmental Protection Agency 2011).

A lean approach maximizes ‘value’ delivered to the customer while minimizing waste. When thinking about sustainability the customer is not necessarily the owner, it can be the community, the environment, the workers, the general contractor, etc. However, because in the real world not all customers are considered in the decision-making process, lean tools and methods could contribute to sustainability only if the customers involved in the decision ‘value’ sustainability (Bae and Kim, 2007).

Lean provides a perspective that rating systems do not provide in terms of whole building and process design. In addition, a common misconception exists that sustainable buildings are more expensive. Matthiessen and Morris (2004) state that the LEED certification of a facility seems to have no relation with the initial cost of the facility. Among buildings of similar value (functionality, performance, LEED rating, capacities, etc.) considerable differences in cost exist. However, better facilities do not have to cost more in design and construction. Moreover, sustainable building design can be produced without certification, which is the case of many projects that prefer to avoid certification costs.

2.11.4.Lean and Decision-Making Approaches

A lean decision-making process should be focused on maximizing ‘value’, optimizing from the whole building perspective and supporting collaboration among stakeholders. Table 2.8 presents the characteristics of a lean vs. non-lean decision-making process (Arroyo et al. 2012a).

From the methods studied in this research, CBA is the most aligned with lean project delivery. CBA can complement the dynamic SBD method throughout its different stages (Parrish 2009, Thanopoulos 2012) since CBA postpones ‘value’ judgment about alternatives as long as possible. In contrast, value-based methods set the weights of the factors early in the decision process. CBA is centered on understanding ‘value’ of the alternatives since it bases the decision on differences between alternatives. CBA clearly separates ‘value’ from cost of the alternatives, which may complement TVD decisions. Further explanation of CBA is presented in Section 3.2.4

Table 2.8 Decision-making approaches (Arroyo et al. 2012a).

Decision-Making Approach	**Not Lean**	**Lean**
Decision-making outcomes	Short term thinking.	Long term thinking.
Stakeholders participation	The decision is made in a closed circle. Decide-present-defend approach.	Early involvement and collaboration among stakeholders.
Systems interrelation	Divide and conquer approach. Each design specialist optimizes his or her part.	Holistic approach. Optimize the whole, not the parts.
Generation of alternatives and decision timing	Point-based design. Explore alternatives within a discipline, select one, and then pass it to the next discipline. Repeat the process one discipline at a time.	Set-based design. Explore alternatives in multidisciplinary teams, but delay design decisions until the last responsible moment to evaluate as many feasible alternatives as possible using consistent factors and criteria for all.
Management of subjectivity	Subjective weighting of factors is made early on the decisions-making process, and is based on assumptions and general categorization.	Subjective decisions are based on anchored questions and are postponed until the last phase of the decisions-making process.
Display of information	Does not explicitly show everyone's choices. Some applications weigh the 'stakeholder's importance'.	Visualization while eliciting preferences helps to build consensus among stakeholders.
Transparency of final decision	The weighting of the factors makes it difficult to know the important differences between the alternatives in the decision.	Transparent process. The advantages of alternatives are discussed and agreed among stakeholders. Clearly states the paramount advantage.
Documentation	Decisions are based on past experience and intuition; little or no documentation is used.	A3 reports are used to clearly state problem, include key information and recommendations. This document is distributed to relevant stakeholders.

2.12. Design Bid Build vs. Integrated Project Delivery

In comparison with Design Bid Build (DBB), Integrated Project Delivery (IPD) is a more collaborative project delivery system. In a DBB project not all relevant internal stakeholders are involved early in the design process. Traditionally, contractors are involved late, or not at all, in the design team.

Distinctions exist between IPD contracts. The first documented IPD project occurred in 2000 in a chilled water plant for the city of Orlando, Florida. Matthews and Howell (2005) presented IPD as an innovative contractual structure that aligns the objectives of all contractors with the objectives of Lean Project Delivery System (LPDS). IPD and LPDS avoid local optimization, and allow for maximizing 'value' and reducing waste at the project level. Sutter Health was one of the early adopters of IPD and LPDS. Sutter Health developed the Integrated Form Of Agreement (IFOA) to support IPD and lean. Will Lichtig, a lawyer, was the author of the first IFOA contract, which was released in 2005. Later, the American Institute of Architects (2007) presented their own version of an IPD contract, however it does not embrace LPDS as the original presentation of Matthews and Howell (2005) or the IFOA.

According to Thomsen et al. (2009), IPD integrated with LPDS have important differences compared to DBB. Table 2.9 presents these differences.

Table 2.9 Differences between DBB and IPD.

	Design Bid Build	**Integrated Project Delivery & Lean Project Delivery**
Commercial Terms	DBB separates the contract into many pieces in which the owner is the only connection among architects, design specialists and contractor.	IPD is based on a multi-party agreement that aligns the interests of the major project internal stakeholders (owner, architect/engineers and contractors) through risk- and reward- sharing programs.
Organization	DBB does not incentivize collaboration across internal stakeholders.	IPD incentivizes collaboration among internal stakeholders. In IPD, construction managers and key trade contractors are involved early in the design phase.
Operating System	Usually DBB bases the project control at the activity level for measuring deviations from planned schedule. Local optimization is encouraged.	IPD allows overall efficiency to be in all internal stakeholders' interest. The product and process are designed together. Work is structured throughout the process to maximize 'value' and reduce waste at the project delivery level using lean construction tools and methods.

Lean adds a focus on the 'operating system'. According to Howell and Lichtig (2010), lean and IPD add: "A production management view into how the work of design and construction actually gets done. Moreover, IPD and lean require the team to openly engage in an explicit effort to align the operating system with a collaborative organizational structure and commercial terms that support project-wide optimization through the use of relational contracts. This creates a coherent approach aimed at optimizing the project, not the pieces and serves the owner's ultimate goal of creating optimal 'value' for minimum cost and time." LPDS and IPD may enhance collaboration and transparency throughout the design process.

Many owners of commercial building projects use a DBB delivery system. However, IPD is becoming more common since it presents important advantages over DBB, resulting in more successful projects in terms of 'value' for the customer, cost and schedule. This new collaborative approach will also require new tools for decision making.

The type of project delivery system may influence the extent to which relevant stakeholders may be known and be involved in the decision-making process. For example, in a DBB project, the general contractor may not be assigned to the project when many design decisions are made. In contrast, a project that uses LPDS and IPD may facilitate the involvement of relevant stakeholders (e.g., general contractor) since they are brought earlier into the project. A more collaborative project delivery system may also benefit the sustainable performance of buildings (Gransberg et al. 2000 and Swarup et al. 2011).

2.13. Group Decision Making

This section presents issues regarding group decision making such as cognitive biases and the argumentation process using rhetoric in design decisions.

2.13.1.Cognitive Biases

In this section the researcher has investigated other fields such as psychology to better understand group decision-making process and how to avoid biases and unnecessary conflicts.

Psychologists and behavioral economists have been studying why people make decisions the way they do. Some agreement in the literature exists about the tricks that our mind plays on us (e.g., Ariely 2008, Haselton et al. 2005, Hilbert 2012, Jermias 2001, Kahneman and Tversky 1972 and 1996, and Kunda 1990). These are known as cognitive biases. Some biases that are relevant to this research are:

- **Framing Effect:** Tversky and Kahneman (1986) originally described this deviation from rational decision-making. Every decision depends on information, but the same problem receives different responses depending on how it is described. People tend to avoid risk when a positive frame is presented but seek risk when a negative frame is presented. For example, more people will support an economic policy if the employment rate is emphasized than when the associated unemployment rate is highlighted (Druckman 2001).
- **Anchoring:** The reference points of the information shape how the decision maker receives and uses it. Anchoring refers to using a predetermined reference point as the launch pad for a decision. The main risk with anchoring to the wrong point is giving excessive weight to an unimportant but salient feature of the problem. Tversky and Kahneman (1974) described anchoring or focalism as a cognitive bias that describes the common human tendency to rely too heavily on the first piece of information offered (the ‘anchor’) when making decisions under uncertainty. During decision making, anchoring occurs when individuals use an initial piece of information to make subsequent judgments. Once an anchor is set, the decision maker judges by adjusting away from that anchor, and a bias toward interpreting other information around the anchor exists. For example, the initial price offered for a used car sets the standard for the rest of the negotiations, so that prices lower than the initial price seem more reasonable even if they are still higher than what the car is really worth.
- **Focusing Illusion:** The focusing effect (or focusing illusion) is a cognitive bias that occurs when people place too much importance on one aspect of an event (or alternative), causing an error in accurately predicting the utility of a future outcome (the importance of an advantage). According to Kahneman et al. (2006), when people consider the impact of any single factor on their well-being—not only income—they are prone to exaggerate its importance. This tendency is referred to as the focusing illusion. The focusing illusion may be a source of error in decisions that people make. In fact, Schkade and Kahneman (1998) noted that, “Nothing in life is quite as important as you think it is while you are thinking about it.”

- **Confirmation Bias:** This happens when we seek out and believe information that confirms our opinions, while ignoring or downplaying information that contradicts them. The confirmation bias is the tendency to search for or interpret information in a way that confirms one's preconceptions. In addition, individuals may discredit information that does not support their views (Mahoney 1977). The confirmation bias is related to the concept of cognitive dissonance whereby individuals may reduce inconsistency by searching for information that re-confirms their views (Jermias 2001 p. 146).
- **Group Polarization Bias:** Specific to group decision making. In social psychology, group polarization refers to the tendency for groups to make decisions that are more extreme than the initial inclination of its members. These more extreme decisions are towards greater risk if individuals' initial tendencies are to be risky and towards greater caution if individuals' initial tendencies are to be cautious (Aronson et al. 2010). The phenomenon also holds that a group's attitude toward a situation may change in the sense that the individuals' initial attitudes have strengthened and intensified after group discussion (Myers and Lamm 1975). Myers and Lamm (1975) demonstrate that group discussion will often amplify the dominant initial inclination of group members. Research has suggested that well-established groups discussing problems that are well known to them suffer less from polarization than newly formed groups do, especially when tasks are new (Myers and Lamm 1976).

According to Kahneman (2011), group decision-making biases may be avoided by first making individual decisions and then following up with a group decision. In this way, individual biases cannot affect others in the group.

2.13.2.Rhetoric in Design and Decision Making

Rhetoric is a natural part of the design process and has caught the interest of researchers in the last 50 years. Indeed, effective rhetoric has been studied and used since the time of the ancient Greeks to persuade and to influence all manner of things. However, little research has been done on rhetoric and design in engineering, specifically during the decision-making portion of the design process.

Ballard and Koskela (2013) discussed the importance of studying rhetoric in design, claiming that the topic has been addressed in many fields (e.g., Buchanan 1985 and 2001, Crilly et al. 2008; Foss 2005) but not in engineering design. This research contributes to closing that gap by studying how rhetoric may support the decision-making process in building related design. This Section presents a synthesis of the basic rhetorical tools, and Section 6.7 presents an example of how rhetoric can be used with the CBA method.

Many decisions need to be made in building design. In practice, few decisions are based on a formal and transparent decision-making method, and they are very likely to be influenced by arguments that only a few members of the design team provide. Arguments may sound appealing at the time of the decision. However, too often decisions need to be changed later in the design process wasting time and resources. This may be due to lack of consensus, failure in considering all relevant perspectives, or because the decisions were made before having relevant data for understanding their impacts.

Rhetoric is the art of discourse, an art that aims to improve the capability of writers or speakers who attempt to inform, persuade, or motivate particular audiences in specific situations (Corbett 1990, Young et al. 1970).

Aristotle defines rhetoric as “the faculty of observing in any given case the available means of persuasion.” (Aristotle 1941). In other words, rhetoric is the art of discovering and delivering all available means of persuasion.

Rhetoric, as understood by Aristotle, involves invention, arrangement, style, memory, and delivery, all of which can be taught. Invention was based on topics, or places from which to launch arguments, such as similarity and difference, better and worse, etc. Arrangement concerned the structure of a speech, style and delivery concerned methods of effective presentation, and memory, obviously restricted to unwritten speeches, concerned aids to memorization.

A speaker knowledgeable in rhetoric supports a message by logical (logos), ethical (ethos), and emotional (pathos) proofs. The use of rhetorical proofs is very common; many would say that some form of logos, ethos, and pathos is present in most public presentations. However, usually few people in design teams use arguments in an appealing manner able to influence decisions. According to Aristotle, the ‘art’ of rhetoric can and should be taught.

The next sections present the three different types of rhetorical proof according to Aristotle.

2.13.2.1. Logos

Logos refers to the use of reasoning, either inductive or deductive, to construct an argument. The term logic evolved from logos. Logos appeals to statistics, mathematics, logic, and objectivity.

Inductive reasoning uses examples (e.g., statistics or historical data) to draw conclusions. Deductive reasoning uses generally accepted propositions to derive desired conclusions. Aristotle emphasized enthymematic reasoning as central to the process of rhetorical invention, though later rhetorical theorists placed much less emphasis on it. Enthymemes are truncated syllogisms, with a missing premise to be provided by the audience. An enthymeme is persuasive because the audience is providing the missing premise. For instance, a manufacturer can make a logical appeal by claiming that their product has 50% more recycled contents than the competition, expecting the ‘audience’ to supply the missing premise ‘More recycled contents are better’.

2.13.2.2. Ethos

Ethos refers to how the character and credibility of a speaker can influence an audience to consider him/her to be believable. This could be any situation in which the speaker is recognized as an expert on the topic. An audience is more likely to be persuaded by a credible source because the source is more reliable. In addition, three qualities contribute to a credible ethos: perceived intelligence, virtuous character, and goodwill.

For instance, if a renowned structural engineer gives his/her opinion about the building design in terms of earthquake performance, it is more likely that the rest of the design team (e.g., owner, architects, MEP, etc.) will accept this opinion. He/she will have a 'strong' credibility because of his/her professional credentials and background.

2.13.2.3. Pathos

Pathos refers to the use of emotional appeals to influence the audience's judgment. This can be done through metaphor, amplification, storytelling, or presenting the topic in a way that evokes strong emotions in the audience. Aristotle used pathos to help the speaker create appeals to emotion in order to motivate decision making. Strong emotions are likely to persuade when there is a connection with the audience. For instance, in building design, architects may evoke the user experience as means of persuasion to incorporate changes in the design.

Finally, this chapter summarizes the information relevant to understanding the literature on decision-making methods, practices in the AEC industry pertaining to sustainability and lean, and some of the aspects of group decision making. The researcher found useful advice in the literature, which was helpful in answering the research questions. However, this chapter may not represent a complete view in all of the aspects of decision-making.

3. THEORETICAL COMPARISON OF 4 MCDM METHODS

The purpose of this chapter is to provide a theoretical comparison of Multiple-Criteria Decision-Making (MCDM) methods to answer the questions ‘What are relevant differences between MCDM methods?’ and ‘How do the relevant differences among MCDM methods affect the decision-making process?’

In order to answer these questions, Section 3.1 presents aspects of MCDM methods that are relevant for the research context. In this research context, the design team chooses the more sustainable alternative by analyzing multiple factors, often with conflicting interests. Section 3.2 offers a description of the characteristics of the 4 types of MCDM methods studied, an example of each, and a discussion about how the methods help (or not) in creating transparency, building consensus, and continuous learning. Finally, Section 3.3 presents the conclusions.

3.1. Comparing MCDM Methods for Choosing a Sustainable Alternative in Commercial Building Design

This section aims to identify which aspects of MCDM methods are relevant or irrelevant for comparison purposes given the scope of this research.

Different methods differ in various regards. As stated in the scope (Section 1.5) the focus of the comparison is the ability of the MCDM method to help in creating transparency building consensus, and continuous learning. The researcher has identified the following factors to compare the MCDM methods:

3.1.1. Creating Transparency

In the research context, creating transparency is desired in order to obtain a clear rationale for a decision and avoid negative iteration (Section 1.4.4). The researcher studied how the MCDM method could help (or not) stakeholders to (1) make transparent trade-offs between attributes, (2) make transparent trade-offs between factors, (3) differentiate between alternatives and understand the ‘value’ they provide, (4) analyze ‘value’ vs. cost, and (5) provide consistency when making changes.

3.1.1.1. Making Transparent Trade-Offs Between Attributes

In order to create transparency for trade-offs between attributes, the researcher believes that the design team may benefit from the following:

- Identify objective attributes of the alternatives, but also make explicit the subjective ‘value’ of the attributes. For example, when describing the comfort of a room, one can measure the temperature and humidity. However, how one-person feels about those attributes needs to be stated clearly, such as “I feel too cold at that temperature and humidity.”
- Analyze the ‘value’ of increments in attributes, instead of assuming ‘values’ for a specific attribute. Increasing temperature from 60 to 70 degrees Fahrenheit is not the same as increasing it form 30 to 40 degrees Fahrenheit. Assuming that every

increment in performance is the same, or assuming that attributes have a natural ratio scale may not be accurate.

- Treat qualitative attributes (e.g., aesthetics, safety, ease of installation, usability, etc.) as subjective attributes and describe them instead of translating them into a numerical scale.
- Treat quantitative attributes (e.g., embodied energy, weight, height, etc.) using units that have a physical meaning (e.g., kg of CO_2, kg, ft, etc.) rather than translating them into percentages or numerical scales.
- Make explicit which attributes are ‘a must have’ and which attributes are ‘a want have’.

3.1.1.2. Making Transparent Trade-Offs Between Factors

In order to make transparent trade-offs between factors the researcher identified the following issues:

- Represent ‘value’ across factors. When making decisions the design team has to represent the ‘value’ of alternatives. This overall ‘value’ is created by trade-offs between different factors. For example, alternative ‘a’ may be better than alternative ‘b’ with regard to factor 1 but worse than alternative ‘b’ with regard to factor 2. This allows the design team to evaluate the ‘value’ of those two differences.
- Analyze specific trade-offs instead of assuming a factor importance. Factors are general categories. For example, when choosing a car, assuming that safety is more important than fuel economy in the abstract, may not help decision makers in creating transparency. Alternatives need to be judged in a particular context, providing as much transparency and information to make sense of the judgments. For example, decision makers need to know what is the specific difference in terms of safety and fuel economy between the alternative cars. Only after that may they assess what trade-offs they are willing to make between safety and fuel economy.

3.1.1.3. Differentiating between alternatives

Differentiating between alternatives is one of the purposes of the analysis in order to make a decision. The researcher identified the following related issues:

- Compare facts. Decisions use facts, which can be qualitative or quantitative attributes of the alternatives. The decision will be more transparent if it is based on facts than if it is based on assumptions.
- Compare ‘values’. The differentiation of the alternatives facilitates understanding the ‘value’ of one alternative in comparison to another.
- Avoid double counting. Decision can be based on positive or negative differences. Decision makers should avoid using pros and cons of alternatives because they may be double counting.
- Consider Uncertainty. Attributes of alternatives may be uncertain, and in such cases it is important to be transparent in describing what is known and not known

about an alternative. However, this research does not consider uncertainty in the comparison of MCDM methods.

- Consider interdependence: Some factors can be interdependent (e.g., energy use and CO_2 emissions). The design team may want to merge similar factors in order to avoid double counting.
- Identify relevant factors. Decisions will be more transparent if the design team identifies factors that differentiate between alternatives, rather than assume predefined factors.

3.1.1.4. Analyzing 'Value' vs. Cost

The design team usually wants to be cost conscious and at the same time achieve project objectives. The researcher identified several issues:

- Cost is a constraint not a 'value'. The allowable cost of a specific project is typically limited, often by the expectation of return on investment (private sector) or by government funding of various origins (public sector). Taking cost into account does not imply selecting the least costly alternative, but rather the alternative that yields the best project outcomes within financial constraints. Cost does not represent 'value' per se, and therefore should not be analyzed in the same way as the attributes of the alternatives.
- Cost can move across decision boundaries. Cost can be distributed in a variety of ways within a given project. It can be shifted between building systems and components within those systems. For example, when choosing a lighting system the design team may first analyze which alternative they prefer in terms of energy usage, aesthetics, light quality, etc. and then decide how much the owner is willing to spend on an alternative that provides greater 'value'.
- Cost is variable. Cost is not an intrinsic characteristic of an alternative. For example, the cost of a light bulb will depend on the quantity that is required, the delivery terms, where it is bought, and the market conditions. The cost of an alternative can be changed by negotiating with suppliers, or by changing the design.
- First and life cycle cost: Considering first and life cycle cost may provide more transparency to the decision. However, the MCDM method does not affect how first or lifecycle cost is calculated, but will affect the 'value' of alternatives.

3.1.1.5. Providing Consistency

The decisions must be consistent:

- Decisions can change if new relevant information is added.
- Decisions should not change if irrelevant information is added or removed. When alternatives are judged against criteria, it is possible to rank alternatives from the most preferable to the least preferable or vice versa. It is logical to expect that when new alternatives are added to a decision problem, the relative ranking of the old alternatives will not change (if the factors and criteria remain the same as before). In addition, 'rank reversal' should not occur when factors that do not differentiate between alternatives are added or removed.

- The intensity of the preferences should not change when irrelevant alternatives or non-differentiating factors are added or removed from the decision.

3.1.2. Building Consensus

Consensus is a general agreement achieved through a group discussion where all opinions and views are heard and understood. The resulting agreement reflects a solution that is acceptable to all members of the group and is respectful of all opinions. Consensus is not what everyone agrees to, nor is it the preference of the majority. Consensus results in the best solution that the group can achieve at the time, in this case choosing the best available design alternative. The root of 'consensus' is 'consent'. This means that even if some of the members of the design team disagree, there is still overall consent to move forward to implement the chosen alternative. This requires co-operation among members of the design team with different design specialties and opinions.

Consensus may not be always desirable. For example, many constraints and requirements in commercial building design exist; building must comply with codes and city requirements. A consensus on whether or not to comply with building codes is not relevant because not complying is not a legal alternative.

This research studies decisions where consensus is desirable. The design team may benefit from building consensus on which is the best alternative because it increases the chances to incorporate multiple perspectives, and it avoids unnecessary iterations. The consensus on the best alternative is based on the available information at the time. However, commercial building design projects are dynamic, people changes (e.g., people change jobs or new design specialist may joint the project or leave), codes change over time, and market conditions change and projects can be put on hold. Therefore, decisions may also change over time.

The researcher evaluated how the MCDM methods help (or not) the design team to (1) aggregate preferences for building consensus, (2) assess 'value' according to the design context, and (3) manage subjectivity.

3.1.2.1. Aggregating Preferences

The researcher identified several issues when aggregating preferences:

- Articulating preferences: preferences can be described in several ways. For example, comparing in pairwise fashion or considering advantages.

3.1.2.2. Assessing 'Value' of Alternatives Based on the Design Context

What is more sustainable depends on the context of the decision. The researcher identified this issue:

- Avoid assumptions. Stakeholders should avoid basing decisions only on previous experiences or on general assumptions. The design team should understand the 'value' of the alternatives based on the design context.

3.1.2.3. Managing Subjectivity

Decisions about what alternative is more sustainable may incorporate subjective attributes and subjective judgments about the 'value' of the alternatives. The researcher identified the following issues:

- Keeping the decision objective as long as possible may benefit the design team.
- Evaluating subjective aspects based on clearly referenced points may help in building consensus.

3.1.3. Continuous Learning

The decision-making process in commercial building design is iterative, and therefore, a MCDM method that provides flexibility may be valuable for the design team. This research evaluates how easy it is to incorporate new design alternatives and factors when using different MCDM methods. In addition, providing a rationale for the final decision, and documenting the decision-making process will allow stakeholders to learn and improve future decisions.

In this research context continuous learning is desired in order to improve the design, reduce negative iteration, and learn for future projects.

The researcher evaluated how the MCDM methods help (or not) the design team to (1)-allow flexibility for design iterations, and (2) integrate multiple decisions.

3.1.3.1. Allowing Flexibility for Design Iterations

A decision-making method should support positive iterations in the design process as new perspectives and new information are incorporated into the decision. When new design specialists are included in the decision, new alternatives, or new information becomes available, and additional iterations may be appropriate. MCDM methods should 'adjust' when new factors or new alternatives are added. The researcher found the following issues:

- Adding new alternatives. Adding new alternatives may mean adding new factors; in that case all alternatives should be reevaluated. In contrast, when new alternatives do not add new factors, only the new alternatives should be evaluated according to the old factors. Therefore, relationships among old alternatives should not require reevaluation.
- Adding new factors. Adding new factors that are interdependent with old factors may require reevaluating the decision. In contrast, when adding new factors that are independent of the old factors, the effect of the old factors in the decision should not require reevaluation.
- Search, creation, or combination of new alternatives: The decision process may support the search, creation or combination of alternatives. However, creating or identifying alternatives is not part of the scope of this research.

3.1.3.2. Integrating Multiple Decisions

The design team requires a whole-system perspective and needs to consider the interdependence of building systems. The researcher identified the following issues:

- Understanding the 'value' of attributes considering the whole building design. For example, when choosing an insulation material for a wall system, a higher R-value may be desirable for saving energy in an extreme climate. However, if the building is not studied as a whole, and it has a high air change rate, selecting the insulation with the higher R-value will not necessarily produce an improvement in energy efficiency. In addition, other properties of the insulation material such as weight may impact structure, and perhaps other building systems.
- Integration of multiple decisions. The design team may benefit by evaluating multiple decisions at the same time in order to choose the best combination of decisions for the building as a whole instead of choosing the best alternative for a single building system.

3.2. Characteristics of MCDM Methods

This section explains the characteristics and assumptions of (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods (including Analytical Hierarchy Process (AHP) and Weighting Rating and Calculating (WRC)), (3) Outranking methods, and (4) Choosing By Advantages (CBA).

In order to provide a clear and consistent language to describe the 4 types of methods, the researcher uses CBA definitions (Table 3.1) because its language is richer.

Table 3.1 CBA definitions (modified from Suhr 1999).

Term	Definition
Alternatives	Two or more construction methods, materials, building designs, or construction systems, from which one or a combination of them must be chosen.
Factor	An element, part, or component of a decision. When assessing sustainability, factors should represent social-, environmental-, and economic aspects. However, in CBA cost is treaded separately from the rest of the factors.
Criterion	A decision rule or a guideline. A 'must' criterion represents conditions each alternative must satisfy. A 'want' criterion represents preferences of one or multiple decision makers.
Attribute	A characteristic, quality, or consequence of one alternative.
Advantage	A benefit, gain, improvement, or betterment. Specifically, an advantage is a beneficial difference between attributes of two alternatives.

3.2.1. Goal-Programming and Multi-Objective Optimization Methods

The emphasis of goal-programming and multi-objective optimization methods is on establishing a desirable or satisfactory level of achievement for each of the factors.

These methods are used in situations in which decision makers find it difficult to express trade-offs or assigning weights to factors, but are able to identify the aspirations or criteria (usually referred to as 'goals' in the literature) for the outcomes of alternatives that they would find satisfying. When just one of the alternatives satisfies all the criteria, it is easy to choose. However, these cases are rare in real-world applications. When many factors with their criteria are considered and no alternative complies with a satisfactory level of achievement for each of them, then the aim is to find a solution which is as near as possible to the target. In order to do that, three methods can be used (Stewart 1992):

(1) Rank the factors and filter alternatives according to the ranking order until only one alternative is left.

(2) Weigh the factors, as done in linear goal programming.

(3) Minimize the maximum weighted deviation from the criteria (goals), as done when using the reference point model.

This research studies only the first method for finding a solution, rank the factors, since the other two methods are similar to what value-based methods do. The application of a goal-programming and multi-objective optimization method, using ranking of factors, can be summarized in the following steps (Figure 3.1): (1) Define factors and criteria for evaluation. (2) Prioritize factors. (3) Formulate a maximization or minimization function including restrictions. (4) Solve the optimization problem. (5) Come to a final conclusion based on the results of this process.

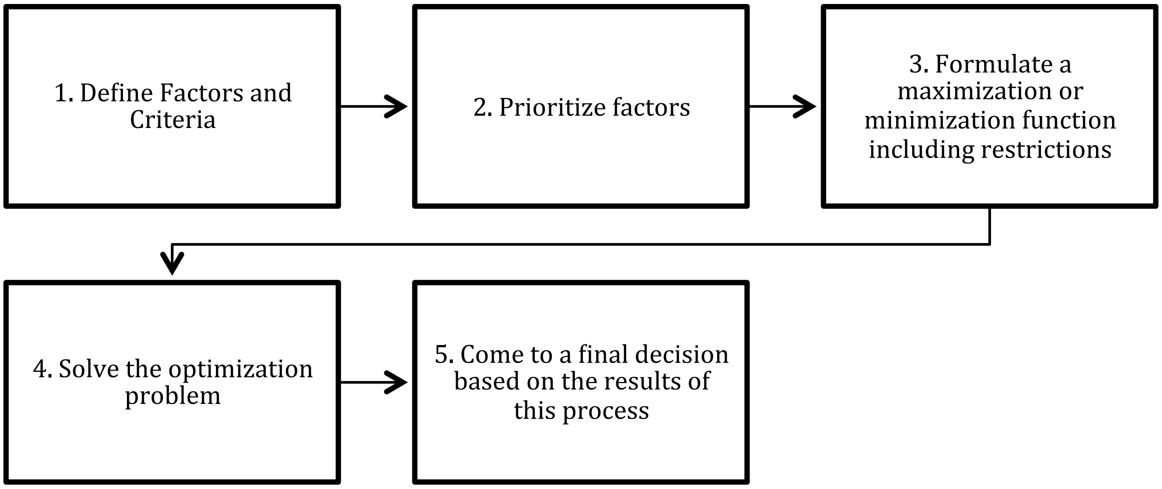


Figure 3.1 Steps in goal-programming and multi-objective optimization methods.

3.2.1.1. Mathematical Description

A multi-objective optimization problem can be represented in the following way when using a ranking of factors. A satisfaction variable, Z_p, is assigned for each factor p. Z_p is maximized (or minimized) for each factor. Usually all higher-priority factors are maintained as hard constraints. Let Z'_i be the satisfaction level to be achieved for any priority factor i, where $i = 1$ to n, and $n \leq p$. Notice that factors 1 to n have hard constraints that must be satisfied, and factors n+1 to p have to be maximized (or minimized). Then the goal-programming method solves the following problem:

$\text{Max } (Z_1, Z_2, Z_3, \dots, Z_n, \dots, Z_p)$ Equation 3.1

Subject to $Z_i \geq Z'_i$ for $i = 1$ to n.

In this case alternatives are evaluated according to a predefined ranking of factors and criteria.

3.2.1.2. Multi-Objective Optimization Method Example: Choosing a Light Bulb

The following example is used to illustrate the four methods described in this chapter. The decision is to choose an 800 lumens light bulb (60W equivalent) from the alternatives: (1) Incandescent light bulb (Figure 3.2), (2) Compact Fluorescent (CFL) light bulb (Figure 3.3), and (3) Light Emitting Diodes (LED) light bulb (Figure 3.4). For the sake of simplicity, this example assumes that each factor has only one criterion for evaluation, and that decision makers will choose the best alternative regardless of the cost.

Figure 3.2 Incandescent light bulb (Getleducated.com 2014).

Figure 3.3 CFL light bulb (Getleducated.com 2014).

Figure 3.4 LED light bulb (Inhabitat.com 2010).

Table 3.2 presents the factors and attributes of the alternatives. The attributes regarding the factor ‘look’ are subjective, and they represent the researcher’s opinion. The look of the light bulb is relevant depending on its use. For example, if the light bulb is installed in an enclosed lamp, the light bulb would not be visible, and therefore, the ‘look’ is not relevant. For this example, we assume the light bulb would be visible.

Relevant definitions for the example:

- *Lumens:* The unit of measurement of the flow of light, or ‘luminous flux’. With light bulbs it provides an estimate of the apparent amount of light the bulb will produce.
- *Color Rendering Index (CRI):* CRI represents the quality of light and its ability to render colors correctly. The maximum is 100, and represents the appearance of colors under daylight.

Table 3.2 Attributes of light bulb alternatives.

Factor	**Alternative 1: Incandescent**	**Alternative 2: CFL**	**Alternative 3: LED**
Energy efficiency (Lumens/Watt)	14 lm/W	60 lm/W	64 lm/W
Readiness (Turn on instantly)	Turns on instantly	Turns on within a second and takes 30 to 60 seconds to achieve full brightness	Turns on instantly
Safety (Mercury content)	No mercury	4 mg mercury /bulb	No mercury
Light quality (CRI)	100	82	93
Look	Nice	Very nice	Ugly

When applying multi-objective optimization to this problem, decision makers can rank factors and define criteria for satisfaction (Z'_i) if it is necessary. For this example, column 1 in Table 3.3 shows the ranking of factors and their criteria, according to the researcher's subjective assessment. In this example, factors 1, 2, and 3 express hard constraints ('must have' criterion) and have Z'_i. Factors 4 and 5 require maximization ('want to have' criteria).

Table 3.3 Using multi-objective optimization method to choose a light bulb.

Factor	**Alternative 1: Incandescent**		**Alternative 2: CFL**		**Alternative 3: LED**	
1. Energy efficiency (criterion: higher than 50 lm/W)	14 lm/W	No	60 lm/W	Ok	64 lm/W	Ok
2. Safety (criterion: mercury content lower than 3 mg/light bulb)	No mercury		4 mg mercury /bulb	No	No mercury	Ok
3. Light quality (criterion: higher than 90 CRI)	100		82		93	
4. Look (criterion: the nicer, the better)	Nice		Very nice		Ugly	
5. Readiness (criterion: the faster, the better)	Turns on instantly		Turns on within a second, and takes 30 to 60 seconds to achieve full brightness		Turns on instantly	

Then decision makers need to judge the alternatives based on the ranking of factors and criteria. Using Factor 1 and its criterion, alternative 1 is discarded. Using Factor 2 and its criterion, alternative 2 is discarded. The solution, then, is found, alternative 3, LED light bulb (Table 3.3). The remaining data show in italics, is no longer relevant in this decision process.

Using this method decision makers do not need to make explicit trade-offs between factors, but they need to agree on the ranking of factors and criteria for evaluation. Note that if the ranking of factors and criteria changes, the result can change. For example, column 1 Table 3.4 shows a second possible ranking. In this case, alternative 2 would be chosen, CFL light bulb.

Table 3.4 Using multi-objective optimization method to choose a light bulb, second case.

Factor	**Alternative 1:** **Incandescent**		**Alternative 2:** **CFL**		**Alternative 3:** **LED**	
1. Energy efficiency (criterion: higher than 50 lm/W)	14 lm/W	No	60 lm/W	Ok	64 lm/W	Ok
2. Look (criterion: the nicer, the better)	Nice		Very nice	Ok	Ugly	
3. Light quality (criterion: higher than 90 CRI)	100		82		93	
4. Safety (criterion: mercury content lower than 3 mg/light bulb)	No mercury		4 mg mercury /bulb		No mercury	
5. Readiness (criterion: the faster, the better)	Turns on instantly		Turns on within a second, and takes 30 to 60 seconds to achieve full brightness		Turns on instantly	

3.2.1.3. Method Assumptions

Assumptions behind goal-programming and multi-objective optimization methods include:

- Decision makers are able to define the ranking of factors and their criteria in order to evaluate the alternatives. The ranking of factors can be constructed without knowing the attributes of the alternatives.
- Cost can be a factor.

3.2.1.4. Discussion

The method assumptions have several consequences. If we think in the context of choosing a sustainable alternative in commercial building design, and we imagine a group of stakeholders with different expertise and interests trying to construct a ranking of factors to evaluate alternatives holistically, several issues may arise.

- *Creating transparency:* After a decision is made, it is easy to explain why an alternative was chosen if the design team followed a multi-objective optimization method. However, (1) it is not clear what the trade-offs were among attributes of the alternatives. This is especially true when more factors and alternatives are incorporated in the decision. In fact, these methods avoid making explicit trade-offs. (2) The differences between alternatives are not highlighted. The design team may be focused on screening alternatives using one factor and criterion at the time. This seems risky when thinking about the design of a building where many issues need to be considered at the same time. (3) Cost can be a factor, and could be ranked first, guiding the selection of an alternative merely by cost without understanding the 'value' of the different alternatives. In addition, this method only results in a solution (the alternative chosen), but does not provide a ranking of the 'value' of alternatives, making it impossible to analyze 'value' vs. cost.
- *Building consensus:* In this case the only consensus that is required by the design team is the ranking of the factors and criteria (if the attributes of the alternatives are known). However, that may be challenging due to (1) Agreeing on which factor and criterion is more important may depend on the interest of each member of the design team. Factors do not represent specific judgments but are general categories, and criteria represent desires, which may be distant from the attributes of the available alternatives. (2) The design team also has the risk of ranking the factors without looking at the attributes of the alternatives, basing the ranking only on previous experiences, and missing the context of the particular decision. (3) In terms of managing subjectivity in this case the design team would need to construct the ranking of factors and criteria first, which is a subjective task, and then evaluate the alternatives according to the ranking, which is a more objective task. As stated before, the researcher thinks that decisions should remain objective as long as possible.
- *Continuous learning:* (1) This method does not provide an overall ranking of the alternatives. Therefore, the design team may not have a clear and shared understanding of what the 'value' of the discarded alternatives is. This may result in missing valuable information for improving the design. (2) If a new alternative is added, the design team can compare it just with the selected alternative using the previous ranking of factors. This may be convenient, but the team may miss the opportunity to look at all the differences between alternatives. (3) If new factors were added, they would need to be placed in the ranking along with its criteria. Then all alternatives would need to be evaluated against the new ranking. (4) Multiple decisions may not be compared using the same factors, and since there is not an assessment of the 'value' of each alternative vs. cost, the analysis cannot be performed for multiple decisions in order to allocate cost vs. 'value' for multiple decisions.

The ranking of factors may be done considering the differences between alternatives. However, it is not a necessary condition of applying the multi-objective optimization method. The rationale for choosing a LED light bulb using the example above (Table 3.3) can be documented as: *The LED light bulb was chosen because it has an energy efficiency higher than 50 lm/W and has a mercury content lower than 3 mg/bulb. In* *addition, the incandescent light bulb was discarded because its energy efficiency is lower than 50 lm/W, and CFL was discarded because it has mercury content higher than 3 mg/bulb.* That rationale is enough for supporting the decision. However, important differences may not be highlighted, such as that CFL or Incandescent light bulbs are nicer than the LED light bulb, and that the incandescent light bulb provides a better light quality than the LED bulb (100 vs. 93 CRI). This may not seem relevant for this decision. However, when designing a building layout, the design team may benefit from knowing the advantages of the discarded alternatives to create new ones. In addition, it may be frustrating for the design team if one of their designs is discarded by just one factor without even considering its performance in other factors and criteria. Moreover, would the design team notice that a big difference in a low ranked factor might be more relevant than a small difference in a high ranked factor?

3.2.2. Value-Based Methods

Value-based methods, also known as value-based methods, are focused on representing a value or utility function to represent the preference of the decision makers. Value-based methods use explicit statements of acceptable trade-offs between different factors as a way of facilitating a construction of preferences.

This research explores two types of value-based methods, AHP and WRC. The researcher selected AHP because it is prevalent in AEC decision-making literature (Section 2.5), and WRC for its widespread use in AEC design practice. These two methods will be described in this section and presented in case studies in Chapters 4 and 5.

The AHP method measures the relative importance of factors and preferences for alternatives through pairwise comparison matrices (Saaty 2007 and 2008a), which are recombined into an overall rating of alternatives by using the eigenvalue method (Saaty 1980). The AHP method is used in cases where decision makers are not comfortable with numerical scores but prefer qualitative or semantic scales (e.g., moderately important, highly important). AHP uses a natural ratio scale, which implies that zero is the natural reference point and that the attributes of the alternatives can be expressed on natural ratio scales, such as mass, distance, etc. Saaty (2008b) summarizes the AHP method in the following steps: (1) Model the choosing problem as a hierarchy containing the decision factors (usually referred to as 'goals' in the AHP literature), the alternatives for reaching it, and the criteria for evaluating the alternatives. (2) Establish priorities among the factors by making a series of judgments based on pairwise comparisons of the factors. (3) Establish priorities among the alternatives for each factor based on pairwise comparisons of attributes. (4) Synthesize these judgments to yield a set of overall priorities for the hierarchy. (5) Check the consistency of the judgments. (6) Come to a final decision based on the results of this process. Figure 3.5 shows the steps to apply the AHP method.

In step (2) when establishing priorities among factors, decision makers are asked to indicate the strength of their preferences for one factor over another on the following scale: 1 Equally Preferred, 3 Weak Preference, 5 Strong Preference, 7 Demonstrated preference, and 9 Absolute preference. After these judgments are done the eigenvalue method provides the weight of factors.

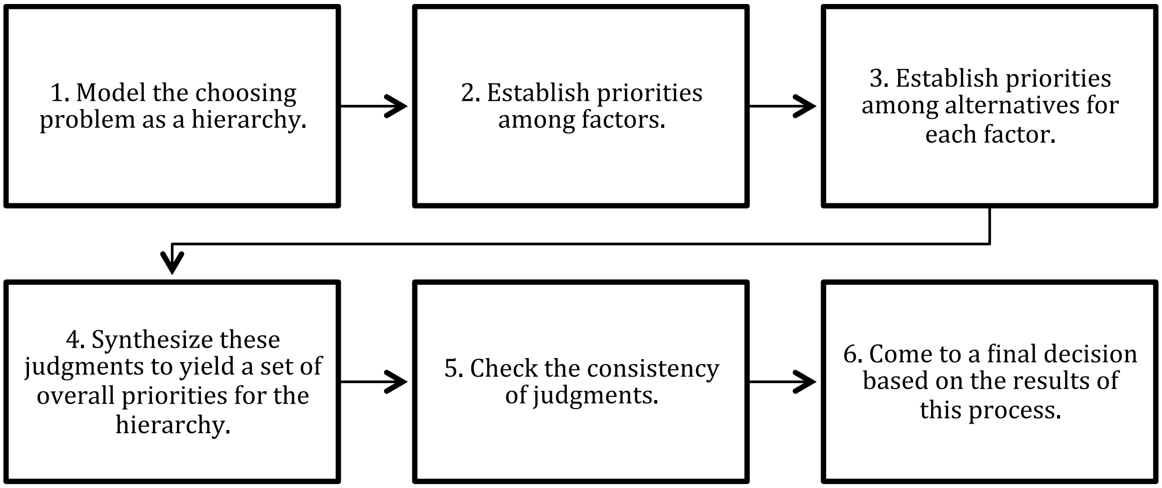


Figure 3.5 Steps in analytical hierarchy process method.

WRC can be described as a simplification of the AHP method. In WRC, the weighting of factors and attributes is done directly. The WRC method can be summarized in the following steps: (1) Identify alternatives. (2) Identify factors and criteria for evaluation. (3) Weigh factors. (4) Rate alternatives for each factor. (5) Calculate the 'value' of each alternative and come to a final decision. Figure 3.6 shows the steps to apply the WRC method.

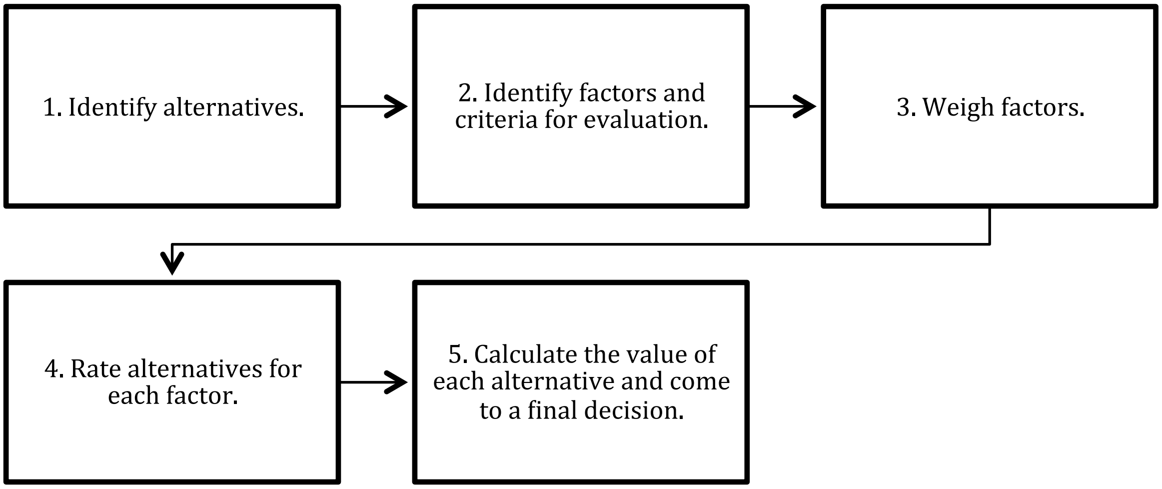


Figure 3.6 Steps in weighting rating and calculating method.

3.2.2.1. Mathematical Description of Value-based Methods

A value-based method can be defined by Equation 3.2.

$U(g^{x}) = w_1U_1(g^{x}_1)+ w_2U_2(g^{x}_2)+ \ldots + w_nU_n(g^{x}_n).$ Equation 3.2

Where:

- x is an alternative
- $U_{X1}, U_{X2}, \ldots, U_{Xn}$ are the marginal utility functions of alternative x corresponding to n factors evaluated according to their criteria.

- g^x is the vector of the attributes of the alternative x for each factor, $g^x = (g^x{}_1, g^x{}_2, g^x{}_3, \ldots, g^x{}_n)$.
- $w_1, w_2, .. w_n$ are the weights representing the trade-offs between different factors. Where $\sum_{i=1}^{n} w_i = 1$.

In many applications the utility function is linear in value-based methods (as is in the case of AHP), and is defined as:

- $U(g^x) > U(g^{x'}) \Leftrightarrow x > x'$ (alternative x is preferred to alternative x')
- $U(g^x) = U(g^{x'}) \Leftrightarrow x = x'$ (alternative x is indifferent or equally preferred as to alternative x')

Different value-based methods vary in how they construct the marginal utility functions (or the 'value' assigned to the attributes) $U_{X1}, U_{X2}, \ldots, U_{Xn}$ and how they construct the weighting of factors (w_i).

According to Belton and Stewart (2002), the marginal utility functions $U_{X1}, U_{X2}, \ldots, U_{Xn}$ can be obtained in three different ways:

1. Definition of a partial value function: decision makers define a function that gives a 'value' to the attributes in terms of a measurable scale according to a criterion.
    a. The definition of the function can be direct:
        i. The function can be monotonically increasing according to a natural ratio scale
        ii. The function can be monotonically decreasing according to a natural ratio scale
        iii. The function can be non-monotonic, i.e., an intermediate point in the scale defines the most or least preferred attribute.
    b. The definition of the function can be indirect when no natural scale exists (von Winterfeldt and Edwards 1986, and Watson and Buede 1988):
        i. Bisection method: in this case the worst expected attribute is assigned the least 'value' and the best expected attribute is assigned the most 'value'. Then decision makers need to identify the point on the attribute scale, which is half way, in 'value' terms, between the two extreme attributes. The next step is to find the midpoints between the two created segments.
        ii. Difference method: in this case decision makers consider increments in the attribute scale in order to assign value to those differences. This ranking gives an idea of the shape of the 'value' function.
2. Construction of a qualitative scale: the values assigned to the attributes are assessed by reference to descriptive explanations of desirable characteristics, which represent a 'value' scale.
3. Direct rating of the alternatives: no attempt is made to define a scale in which the 'values' assigned to the attributes are independent of the alternatives being evaluated. The decision makers simply specify a number or a position in a visual scale, which reflects the 'value' of the alternatives in relation to a specified reference point.

The AHP method recommends that decision makers normalize quantitative attributes, assuming a linear function according to a natural ratio scale, and compare qualitative attributes in a pairwise fashion using a relative scale.

In WRC decision makers can use any of the three approaches for finding marginal utility functions. However, in many applications decision makers use linear marginal utility functions, using either a monotonically increasing or decreasing function according to a natural ratio scale.

The process of assigning weights to factors (w_i), namely ‘importance weights’, has been the focus of extensive debate. Many agree that not every factor has the same weight in a decision, but the question is how to assign those weights in a meaningful way. The AHP method requires decision makers to establish priorities by pairwise comparison of factors. The WRC method allows for direct weighting of factors. In both cases, decision makers are required to answer questions such as what is more important in choosing a light bulb, energy efficiency or light quality? Usually decision makers will be able and willing to provide an answer and assign a numerical rating or weighting to factors, such as “energy efficiency is 3 times more important than light quality” or “energy efficiency weights 40% and light quality weights 20% out of 100% for all the factors”. However, according to Belton and Stewart (2002 p. 134) “it has been argued by many that the responses to such questions are essentially meaningless. The questions are open to many different interpretations, people do not respond to them in any consistent manner and responses do not relate to the way in which weights are used in the synthesis of information”.

Belton and Stewart (2002) present ‘swing weight’ as an alternative to ‘importance weight’, which is an attempt to provide a better-defined concept to represent a scaling factor that relates ‘values’ from one factor to another.

- Swing weight method: the ‘swing’ is considered from the worst value to the best value (i.e., form $U_i(g^{x}_i)$ to $U_i(g^{x'}_i)$, where alternative x has the worst attribute for factor i and alternative x’ has the best attribute for factor i according to a given criterion). The decision makers are asked to analyze which ‘swing’ gives the greatest increase in overall value, then this factor will have the highest weight (w_i). The process is repeated on the remaining set of criteria, until the order of the value resulting from a ‘swing’ of every factor from worst to best has been determined.

3.2.2.2. Value-Based Method Example: Choosing a Light Bulb

This example shows how the WRC method works when using direct weighting of factors and linear marginal utility functions. In this case, decision makers need to assign w_i (weights of factors). The second column of Table 3.5 shows w_i. The marginal utility functions for factors energy efficiency and light quality were calculated linearly using a natural scale for valuing attributes from 0 to 5, where 5 is the best score. The marginal utility functions for factors readiness, safety, and look were directly rated using a scale from 0 to 5. Finally, the total score is calculated using Equation 3.2. In this case the solution will be alternative 3, LED light bulb.

Table 3.5 Using value-based method to choose a light bulb.

Factor	**Weight**	**Alternative 1** **Incandescent**	**U**	**Alternative 2** **CFL**	**U**	**Alternative 3** **LED**	**U**
Energy efficiency (Lm/W)	30%	14 Lm/W	1.1	60 Lm/W	4.7	64 Lm/W	5.0
Readiness (Turn on Instantly)	10%	Turns on instantly	5	Turns on within a second, and takes 30 to 60 seconds to achieve full brightness	3	Turns on instantly	5
Safety (Mercury content)	30%	No mercury	5	4 mg mercury /bulb	2	No mercury	5
Light quality (CRI)	20%	100	5	82	4.1	93	4.7
Look	10%	Nice	4	Very nice	5	Ugly	2
Total U	100%		3.7		3.6		4.4

3.2.2.3. Method Assumptions

Some of the assumptions of value-based methods are:

- Marginal utility functions (U_{X1}, U_{X2}, …, U_{Xn}) exist and usually are based on the assumption that attributes have a natural scale.
- Factors can be weighted. That means that decision makers can prefer one factor (high order abstraction concept) over another.
- Factors can be identified and weighted independently of alternatives' attributes, except when the 'swing weight' method is used.
- Cost can be a factor

Assumptions specific to AHP are:

- Quantitative attributes can be normalized assuming a natural ratio scale.
- Factors are independent, so the conversion rates (w_i) between factors (for integrating the utility function) are constant.

3.2.2.4. Discussion

Value-based methods may have different impacts depending on how the design team constructs the weight of factors (w_i) and marginal utility functions. The method may not help in creating transparency, building consensus, and continuous learning if the design team directly assigns weights to factors without using the 'swing weight' method or if they assume linear marginal utility functions. Some of the issues include:

- *Creating transparency:* The overall score of the alternatives provides a rationale for choosing an alternative. However, (1) When using fixed weights during the evaluation of alternatives, stakeholders assume that trade-offs between factors are fixed. For example, an increment in the marginal utility of 'light quality' is always twice as valuable as an increment in ‘readiness’. However, this may not always reflect reality. For example, increasing CRI over 90 for ‘light quality’ may not be more valuable. (2) In addition, assuming that every increment in the marginal utility of ‘light quality’, or any factor, is the same, may not always reflect reality. For example, a difference in CRI from 80 to 90 may be more valuable than an increment from 90 to 100. (3) The differences between alternatives may not be highlighted if factors that do not differentiate between alternatives are given high weights, which can mask the true difference between alternatives. (4) Cost can be a factor, which allows for mixing cost and ‘value’ of the alternatives. If that is the case, the design team may not be able to make an analysis of ‘value’ vs. cost.

- *Building consensus:* In this case the design team needs to reach consensus on the weight of the factors and the ranking of attributes. (1) Agreeing on which factors and criteria have more weight may be a source of conflict, especially when members of the design team have different interests. As discussed, factors do not represent specific judgments but general categories. (2) Factors can be weighted regardless of the attributes of the alternatives by basing the weights on previous experiences. Therefore, the design team may miss the context of the particular decision. (3) In terms of managing subjectivity in this case, the design team would need to assign weights to factors and criteria first, which is a subjective task. Then, they would need to rate the alternatives for each factor, according to their attributes, which is also a subjective task. Although the calculation is objective, it is based on subjective scales.
- *Continuous learning:* This method provides an overall ranking of the alternatives. Therefore, (1) The design team can have a score representing the ‘value’ of the discarded alternatives. However, the advantages of the discarded alternatives may not be highlighted. (2) If a new alternative is added, its attributes need to be rated, and the design team may apply the same weights to factors. In contrast, if the team applies the ‘swing weight’ method the weights may change to better represent the decision context. (3) When new factors are added, they need to be assigned a weight, which may change the weight of the previous factors if the design team uses a fixed scale (e.g.,$\sum_{i=1}^{n} w_{\mathrm{i}} = 1$, such in AHP). Then a calculation is required to evaluate all alternatives according with the new weights of factors. (4) Multiple decisions can be compared using ‘value’ vs. cost. However, cost cannot be a regular factor, and the scale of the ‘value’ for each decision may need to be readjusted for comparison with other decisions.

The rationale for choosing a LED light bulb using the example above (Figure 3.6) can be documented as: *The LED light bulb was chosen because it has the better overall score of 4.4 points vs. CFL that has 3.6 and Incandescent that has 3,7 points.* That rationale is enough for supporting the decision. However, the differences between attributes of the alternatives may not be highlighted.

3.2.3. Outranking Methods

The outranking methods differ from value-based methods in that they do not have an aggregative value function, in which alternatives can be scored in an overall ranking. The result of the outranking methods is not a score for each alternative, but a determination that one alternative in a set outranks the others. “Alternative ‘a’ is said to outrank another alternative ‘b’ if, taking account all available information regarding the problem and the decision-maker’s preferences, a strong enough argument that ‘a’ is at least as good as ‘b’ and no strong argument to the contrary” (Belton and Stewart 2002 p. 233).

Outranking methods use pairwise comparisons to assess preferences, indifferences, and incomparabilities between alternatives. For example, if alternatives ‘a’ and ‘b’ are compared for a factor with a criterion i, several outcomes are possible: ‘a’ can be preferred to ‘b’ in regard to criterion i, ‘b’ can be preferred to ‘a’, ‘a’ and ‘b’ can be indifferent, or ‘a’ and ‘b’ can be incomparable due to lack of information.

Even though this method requires ranking of factors, weights do not represent trade-offs. According to Doumpos and Zopounidis (2002), the main two differences between value-based methods and outranking methods are:

- Outranking relation is not transitive. This means that it enables the modeling and representation of situations when transitivity does not hold.
- Because of possible incomparability, the outranking relation is not complete.

Roy created and first used ELECTRE in 1965, which is one of the best-known outranking methods. Roy (1991) describes ELECTRE as a method that provides weaker preference models than value-based methods. ELECTRE is built with less effort, and fewer hypotheses than value-based methods, but does not always allow for a conclusion to be drawn. ELECTRE can be described in the following steps (Figure 3.7): (1) Define factors and criteria for evaluation. (2) Weigh factors. (3) Define scales for attributes and ‘veto’ thresholds. (4) Calculate concordance and discordance index. (5) Construct outranking relations. (6) Arrive at a final decision if enough evidence to support the superiority of one alternative exists.

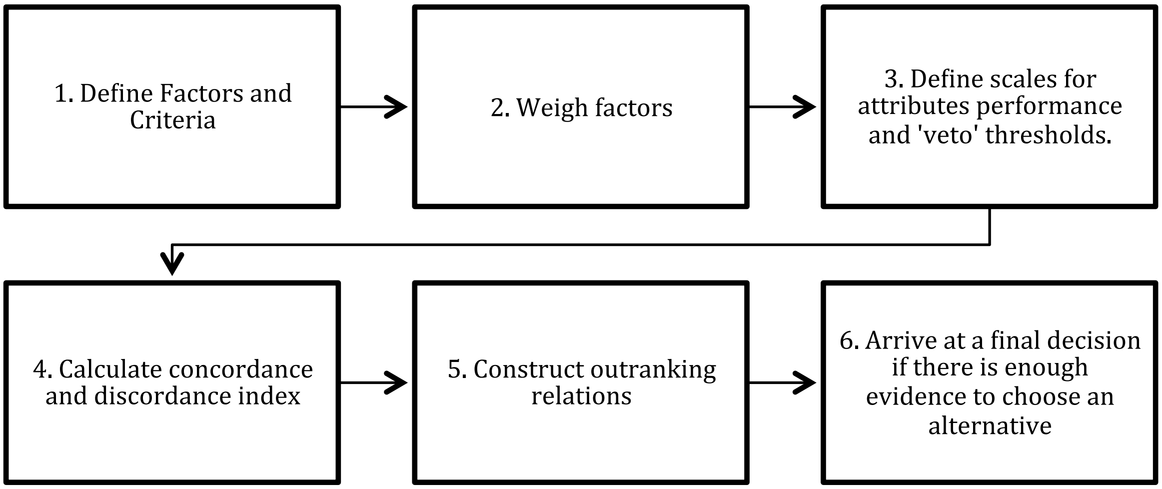


Figure 3.7 Steps in ELECTRE, an outranking method.

3.2.3.1. Mathematical Description

The emphasis is on strength of evidence for the assertion that alternative ‘a’ is at least as good as alternative ‘b’.

Decision makers need to set an indifference threshold (Rogers and Bruen 1998). Alternative ‘b’ is weakly preferred to ‘a’ in terms of factor i if:

$Z_i(b) > Z_i(a) + q_i[Z_i(a)]$

Alternative ‘b’ is strictly preferred to ‘a’ in terms of factor i if:

$Zi(b) > Zi(a) + pi[Zi(a)]$

For consistency, $pi[Zi(a)] > qi[Zi(a)]$.

Where,

- $Z_i(a)$ is the partial preference function, similar to a utility function, of alternative ‘a’ with regards to factor i

The outranking relation is constructed by considering the concordance and discordance indices. The concordance index between alternatives ‘a’ and ‘b’, symbolized by $C(a,b)$, represents the strength of support provided by the available information, for the hypothesis that alternative ‘a’ is at least as good as alternative ‘b’. This index takes a value between 0 and 1; higher values represent stronger evidence that ‘a’ is superior to ‘b’.

$$C(a,b) = \frac{\sum_{i \epsilon Q(a,b)} w_j}{\sum_{i=1}^{m} w_j} \qquad \text{Equation 3.3}$$

Where $Q(a,b)$ is the set of factors in which ‘a’ is equal or preferred to ‘b’, and w_j is the weight of the factor j.

The discordance index between alternatives ‘a’ and ‘b’, symbolized by $D(a,b)$, represents a ‘veto’, in the sense that if the $Z_i(a)$ is below a minimum acceptable level or the difference between $Z_i(b) - Z_i(a)$ is greater than some threshold, then ‘a’ can not outrank ‘b’. This is analyzed for every factor regardless of the weight of the factor.

$$D(a,b) = \begin{bmatrix} 1\ if\ Zi(b) - Zi(a) > ti\ for\ any\ i \\ 0\ otherwise \end{bmatrix} \qquad \text{Equation 3.4}$$

Then outranking relations are constructed. First, decision makers need to specify concordance and discordance thresholds, C* and D* respectively. Alternative ‘a’ outranks alternative ‘b’ if $C(a,b) \geq C*$ and if $D(a,b)\ is \leq D*$. The values of C* and D* will determine how strict the outranking relation is.

3.2.3.2. Outranking Method Example: Choosing a Light Bulb

The first part of the problem will be very similar to a value-based method. Decision makers need to define the weight and $Z_i(a)$ for each factor i and alternative (Table 3.6).

Table 3.6 Weights of factors and $Z_i(a)$ for the outranking method.

Factor	**Weight**	**Alternative 1 Incandescent**	**Z**	**Alternative 2 CFL**	**Z**	**Alternative 3 LED**	**U**
Energy efficiency (lm/W)	30%	14 Lm/W	1.1	60 Lm/W	4.7	64 Lm/W	5.0
Readiness (Turn on Instantly)	10%	Turns on instantly	5	Turns on within a second, and takes 30 to 60 seconds to achieve full brightness	3	Turns on instantly	5
Safety (Mercury content)	30%	No mercury	5	4 mg mercury /bulb	2	No mercury	5
Light quality (CRI)	10%	100	5	82	3	93	4
Look	20%	Nice	4	Very nice	5	Ugly	2

With this information, the design team can measure the concordance index for each pair of alternatives. C(alt.1,alt.2) represents the strength of support from the information given, for the hypothesis that alternative 1 is as good as alternative 2, and it is measured by the relative weights of the factors in which alternative 1 is as good as alternative 2 divided by the total weight of factors (Equation 3.3). For example, C(alt.1,alt.2) = (10%+30%+10%)/(100%) = 0.5. Table 3.7 presents the concordance indices.

Table 3.7 Concordance indices.

	Alternative 1 Incandescent	**Alternative 2 CFL**	**Alternative 3 LED**
Alternative 1: Incandescent	1	0.5	0.7
Alternative 2: CFL	0.5	1	0.002
Alternative 3:LED	0.7	0.8	1

Decision makers need to establish preference thresholds including ‘veto’ references, represented by t_i. In this example we will define $t_i = 3$ (Equation 3.4). Thus, alternative ‘a’ cannot outrank ‘b’ if $Z_i(b) - Z_i(a)$ is greater than 3. For example, the difference in energy efficiency of alternative 2 vs. alternative 1 (4.7-1.1 = 3.6) is greater than 3. Therefore, alternative 1 cannot outrank alternative 2. Table 3.8 presents the discordance indices. An entry of 1 in D(a,b) indicates that ‘a’ cannot outrank ‘b’.

Table 3.8 Discordance indices.

	Alternative 1 Incandescent	**Alternative 2 CFL**	**Alternative 3 LED**
Alternative 1: Incandescent	-	1	1
Alternative 2: CFL	1	-	1
Alternative 3:LED	0	0	-

Finally, decision makers need to construct the outranking relations, in this example C*=0.6, and D*=0.1. However, from the discordance index we can see that alternative 1 cannot outrank alternatives 2 or 3, and alternative 2 cannot outrank alternatives 1 or 3. Therefore, alternative 1 and alternative 2 are incomparable. To solve the problem one must ask if alternative 3 outranks alternatives 1 and 2. The answer is yes because C(Alt.3,Alt.1)>C*, D(Alt.3,Alt.1)<D*, C(Alt.3,Alt.2)>C*, and D(Alt.3,Alt.2)<D*. Figure 3.8 presents the final outranking relationship. The final decision should be to choose alternative 3.

Figure 3.8 Outranking relationship for light bulb example.

3.2.3.3. Method Assumptions

Outranking methods assume that decision makers can ‘quantify’ their preferences, but it uses relations in a pairwise comparison of factors to construct preferences.

Outranking methods also assume that preferences and values are often not pre-existing but are formed within a particular decision-making context. This is the usual case in group decision making in building design. Outranking methods help decision makers to construct their preferences.

- It also assumes that factors can be weighted, although it does not use them in the same way as value-based methods.
- Cost can be a factor.

3.2.3.4. Discussion

The assumptions of this method have several consequences.

- *Creating transparency:* (1) Decision makers can only provide an outranking relation among the alternatives. Therefore, it is not clear what the trade-offs were among attributes of the alternatives. This is especially true when more factors and alternatives are incorporated in the decision. (2) The differences between alternatives are used to construct the preferences but may not be highlighted. (3) Cost can be a factor, and influence the outranking relation. This method provides an outranking relation, but not an overall ‘value’ of the alternatives making it impossible to make an analysis of 'value' vs. cost as in the case of multi-objective optimization methods (when based on rank of factors).

- *Building consensus:* In this case the design team needs to reach consensus in the weighting of factors and the rating of attributes. Even when the factors are not used in the same way as that the value-based methods, they are required to construct the outranking relationship. However, (1) As discussed before, agreeing on which factor and criterion is more important is subjective. (2) The design team is more likely to base weights on the attributes of the alternatives. (3) In terms of managing subjectivity in this case, the design team would need to assign weights to factors and criteria, and rank attributes, which may be a subjective task, and then compare the alternatives, which is a more objective task.
- *Continuous learning:* (1) This method does not provide an overall ranking of the alternatives. Therefore, the advantages of the discarded alternatives may not be visible. (2) If a new alternative is added, all outranking relationships need to be calculated for that alternative. (3) If a new factor were added, the design team would need to assign a weight to it and recalculate the outranking relationship of all alternatives. (4) Multiple decisions may not be compared using this method.

The rationale for choosing a LED light bulb using the example above can be documented as: *The LED light bulb was chosen because it outranks CFL and incandescent lights, and there is no evidence that CFL or Incandescent light bulb outrank LED.*

3.2.4. Choosing By Advantages

Choosing By Advantages (CBA) is a system to make decisions using well-defined vocabulary to ensure clarity and transparency in the decision-making process (Suhr 1999). According to this system, it is important to identify which factors will reveal significant differences between alternatives, not what factor (in the abstract) will be important in the decision (Koga 2008, Suhr 1999, 2000, 2008, 2009, and Suhr et al. 2003).

CBA decisions are based on Importance of Advantages (IofAs), not advantages and disadvantages, thereby avoiding a common way of double counting factors. Once the advantages of each alternative are found, stakeholders need to assess the importance of these advantages making comparisons among them. The weighting process should be only on the advantages, not criteria, attributes, or other types of data (Suhr 1999, p.80)

The CBA system has four principles: (1) decision makers must learn and skillfully use sound methods of decision making; (2) decisions must be based on the importance of the advantage; (3) decisions must be anchored to the relevant facts; (4) different types of decisions call for different sound methods of decision making.

In addition, CBA anchors decisions to relevant facts (principle 4). As stated in Parrish and Tommelein (2009): "Attributes are inherent to an alternative, so summarizing them does not involve subjective judgment. Determining the advantages of each alternative does not require subjective judgment itself, though advantages may depend on the 'want' criteria in a given factor, which are subjective. Assigning a degree of importance to each advantage is the first task that requires decision makers to make 'value' judgments about alternatives, and CBA postpones it as long as possible."

CBA includes methods for virtually all types of decisions, from very simple to very complex. Suhr (1999) presents *instant CBA* for simple decisions involving two mutually exclusive alternatives, *two-list method* for two mutually exclusive alternatives of equal cost, and the *tabular method* for moderately complex decisions involving more than two mutually exclusive alternatives. Other CBA methods exist for nonexclusive proposals where a proposal consists of two or more nonexclusive plans. The researcher will explore the tabular method for moderately complex decisions, which is appropriate for the "choosing problem" in building design because it includes mutually exclusive alternatives that do not necessarily have the same cost.

CBA Tabular method divides the decision-making process in five phases: (1) the stage-setting phase, (2) the innovation phase, (3) the decision-making phase, (4) the reconsideration phase, and (5) the implementation phase.

The CBA Tabular method for moderately complex decisions can be summarized in 7 steps. In step 1, Stakeholders identify alternatives likely to yield important advantages over other alternatives. In step 2, they have to define factors to evaluate attributes of alternatives. In step 3, stakeholders need to agree on the criteria for each factor. Criteria can be either a desirable (want) or a mandatory (must) decision rule. In step 4, stakeholders summarize the attributes of each alternative. In step 5, they decide the advantages of each alternative. In step 6, they decide the importance of each advantage. Stakeholders need to explicitly state their preferences for the advantages. They have to select the paramount advantage, which is the most important advantage and is usually assigned 100 points. However, the choice of scale does not distort the evaluation; the higher score is assigned to the paramount advantage and is used as a reference point to compare to other advantages. Then stakeholders need to assign importance of other advantages based on a scale defined by the selection of the paramount advantage. It is not assumed that advantages are independent; therefore, similar advantages can be grouped or one advantage can be assigned zero importance if stakeholders estimate it does not provide any additional 'value'. The importance of advantages for each alternative is summed, and finally, stakeholders evaluate cost data in step 7. Figure 3.9 summarizes the 7 steps.

In order to apply CBA correctly, decision makers need to have a clear, accurate, sensory-reach perception of each advantage (Suhr 1999). According to Suhr, 3 principles that need to be respected in the weighting of advantages. The principles are:

1. No such thing as zero advantage exists. Therefore, in a table display rationale non-advantage and its non-importance are represented as blank spaces.
2. All the advantages of all the alternatives must be assigned a weight on the same scale of importance, and that is the only purpose of selecting a paramount advantage. Selecting the paramount advantage establishes a scale of importance for the decision.
3. Decision-making is not a branch of mathematics. Therefore, we must decide, not calculate, the importance of each advantage, based on the following 4 considerations.

Suhr (1999) describes four basic considerations in the process of assigning importance to the advantages that decision makers must understand, in addition to other considerations that may appear.

1. The purpose and circumstances of the decision. CBA is context based. Therefore, the CBA process begins with identifying a purpose to be achieved. Alternatives are judged based on the circumstances of the decision.
2. The understanding of customer needs. The needs and preferences of the customers and other stakeholders, including those who will be affected by the decision and others who will be interested in the decision.
3. The magnitudes of the advantages. An advantage of almost zero has an importance of almost zero. Bigger advantages usually should have bigger importance.
4. The magnitudes of the scales associated with the attributes. Usually the relationships between attributes, advantages and importance of advantages are nonlinear.

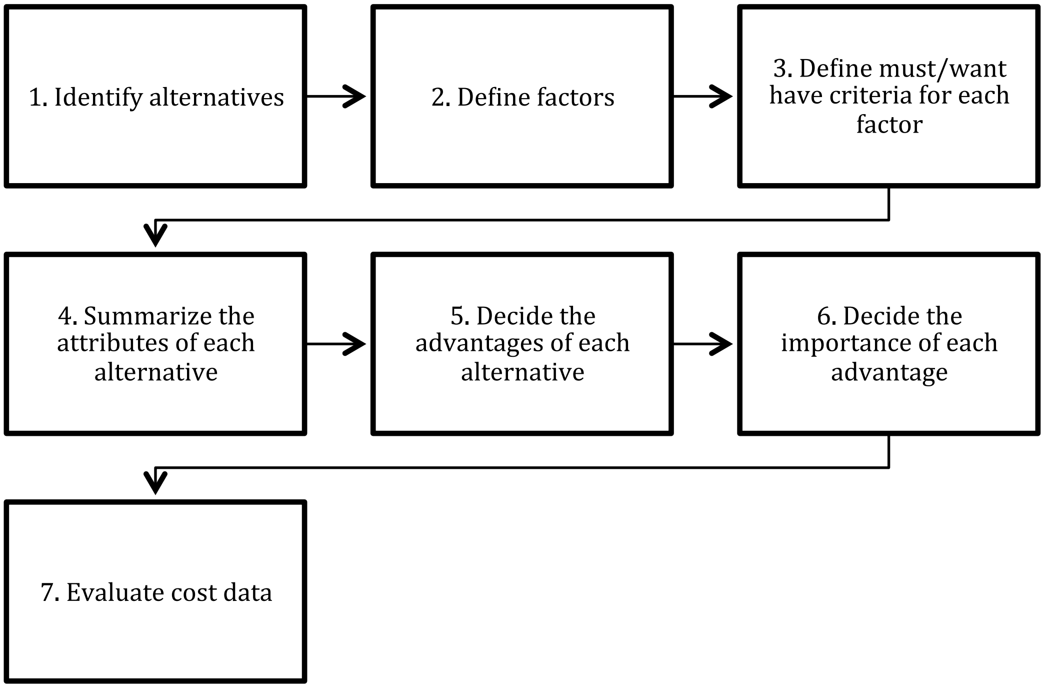


Figure 3.9 Steps in choosing by advantages method (Adapted from Suhr 1999).

A practical way of assigning IofAs to advantages is to write them in post-it notes, then draw a scale from 0 to 100 (or any other convenient scale, as defined by the paramount advantage), and place the notes according to their importance relative to others. The first task is to identify the most important advantage for each criterion and then choose the paramount advantage from them.

By using the CBA method, the design team can develop a chart that represents cost (e.g., cost of material per ft^2, cost of installation per ft^2, life-cycle cost, etc.) vs. importance of advantages. Figure 3.10 presents an analysis of ‘value’ vs. cost, each dot represents an alternative. This chart provides decision-making information. The design team needs to make trade-offs between the cost of the alternatives and the Importance of the Advantages (IofA). For example, in Figure 3.10 if the project has a budget of 8, the team will choose Alternative 1 because it has more IofAs for less cost compared to Alternatives 2, 4, and 5. In addition, alternative 3 has more IofAs than Alternative 1, but is not under the budget cost. The design team should analyze if it is worth it to spend the extra money to obtain the most Advantageous Alternative.

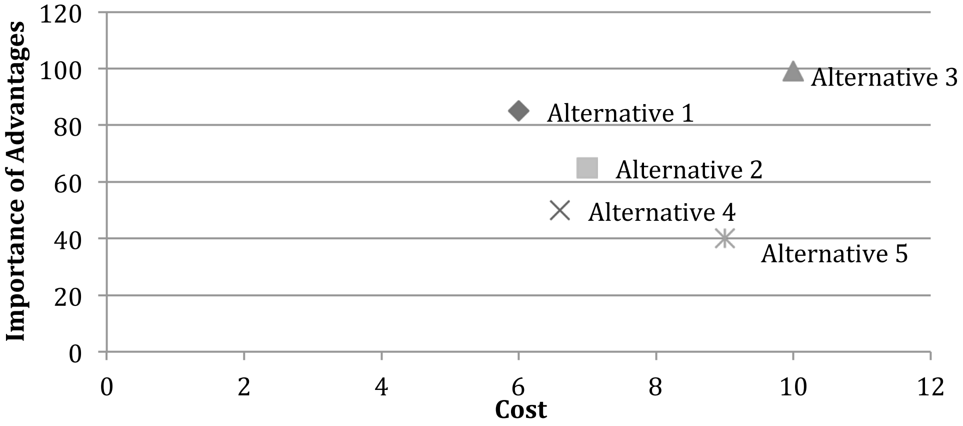


Figure 3.10 Example of cost vs. importance of advantages chart.

This process is highly collaborative; the design team should be involved at every stage and consider interactions with other building systems. Once an alternative has been selected, the design team will re-examine their selection as a whole, one more time, incorporating a holistic analysis into the sustainability decision-making process. This phase is called the reconsideration phase (4), in which decision makers may raise questions. For example, ‘Are there any additional alternatives that should be considered?’, ‘Does the importance score accurately represent the viewpoint of the stakeholders?’, or ‘How is the whole building design optimized by choosing a set of alternatives considering multiple building systems?’

The use of rhetoric and CBA to facilitate the decision-making process is also explored in this research. Section 6.7 presents an example that evaluates the use of rhetorical tools when applying CBA.

3.2.4.1. Mathematical Description

The emphasis of CBA method is on the positive differences (advantages) between alternatives. An advantage is the beneficial difference between attributes of two alternatives (one of which is the least preferred)

- Advantage:
  - $Ag^x_i = |g^x_i - g^o_i|$, Advantage of alternative X over the worst alternative for factor i.
- Where,
  - g^o_i is least preferred attribute for factor i.
  - In contrast with most other methods, CBA does not require w_i or $U(g)$. It requires making trade-offs between advantages, which is based on the particular decision-making context.
- Equation 3.5 describes the total importance of advantages of alternative x.

$$I(g^x)=I_1(Ag^x_1)+ I_2(Ag^x_2)+ \ldots + I_n(Ag^x_n) \qquad \text{Equation 3.5}$$

In order to obtain $I_i(Ag^x)$, stakeholders are asked to set a reference point, the paramount advantage $I(Ag)^*$. Then all $I_i(Ag^x)$ are compared against $I(Ag)^*$.

Then

- $I(Ag^x) > I(Ag^{x'}) \Leftrightarrow x > x'$ (alternative x is preferred to alternative x')
- $I(Ag^x) = I(Ag^{x'}) \Leftrightarrow x = x'$ (alternative x is indifferent to alternative x')

3.2.4.2. CBA Method Example: Choosing a Light Bulb

Decision makers describe advantages based on factors and criteria established in the first column of Table 3.9.

Table 3.9 Using CBA method to choose a light bulb.

Factor (Criterion)	**Alternative 1: Incandescent**		**Alternative 2: CFL**		**Alternative 3: LED**	
Energy Efficiency (Lumens/watt)	Att.: 14 Lm/W		Att.: 60 Lm/W		Att.: 64 Lm/W	
(Higher is better)	Adv.:	Imp.:	Adv.: 46 LM/W higher than alt 1	Imp.: 90	Adv.: 50 LM/W higher than alt 1	Imp.: 100
Readiness	Att.: Turns on instantly		Att.: Turns on within a second, and takes 30 to 60 seconds to achieve full brightness		Att.: Turns on instantly	
(Turn on instantly is better)	Adv.: turns on instantly vs. slight delay	Imp.:10	Adv.:	Imp.:	Adv.: turn on instantly vs. slight delay	Imp.:10
Safety	Att.: No mercury		Att.: 4 mg mercury/ bulb		Att.: No mercury	
(No mercury content is better)	Adv.: it as no mercury vs. 4mg/bulb	Imp.:10	Adv.:	Imp.:	Adv.: it has no mercury vs. 4mg/bulb	Imp.:10
Light Quality	Att.: 100 CRI		Att.: 82 CRI		Att.: 93 CRI	
(Higher is better)	Adv.: 18 more CRI points than alt. 2	Imp.:50	Adv.:	Imp.:	Adv.: 9 more CRI points than alt. 2	Imp.: 45
Look	Att.: Nice		Att.: Very nice		Att.: Ugly	
(Nicer is better)	Adv.: nicer than alt. 3	Imp.:10	Adv.: much nicer than alt. 3	Imp.:10	Adv.:	Imp.:
Total IofAs		80		110		165

Then they weigh the advantages represented in a scale of importance (IofA). In this case, using a scale of IofA from 0 to 100, where 100 is assigned to the most important advantage, also known as the paramount advantage (here 64 Lm/W vs. 14 Lm/W). In order to assign IofA to other advantages, decision makers compare the advantages to the paramount advantage. Finally, decision makers can sum the IofAs of each alternative and come to a conclusion. In this case alternative 3 has the higher IofAs.

3.2.4.3. Method Assumptions

CBA assumes that decision makers can 'quantify' their preferences. However, CBA requires decision makers to identify the advantages of alternatives prior to constructing their preferences.

- CBA assumes that advantages can be weighted based on pairwise comparisons with other advantages. Therefore, it is possible to aggregate advantages.
- In contrast with most other methods, CBA does not require factor weights (w_i) or attribute weights (U). Trade-offs are made directly among advantages.
- Cost cannot be a factor.

3.2.4.4. Discussion

The assumptions of this method have several consequences.

- *Creating transparency:* (1) Decision makers can provide a rationale for the decision and state what the trade-offs were among attributes of the alternatives. (2) The differences between alternatives are used to construct the advantages and those are highlighted. (3) Cost cannot be a factor, and is it possible to make an analysis of 'value' vs. cost.
- *Building consensus:* In this case the design team needs to reach consensus in the weighting of advantages and criteria for evaluation. (1) The method may help in building consensus when the design team agrees on the advantages of the alternatives, based on the difference between their attributes. However, it may be challenging for the design team to agree on the importance of the advantages. (2) The design team is more likely to base decisions on attributes of the alternatives. (3) In terms of managing subjectivity in CBA the design team compares known attributes, which is an objective task, and then weighs the advantages, which is a subjective task.
- *Continuous learning:* (1) This method provides an overall ranking of the alternatives and provides advantages of the discarded alternatives. (2) If a new alternative is added, the design team needs to describe and assign a weight to its advantages. (3) If a new factor and criterion is added, the design team needs to assess which alternatives have advantages for that factor, and weight the importance of these advantages. (4) Multiple decisions can be compared using this method.

The rationale for choosing a LED light bulb using the example above can be documented as: *The LED light bulb provides more important advantages than CFL and incandescent lights. The LED light bulb has 50 lm/W more than the incandescent one (65 lm/W vs. 14 Lm/W); the LED light bulb turns on instantly vs. CFL turns on within a second and takes 30 to 60 seconds to achieve full brightness; the LED light bulb has no mercury vs. CFL has 4 mg/bulb; and the LED light bulb has 93 CRI vs. CFL has 82 CRI.* The advantages of the discarded alternatives are also highlighted: *The CFL bulb has 46 lm/W higher than* *the incandescent one (46 lm/W vs. 14 Lm/W); and The CFL bulb is much nicer than the LED bulb. Finally, the incandescent light bulb turns on instantly vs. CFL turns on within a second and takes 30 to 60 seconds to achieve full brightness; the incandescent light bulb has no mercury vs. CFL has 4 mg/bulb; the incandescent light has 100 CRI vs. CFL has 82 CRI; and the incandescent light bulb is nicer than the LED bulb.* In this way all relevant differences are highlighted. In CBA the attributes of the alternatives are not translated to any other scale, and the comparisons among alternatives are made using the original attributes units.

3.3. Conclusions

In light of the differences between MCDM methods, the researcher concludes that:

- Multi-objective optimization methods that rank factors do not seem to create transparency because they do not make explicit trade-offs. Achieving consensus on the ranking of factors may be challenging. These methods do not provide enough guidance to make an analysis of 'value' vs. cost, which would be helpful for continuous learning. Therefore, these methods are not recommended for choosing a sustainable alternative, when few alternatives are evaluated and where attributes are known. The researcher agrees with Belton and Stewart (2002), who recommend multi-objective optimization methods to identify a small set of alternatives from a large or even infinite set for more detailed evaluation. However, decision makers need to be aware that the ranking of factors and criteria will affect the outcomes.
- Value-based methods may not create transparency, especially when assuming linear trade-offs. Also value-based methods may not help in building consensus if when assigning weights to factors decision makers do not consider the differences between alternatives. These methods allow for an analysis of 'value' vs. cost, which is important for continuous learning and for comparing multiple decisions.
- Outranking methods in this context do not seem to create transparency because trade-offs are not clear. These methods may help in building consensus because the weight of factors is used for constructing concordance and discordance indices and not for directly assigning weights to attributes. However, the design team still needs to agree on the weighting of the factors. These methods do not produce a final ranking of the alternatives. Therefore, it is not possible to evaluate 'value' vs. cost of alternatives, and this may be detrimental for continuous learning, especially when multiple iterations may be required.
- CBA methods help in creating transparency in the trade-offs by focusing on the advantages of the alternatives. CBA methods help in building consensus because they base judgments on differences between alternatives. However, the weighting of advantages can still be challenging. CBA provides a good basis for continuous learning because it is possible to construct an analysis of 'value' vs. cost. CBA also allows comparing multiple decisions if the scale of IofAs is adjusted.

In the following chapters the researcher will explore more deeply the differences between value-based methods and CBA.

4. COMPARATIVE CASE STUDIES 1 AND 2: ANALYTICAL HIERARCHY PROCESS vs. CHOOSING BY ADVANTAGES

This chapter compares and contrasts the Analytical Hierarchy Process (AHP) with the Choosing By Advantages (CBA) decision-making methods using two case studies. The researcher chose these two methods because AHP is widely used inside and outside the Architecture Engineering and Construction (AEC) industry, and CBA provides important differences. Few academic studies of CBA exist, despite the US Forest Service using CBA since the 1980s, and more recently the AEC industry, especially in the lean construction community, also using CBA.

Table 4.1 defines terms relevant to AHP and CBA. This chapter uses CBA definitions to describe both methods because its language is richer.

Table 4.1 CBA and AHP definitions (Arroyo et al. 2013)

Term	AHP Definition, Saaty 2008b:	CBA Definition, Suhr 1999:
Alternatives	Two or more construction methods, materials, building designs, or construction systems, from which one must be chosen.	
Factor	Elements of the hierarchy usually represented as a tree.	An element, part or component of a decision.
Criterion	AHP makes no distinction between factors and criteria.	A decision rule, or a guideline. It can be a ‘must’ or a ‘want’ criterion.
Attribute	Not defined in AHP. However, it uses normalized performances of alternatives.	A characteristic, quality, or consequence of one alternative.
Advantage	Not defined in AHP.	A benefit, gain, improvement, or betterment. It is a beneficial difference between attributes of two alternatives.

4.1. Comparative Case Study 1: Choosing a Wall System

4.1.1. Introduction

This case study was the first attempt of the researcher to illustrate and compare the application of AHP and CBA. Few researchers have compared these methods before, Parrish (2009), mentioned some of the differences in her PhD dissertation, but with less details, since her focus was set-based design. This case study presents partial applications of AHP and CBA for choosing an exterior wall assembly. The attributes available for comparing the alternatives were generic; therefore, the researcher did not justify any final decision, but compared the steps that the design team would follow in order to apply the two decision-making methods. The researcher published this case study in a paper presented at the Annual Conference of the International Group for Lean Construction (Arroyo et al. 2012a).

4.1.2. Case-Study Background

The case study is hypothetical, and it is not related to any particular construction project. Therefore, the actual design team and the preferences illustrated here are hypothetical as well. However, in order to provide some context to the decision, this case assumes the comparison of different exterior wall assemblies pertains to a one-story commercial building in Northern California, specifically in Berkeley. The researcher assumed that the design team for this decision was the owner, architects, energy consultant, contractor, and users. Therefore, decision makers need to consider multiple perspectives. The researcher also assumed that the design team was facing trade-offs such as trying to minimize embodied energy and maximize thermal control at the same time, while considering durability and buildability.

4.1.3. Case-Study Protocol

The case-study protocol describes the steps that the researcher followed when applying AHP and CBA in choosing exterior wall assemblies.

1. Researched exterior wall assembly data, including available types, characteristics and costs. The researcher extracted information for the alternatives and their attributes from a report published in Building Science (Straube and Smegal 2009).
2. Studied AHP and CBA literature and examples of use, as were presented in Chapter 2.
3. Described alternatives and factors used for applying AHP and CBA based on the information gathered.
4. Developed a partial application of AHP and CBA with the information gathered.

4.1.4. Alternatives, Factors, and Criteria for Evaluation

The researcher compares two alternatives: (1) standard wall construction (Figure 4.1), and (2) double-stud wall construction (Figure 4.2).

The researcher considered the following factors and criteria derived from Straube and Smegal (2009) to represent the desires of the hypothetical design team.

(1) *Thermal Control:* refers to the amount of energy that the building needs to maintain in order to achieve a thermal comfort level for its occupants. This is expressed as a characteristic measured by the R-value of the whole-wall system. The R-value is a measure of thermal resistance, calculated as the ratio of the temperature difference across an insulator and the heat flux (heat transfer per unit area per unit time) through it. The R-value unit used in the US is $^{o}F/(Btu/(hr*ft^2))$. The criterion for selection is the higher the R-value, the better the insulation properties.

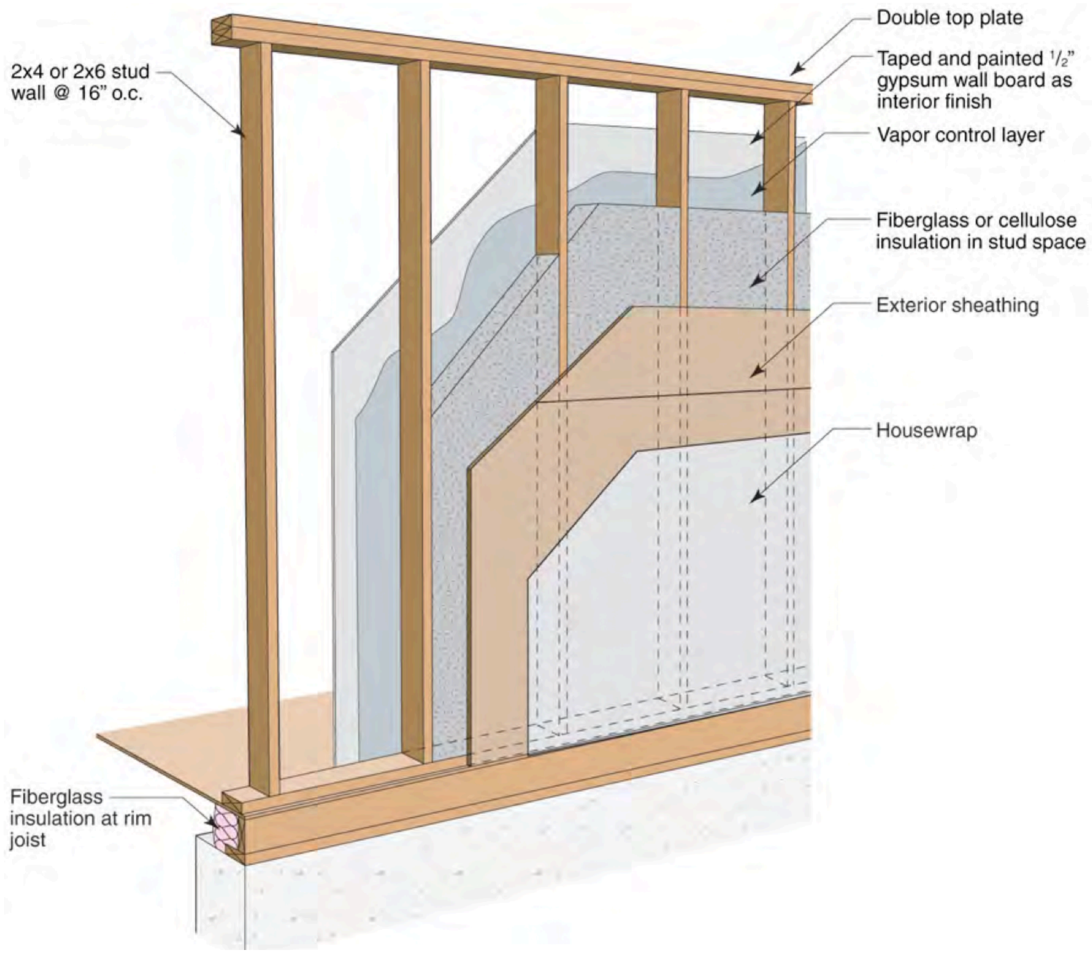


Figure 4.1 Standard wall construction (Straube and Smegal 2009).

(2) *Durability:* refers to how long the building will last, and depends on the ability of the wall to stop rain, moisture, and air leakage. The criterion for selection is the building must last at least 50 years.

(3) *Buildability:* refers to the ease of building the wall assembly considering the current available knowledge in light of Northern California AEC building practices. The criterion for selection is the easier to build, the better.

(4) *Material Use:* refers to the quantity of material used for the wall assembly. This determines the embodied energy of the wall. The criterion for selection is the less material used, the better.

4.1.1. AHP Application

The researcher defined step (1) of the AHP method, which models the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives by providing alternatives and factors for evaluation. This case study focuses on analyzing and discussing step (2) of the AHP method, which establishes priorities among the factors by making a series of judgments based on pairwise comparisons of the elements (Section 3.2.3 for a description of the AHP method).

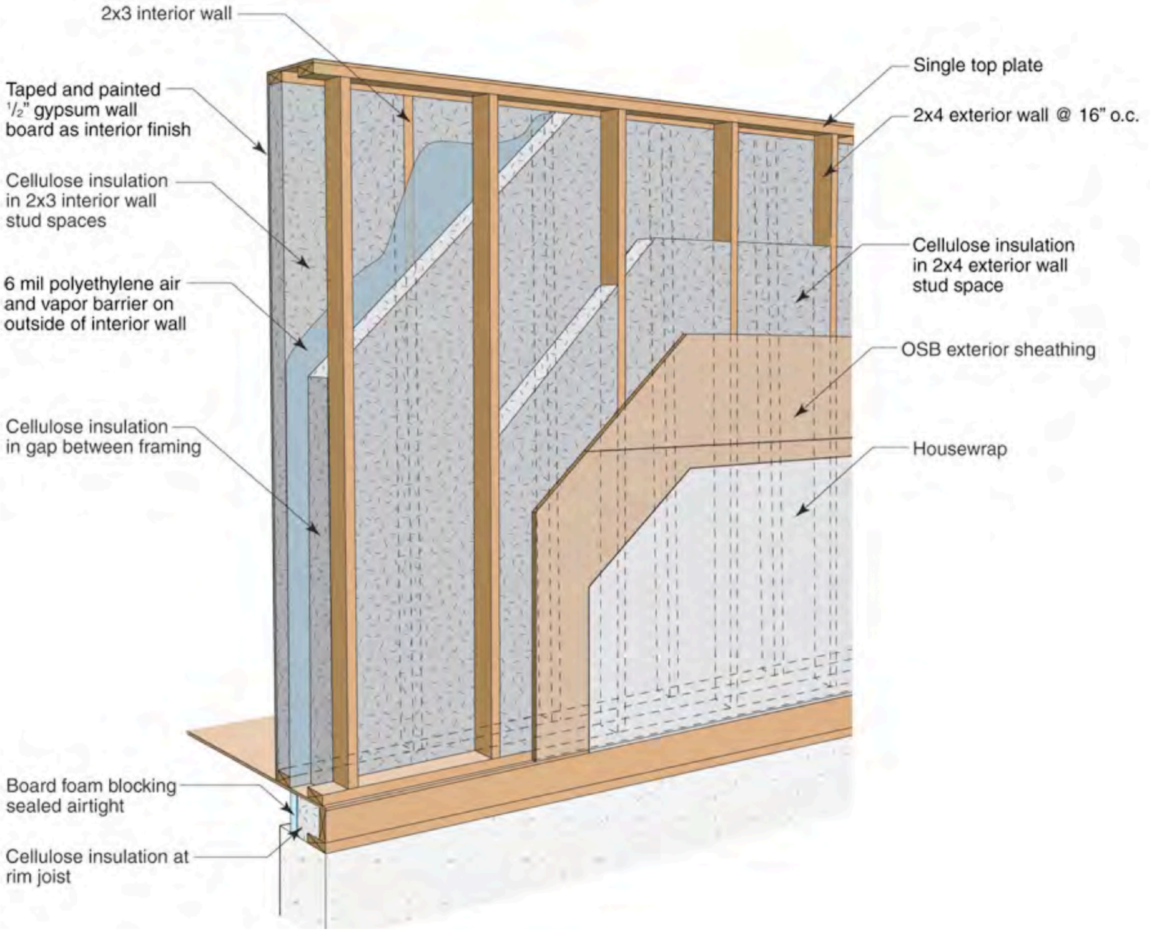


Figure 4.2 Double-stud wall construction (Straube and Smegal 2009).

In this step (2), decision makers assess the relative importance of factors and preferences for alternatives through pairwise comparison matrices, which then are recombined into an overall rating of alternatives by using the eigenvalue method. When assigning weights to factors, decision makers are asked to indicate the strength of their preferences for one factor over another on the following scale: 1 equally preferred, 3 weak preference, 5 strong preference, 7 demonstrated preference, and 9 absolute preference. Table 4.2 presents the matrix of 'value' judgments for the factors, the researcher assumed these numbers with the purpose of developing an example. These numbers reflect the 'value' preferences of the factors expressed as a ratio. For example, number 3 in the second column and first row of the matrix means that thermal control is weakly preferred over durability, and correspondingly the first column second row has the inverse value of 1/3.

Table 4.2 AHP step 2, establish priorities among the factors.

Factors:	**1- Thermal Control**	**2- Durability**	**3- Buildability**	**4- Material Use**
1- Thermal Control	1	3	1/3	1/5
2- Durability	1/3	1	3	3
3- Buildability	3	1/3	1	1/5
4- Material Use	5	1/3	5	1

Creating these relationships between the factors requires a high level of abstraction. Finally, when the eigenvalue of this matrix is calculated, it provides the weights of the factors, which assumes linear trade-offs between performances of the alternatives.

The next steps are: (3) decision makers synthesize these judgments to yield a set of overall priorities for the hierarchy, (4) decision makers check the consistency of the judgments, and (5) decision makers come to a final decision based on the results of this process. Accordingly, steps 3 to 5 require a defined context, which does not exist in this case study; therefore, those steps are not expanded on here.

4.1.2. CBA Application

In CBA decisions are based on advantages of alternatives in order to differentiate between them. Once the advantages of each alternative are found, the CBA method requires the design team to assess the importance of these advantages by making comparisons between them. Chapter 3 presents a complete description of the CBA method.

Section 4.1.4 presents the first CBA steps: (1) Identify alternatives; (2) Define factors; and (3) Define 'must' and 'want' have criteria for each factor. The focus of this case study is on step (4), in which the design team summarizes the attributes of each alternative and step (5), in which the design team decides the advantages of each alternative. Table 4.3 presents a summary of the attributes of each alternative (step 4).

According to the CBA tabular method, the advantages of each alternative must be highlighted (step 5) before deciding which alternative provides the most important advantage in any particular factor. Table 4.4 presents the advantages of each alternative relative to the least-preferred one.

Step (4) of the CBA decision-making phase is somehow an objective description of the alternatives. Step (5) may contain subjectivity; therefore, the design team needs to agree on the criteria for judging the alternatives. In this case, the design team should find it easy to agree with the 'want' criteria (the design team wants the wall with a higher R-value, easier to construct, and with less material use).

Table 4.3 CBA step 4, summarize the attributes of each alternative.

Factors **(Criteria)**	**Attributes of standard wall construction**	**Attributes of double-stud wall construction**
1.Thermal control (The higher R-value the better)	R-10 (2x4 wall with R-13 stud space insulation)	R-15 (2x4 wall with fiberglass batt)
2. Durability (It must last 50 years)	Depends on exterior barrier	Depends on exterior barrier
3. Buildability (The easier the better)	Easy to construct. Designers, trades and subcontractors are used to it	Not very complicated, but it requires custom frames for penetrations (e.g., windows and doors).
4. Material use (The less the better)	Framing lumber could be minimized further if advanced framing were used.	Wall framing material is increased significantly due to secondary interior wall.

Table 4.4 CBA step 5, decide the advantages of each alternative.

Factors **(Criteria)**	**Attributes of standard wall construction**	**Attributes of double-stud wall construction**
1. Thermal control (The higher R-value the better)	-	R-value is higher by 5°F*hr*ft^2/Btu than standard wall
2. Durability (It must last 50 years)	-	-
3. Buildability (The easier to build, the better)	Is easier to construct than double stud	-
4. Material use (The less the better)	Uses less material than double stud	-

Step (6), which decides the importance of each advantage, and (7) which analyses the cost of the alternatives, are discussed but not fully developed. This is because those steps require a subjective ‘value’ judgment that will depend on the stakeholders involved in the decision-making process and the context of a particular building. Figure 4.3 represents the process of deciding the Importance of Advantages (IofAs), and presents a scale of IofAs from 0 to 100, on which advantages need to be placed.

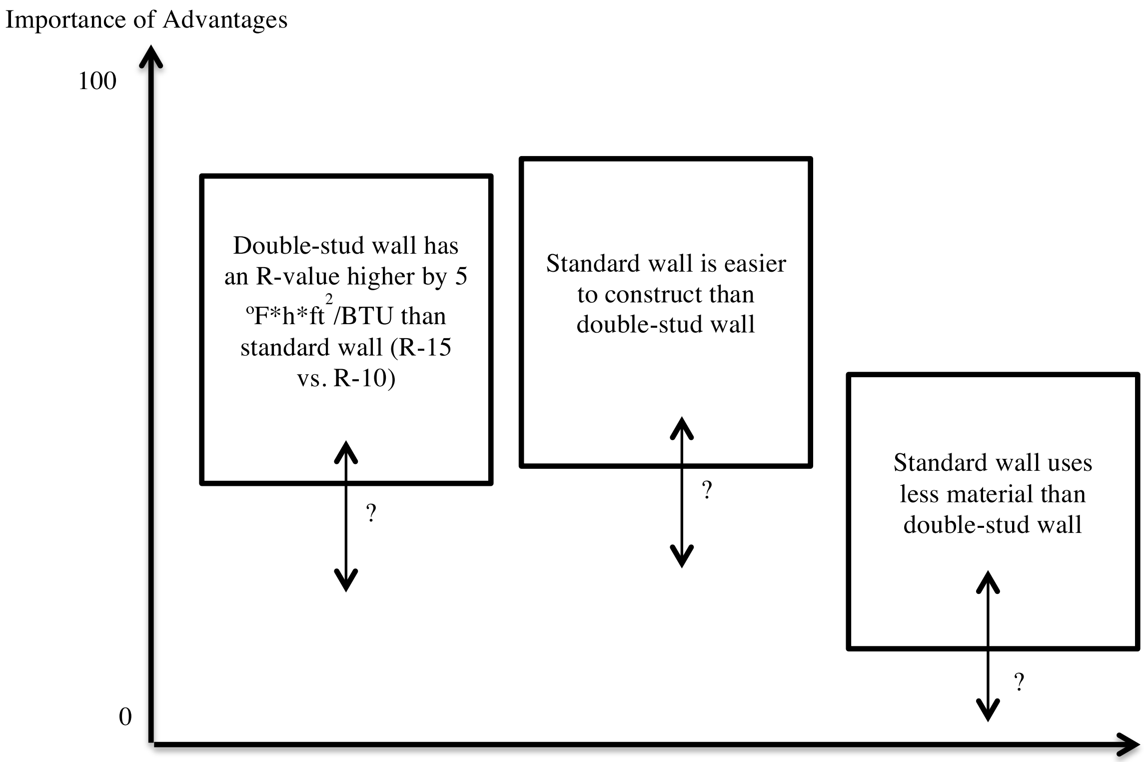


Figure 4.3 CBA step 6, decide the importance of the advantages.

4.1.3. Discussion

The focus of the comparison is on the process of weighting the factors (step 2) in AHP and identifying advantages (steps 4 and 5) in CBA. The following six factors present differences between these two methods. Table 4.5 summarizes the differences between AHP and CBA.

1. *Trade-offs between factors (Must not assume linear trade-offs between factors)*

AHP assumes linear trade-offs between factors. However, this assumption is not always correct. For example, stakeholders may not want the building to last much more than 50 years. If so, the trade-off function will change after 50 years of durability is achieved.

In CBA trade-offs between the factors do not have to be linear.

2. *Focus on differentiating between alternatives (Must help differentiate between alternatives)*

In AHP the importance of the factors can be disconnected from the difference between the alternatives. For example, in AHP it is possible to assign an important factor weight to durability, even when the alternatives have no difference with regard to that.

In CBA the focus is on differentiating between alternatives. In this case, the factor durability has no relevance in the decision due to the fact that no alternative has an advantage over another.

Table 4.5 Differences between AHP and CBA highlighted in comparative case study 1.

Factors **(Criteria)**	**Analytical Hierarchy Process**	**Choosing By Advantages**
1. Trade-offs between factors (Must not assume linear trade-offs between factors)	Assumes linear trade-offs between factors.	Does not assume linear trade-offs between factors.
2. Focus on differentiating between alternatives (Must help differentiate between alternatives)	May not focus on the importance of the advantages between attributes of alternatives.	Bases the decision process on the importance of the advantages.
3. Analyzing Cost (Must be treated separated from value)	Cost can be a factor and be mixed with the intrinsic 'value' of the alternative.	Cost cannot be a factor and is treated separate from 'value'.
4. Collaboration (Must avoid conflicting trade-offs about general ideas)	May create conflicts among the design team in resolving opposing interests when assigning weights to factors.	Help the design team to make decisions based on differences between alternatives and minimize conflict.
5. Context specific (Must consider a specific context for all judgments)	Judgments about weights of factors are not anchored to relevant facts and may be done without specific context.	Bases subjective decisions in the differences between alternatives (advantages) that are linked to the decision context
6. Flexibility (Must facilitate the incorporation of new alternatives)	If new alternative is added the score of old alternatives needs to be recalculated.	If a new alternative is added the advantages regarding that alternative need to be assessed.
7. Flexibility (Must facilitate the incorporation of new perspectives or factors)	If a new factor is added, the weights of factors need to be recalculated.	If a new factor is added, the advantages regarding that factor need to be assessed.

3. *Analyzing Cost (Must be treated separated from value)*

In AHP cost can be a factor. However, it is not mandatory.

In CBA, cost, is neither a factor nor a criterion and is treated separately as a constraint. Assuming that the estimated first cost for the standard wall construction is about $\$50/m^2$ and for the double-stud wall construction about $\$80/m^2$, two scenarios are possible. The first is that stakeholders 'value' the advantages in buildability and material use of the standard wall construction over the advantage in thermal control of double-stud wall construction. In that case, they should use the single stud wall, which is cheaper. The second scenario is that stakeholders 'value' the advantage in thermal control of double-stud wall construction over the advantages in buildability and material use of the standard wall construction. Then the relevant questions are: does the design team want to pay $\$30/m^2$ more and does the design team have the financial ability to pay for that higher first cost?

4. *Collaboration (Must avoid conflicting trade-offs about general ideas)*

In AHP, decision makers may find it difficult to collaborate when they have to assign weights to factors based on general ideas (e.g., energy efficiency, safety, aesthetics, etc.), which may correspond to the focus of individual specialists (e.g., mechanical engineer, structural engineer, architect, etc.). This may lead to argumentation that is not based on the alternatives being considered, but on the previous experiences of the specialists.

In CBA, decision makers may build consensus more easily since they base judgments on facts, which are differences between alternatives.

5. *Context specific (Must consider a specific context for all judgments)*

In AHP, the process of weighting factors requires a high level of abstraction. The questions the (hypothetical) design team should answer are: What is more important, buildability or material use? Thermal comfort or durability? However, it is hard to defend that thermal control is more important than durability without considering the relevant differences between alternatives.

In CBA, the criteria depend on the project context, such as climate conditions, building orientation and building users. Once the advantages are decided, CBA leads to subjective questions anchored to the relevant facts such as: What is more important, the advantages in buildability and material use of the standard wall vs. the advantage in thermal control of the double-stud wall? The importance of advantages depends on how big the advantage is and how that size of advantage is 'valued' by the design team according to the project context.

6. *Flexibility (Must facilitate the incorporation of new alternatives)*

CBA has the flexibility to add more alternatives with no impact on the previous assessment of alternatives. This is assuming that the new alternatives do not require adding new factors. In AHP, the impact on previous alternatives is not that obvious since rank-order reversal can occur. If a new alternative is added, the scores of the old alternatives need to be recalculated. Other alternatives may be Structured Insulated Panel Systems (SIPs), truss wall, concrete, etc.

7. *Flexibility (Must facilitate the incorporation of new perspectives or factors)*

If new factors are added in the CBA table, a new row will be created, adding new advantages that need to be compared against the paramount advantage. However, this should not impact the previous assessment of old advantages. This contrasts with the AHP method, which requires recalculating the weight of factors each time a new factor is added to the decision. Some factors that can be added to the analysis are: embodied energy of materials, aesthetics, etc.

8.

4.1.4. Conclusions

In conclusion, the AHP method may not help in creating transparency for choosing which alternative is more sustainable because (1) it assumes linear trade-offs between factors; (2) it may not help in differentiating between alternatives; and (3) it may incorporate cost and mix it with the 'value' of the alternative. The AHP method may not help in building consensus because (4) it may create conflicts among members of the design team when assigning weights to factors; and (5) it may not be based on the decision context when making judgments about the weights of factors. The AHP method may not help in continuous learning because (6) it requires recalculating the ranking of old alternatives if a new alternative is added; and (7) it requires recalculation of the weights of factors if a new factor is added.

In contrast, CBA may help in creating transparency because (1) it does not assume linear trade-offs between factors; (2) it helps in differentiating between alternatives by defining advantages among them; and (3) it does not allow mixing cost and 'value'. CBA may help building consensus because (4) it helps in minimizing conflict by basing decisions on differences between alternatives; and (5) it bases advantages on the context in which the available alternatives exist. CBA may help in continuous learning because (6) it does not require recalculations if a new alternative is added (if that alternative do not incorporate a new factor); (7) it does not require recalculations if a new factor is added. Therefore, CBA provides a better method than AHP to support the design team decisions when the attributes of the alternatives are known.

4.2. Comparative Case Study 2: Choosing an Insulation Material

4.2.1. Introduction

This case study compares more deeply the application of AHP and CBA. The case study uses a real project; therefore, the decision has a real context. The two methods are fully applied and compared, adding new perspectives relative to those used in the comparative case study 1 (Section 4.1). The researcher presented part of this case study at the American Society of Civil Engineers (ASCE) Conference for Sustainable Design, Engineering and Construction (CSDEC) (Arroyo et al. 2012b). In addition, the researcher published part of this case study in a paper that is currently in press for the Journal of Construction Engineering and Management from ASCE (Arroyo et al. 2014a, with permission from ASCE).

4.2.2. Case-Study Background

This case study illustrates how AHP and CBA may be used to select insulation materials. Specifically, it evaluates the selection of cotton vs. fiberglass for use on a 6-story building in Northern California. The stakeholders involved are the owner, architect, general contractor, and drywall subcontractor. The objective is to select a sustainable insulation material considering social-, environmental-, and economic factors.

4.2.3. Case-Study Protocol

The case-study protocol describes the steps that the researcher followed for applying AHP and CBA for choosing between cotton and fiberglass in this project. These steps are:

1. Interviewed the general contractor (HMH Builders) in order to understand how decisions were made in practice. During the interviews, the researcher explored different decisions until selecting the decision about choosing insulation material. The researcher selected that decision because it was documented through 2 written reports prepared by the general contractor (HMH Builders 2012a and 2012b), and it had multiple stakeholders involved.

2. Studied reports that the project participants created in order to document the decision.
3. Derived alternatives and attributes from the available reports.
4. Studied AHP and CBA literature and examples of use, as presented in Chapter 2.
5. Developed an application of AHP and CBA with the information provided for decision-making.
6. Finally, sent the report to the interviewees for feedback, and incorporated it in the report.

4.2.4. Alternatives, Factors, and Criteria for Evaluation

The alternatives considered were cotton (Figure 4.4) and fiberglass (Figure 4.5), according to the general contractor's reports.

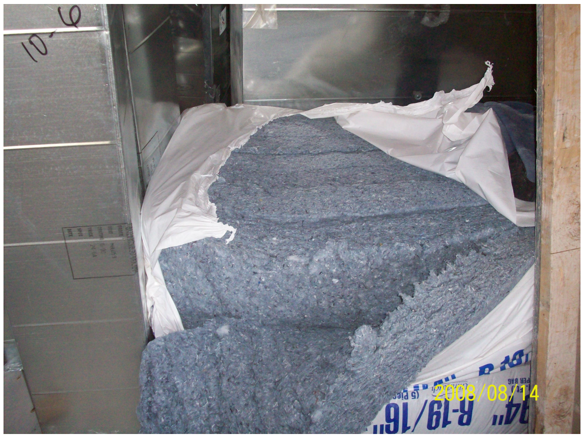


Figure 4.4 Cotton insulation (HMH Builders 2012a).

Figure 4.5 Fiberglass insulation (HMH Builders 2012a).

Table 4.6 summarizes information obtained from the general contractor's reports and made available to the decision makers. This information is location-and-project specific and considers information provided by manufacturers of cotton and fiberglass available within the project area. Apart from cost, which is treated separately in both methods in this case study, the design team considered nine factors.

According to HMH Builders (2012b), the big difference in terms of installation is explained because cotton needs to be cut with a small, hand held saw, which is much more cumbersome to work with than a sheet rock knife as is used with fiberglass. In addition, cotton insulation is heavy, so in toping down situations, friction is often not enough to hold the insulation in place, and it can slip. On this particular project, screws needed to be drilled into the studs on either side of the insulation to hold it in place. Fiberglass can quickly be stapled to the wall, where cotton is too dense to allow for this fix.

Table 4.6 Attributes of insulation material alternatives.

#	Factor	Cotton	Fiberglass
1	Recycled contents	85% by mass	20% by mass
2	Chemical irritants (Heath issues)	No, it is treated with non-toxic borates to resist fire, mold and vermin.	Yes, fibers may cause skin, eye and upper respiratory tract irritation.
3	Density	Heavy (2.5 lb/ft^3)	Light (0.5 lb/ft^3)
4	Sound privacy (STC Rating)	Depends on the wall assembly.	Depends on the wall assembly.
5	Insulation capacity	R-19 (5-1/2" thickness) (other thicknesses can be used)	R-19 (6-1/4" thickness) (other thicknesses can be used)
6	Recyclability	100%	40%
7	Fireproof	Can only be used in areas rated 1-hour or less.	Can be used in any area of the building.
8	Handling material	Wear mask, no gloves. Hard to cut.	Wear mask and gloves. Easy to cut.
9	Installation	200 ft^2/day per person. Does not come with a vapor barrier for exterior installation. Needs to be screwed to the wall.	2,500-3,000 ft^2/day per person. It comes with a vapor barrier for exterior installation. Is easily stapled to the wall.
	Material first cost	\$1.20/ft^2 plus transportation. Available only from Arizona. A typical semi-truck can carry 200 bags of cotton or 15,000 ft^2.	\$0.47/ft^2 plus transportation. Available locally. A typical semi-truck can carry 1050 bags of fiberglass or 105,000 ft^2.

4.2.5. Comparing Advantages and Disadvantages

The researcher was unable to discern whether or not the team had applied a particular decision-making method to their final decision. In fact, from the reports investigated, one can extract a list of advantages and disadvantages of each alternative without a clear structure for comparison. The main problem with considering advantages and disadvantages for decision making is that the same difference between two alternatives may be discussed twice or more. For example, the fact that cotton has 85% recycled contents vs. fiberglass only 20% can be seen as both an advantage of cotton or a disadvantage of fiberglass. Considering both for the decision, leads to double counting of factors.

In this decision, the general contractor was in charge of preparing the reports and gathering information from manufacturers and subcontractors in order to give a recommendation to the owner who made the final decision. This project was targeting LEED gold certification; therefore they had incentives to obtain points from the insulation material. The final decision in this case was to use cotton in the first two floors and fiberglass in the remaining four floors. This configuration allowed the project to obtain LEED points for using cotton, and at the same time to not spend so much extra time in the installation process.

4.2.6. AHP Application

Use of the AHP follows these steps (Saaty 1980):

(1) Model the problem as a hierarchy containing the decision goal, the alternatives for reaching it, and the criteria for evaluating the alternatives. Figure 4.6 shows the hierarchy of the factors for this example.

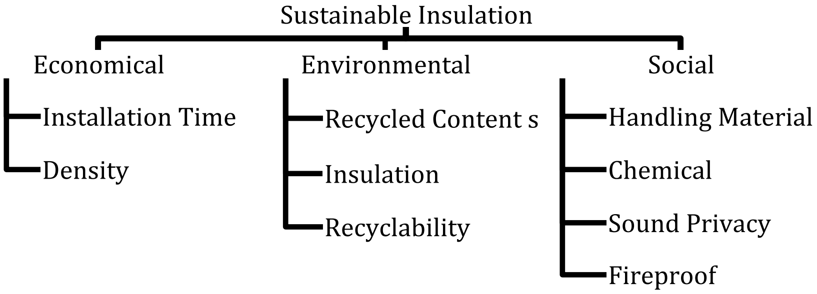


Figure 4.6 AHP step 1, model the problem as a hierarchy.

(2) Answer a series of pairwise comparison questions in order to establish priorities among factors, assuming they are independent of each other. Using the same scale described in comparative case study 1 (from 1 to 9, where 1 represents equal preference and 9 absolute preference) stakeholders need to indicate the strength of their preferences for one factor over another. This leads to a numerical evaluation of the alternatives according to each factor.

Now assume that Table 4.7 expresses the stakeholders' preferences when comparing factors, e.g., the number 3 (in row factor 1, column factor 2) means that stakeholders have a weak preference for recycled contents over chemical irritants content. To be consistent in this method, the opposite value (row factor 2, column factor 1) has the inverse ratio 1/3.

(3) Synthesize these judgments to yield a set of overall priorities for the hierarchy. By calculating the eigenvalue vector of the preference matrix, one obtains relative weights of the factors (Table 4.7). In addition, the alternatives need to be judged per factor, for some factors the quantitative values are used to create a linear scale. For example, since cotton has 85% recycled contents and fiberglass 20%, the two values are normalized, and the interpretation would be cotton is 0.81/0.19 or 4.25 times more preferable than fiberglass in that regard. When the design team requires qualitative factors, the same relative scale used for comparing factors before is used. Table 4.8 shows the result of the preferences of alternatives per factor.

Table 4.7 AHP step 2, establish priorities among the factors.

Factors:	#	**1 Recycled contents**	**2 Chemical irritants content**	**3 Density**	**4 Sound privacy**	**5 Insulation capacity**	**6 Recyclability after use**	**7 Fireproof**	**8 Handling material**	**9 Installation**
Recycled contents	1	1	3	3	7	7	1	5	3	1
Chemical irritants content	2	1/3	1	1/3	3	3	1/3	1	1/3	1/3
Density	3	1/3	3	1	5	5	1/3	3	1	1/3
Sound privacy	4	1/7	1/3	1/5	1	1	1/5	1/3	1/3	1/7
Insulation capacity	5	1/7	1/3	1/5	1	1	1/7	1/3	1/5	1/7
Recyclability after use	6	1	3	3	5	7	1	3	3	1
Fireproof	7	1/5	1	1/3	3	3	1/3	1	1/5	1/5
Handling material	8	1/3	3	1	3	5	1/3	5	1	1/3
Installation	9	1	3	3	7	7	1	5	3	1
Factor weights:		22%	6%	10%	3%	2%	20%	5%	11%	22%

Table 4.8 Weights of attributes.

Factors:	**1 Recycled contents**	**2 Chemical irritants content**	**3 Density**	**4 Sound privacy**	**5 Insulation capacity**	**6 Recyclability after use**	**7 Fireproof**	**8 Handling material**	**9 Installation**
Cotton	0.81	0.88	0.1	0.5	0.5	0.71	0.25	0.17	0.07
Fiberglass	0.19	0.13	0.9	0.5	0.5	0.29	0.75	0.83	0.93

(4) Check the consistency of judgments (Equation 4.1). The Consistency Index (CI) of the matrix is measured as:

CI = (Principal eigenvalue - size of matrix)/ (Size of matrix - 1) Equation 4.1

The principal eigenvalue is 9.42, and therefore CI = 0.0519 and the consistency ratio is 0.0358, using a comparative value of 1.45 (Belton and Stewart 2002). A consistency ratio less than 0.1 means that the values are consistent.

(5) Come to a final decision based on the results of this process. By multiplying the factor weight with the preference of the alternatives, the result is that fiberglass is preferred over cotton by 0.55/0.45. Since in our example fiberglass also costs less than cotton, the final decision should be fiberglass. It is important to highlight again that the focus of this case study is not to argue which material should be selected, but how the method used for material selection affects the decision.

4.2.7. CBA Application

Use of the CBA follows these steps (Suhr 1999):

(1) Identify alternatives; (2) Define factors; (3) Define 'must' and 'want' have criteria for each factor, and (4) Summarize the attributes of each alternative (Table 4.9).

Table 4.9 CBA steps 1 to 6.

Factors (Criteria)	**Alternative 1: Cotton**		**Alternative 2: Fiberglass**	
1. Recycled contents	Attribute: 85%		Attribute: 20%	
(Higher is better)	Adv.: *65% more recycled contents*	Imp.: 40	Adv.:	Imp.:
2. Chemical irritants	Att.: Does not have irritants		Att.: Has irritants	
(Without is preferred)	Adv.: *Does not have irritants vs. has*	Imp.: 60	Adv.:	Imp.:
3. Density	Att.: Heavy (2.5 lb/ft^3)		Att.: Light (0.5 lb/ ft^3)	
(Lower is better)	Adv.:	Imp.:	Adv.: *2 lb/* ft^3 *lighter*	Imp.: 10
4. Sound privacy (STC)	Att.: Acceptable		Att.: Acceptable	
(Higher is better)	Adv.: -	Imp.:	Adv.: -	Imp.:
5.Insulation capacity	Att.: R-19		Att.: R-19	
(Higher is better)	Adv.: -	Imp.:	Adv.: -	Imp.:
6. Recyclability	Att.: 100%		Att.: 40%	
(Higher is better)	Adv.: *60% more recyclability*	Imp.: 50	Adv.:	Imp.:
7. Fireproofing	Att.: Less than one hour		Att.: More than 1 hour	
(Higher hour rating is better)	Adv.:	Imp.:	Adv.: *Slightly less flammable than cotton*	Imp.: 5
8. Material handling safety	Att.: Wear mask, no gloves. Very hard to cut		Att.: Wear mask and gloves. Easy to cut	
(Easier is better)	Adv.:	Imp.:	Adv.: *Need gloves but easier to cut*	Imp.: 10
9. Installation	Att.: 200 ft^2/day pp.		Att.: 2,500-3,000 ft^2/day pp.	
(Faster is better)	Adv.:	Imp.:	Adv.: *2300-2800* ft^2*/day/pp. faster.*	Imp.: 100
Total IofAs		150		125

(5) Decide the advantages of each alternative. On one hand, advantages of cotton over fiberglass are that (a) it has 65% more recycled contents; (b) it does not have irritants; and (c) it is 60% more recyclable. On the other hand, advantages of fiberglass over cotton are that (d) it is slightly less flammable; (e) it is 2 lb/ft^2 lighter; (f) it is easier to cut; and (g) it is 2,300-2,800 ft^2/day/per-person faster to install.

Note that neither alternative has an advantage over the other with regards to insulation capacity or sound privacy. Therefore, these factors have no importance in this particular decision.

Table 4.9 shows the attributes of the alternative, which are relatively objective because they are inherent to the alternatives. They represent measurable characteristics, which are agreed upon units of measurement. Consequently stakeholders should be able to agree on the advantages of each alternative relative to the other.

(6) Decide the importance of each advantage. Stakeholders need to explicitly state their preferences for the advantages. First, they have to select the paramount advantage, which is assigned 100 points here. Then, they need to assign an importance score to other advantages based on the scale defined by the selection of the paramount advantage. The values used here are hypothetical and do not represent the general contractor's or owner's 'values'. Finally, they sum the IofAs for each alternative (Table 4.9). In this example, the alternative with the higher IofAs is cotton. This means that the (presumed) stakeholders' 'value' the advantages of cotton over fiberglass (see (2) a, b, and c) more than the advantages of fiberglass over cotton (see (2) d, e, f, and g).

Finally, (7) evaluate cost data if applicable. Since in our example fiberglass costs less than cotton, the choice is not obvious. Are the stakeholders willing to pay \$0.73/ ft^2 more to use cotton? What else must they consider (e.g., availability of the needed funds, the lifecycle cost of the alternatives, the relation between the selection of an insulation material vs. different building systems, CO_2 emissions)? A CBA analysis can include such considerations.

4.2.8. Discussion

In order to further highlight AHP and CBA assumptions and differences, the next section provides three hypothetical examples of modifications to the original application example.

1. AHP impacts of removing factors that do not differentiate between alternatives

First, note that the original example showed no difference between cotton and fiberglass regarding sound privacy (factor 4) and insulation capacity (factor 5). If one takes out these non-discriminating factors (since the alternatives perform equally), it would be logical and intuitive for the preferences for one alternative over the other to not change. However, Table 4.10 shows that when using AHP, the result of the decision changes when one removes these two factors. While fiberglass was preferred over cotton by 0.55/0.45, now cotton is preferred over fiberglass by 0.51/0.49. This change results from the variation in factor weights, even when all preferences were maintained equally among the remaining factors. When using CBA, however, the preference of one alternative over the other does not change if one removes a non-discriminating factor. Since the alternatives perform equally, no advantage exists, and therefore no IofA exists.

Table 4.10 Impacts of removing non-differentiating factors in AHP.

Factors:	**1 Recycled contents**	**2 Chemical irritants content**	**3 Density**	**4 Sound privacy**	**5 Insulation capacity**	**6 Recyclability after use**	**7 Fireproof**	**8 Handling material**	**9 Installation**	**Total Score**
AHP original factor weights	22%	6%	10%	3%	2%	20%	5%	11%	22%	
Cotton attribute weight	0.81	0.88	0.10	0.50	0.50	0.71	0.25	0.17	0.07	
Fiberglass attribute weight	0.19	0.13	0.90	0.50	0.50	0.29	0.75	0.83	0.93	
Contribution per factor using all factors with the original weights										
Contribution to total score cotton	0.17	0.05	0.01	0.01	0.01	0.14	0.01	0.02	0.02	0.45
%	39%	11%	2%	3%	3%	32%	3%	4%	4%	
Contribution to total score fiberglass	0.04	0.01	0.09	0.01	0.01	0.06	0.04	0.09	0.20	0.55
%	9%	2%	21%	3%	3%	13%	8%	20%	45%	
Contribution per factor if one takes away sound privacy and insulation										
New factor weights	27%	5%	11%			26%	4%	13%	13%	
Contribution to total score cotton	0.22	0.05	0.01	0.00	0.00	0.19	0.01	0.02	0.01	0.51
%	49%	11%	3%	0%	0%	42%	2%	5%	2%	
Contribution to total score fiberglass	0.05	0.01	0.10	0.00	0.00	0.07	0.03	0.11	0.12	0.49
%	12%	2%	23%	0%	0%	17%	7%	23%	26%	

2. AHP impacts of assigning high weights to factors that do not differentiate between alternatives

Second, AHP and CBA differ in the way preferences are expressed. AHP separates the weights of the factors from the weights of the attributes. In addition, the weights of the factors may be determined independently of the alternatives considered, and the weights of the attributes depend on the available alternatives. In contrast, CBA weighs the advantages, which are a combination of data (differences between attributes of specific alternatives) and the relative importance of other advantages. For this reason AHP may not highlight differences between alternatives. If stakeholders give high importance to factors in which the alternatives have no important differences, the alternatives will have an overall similar rating.

Table 4.11 illustrates how the AHP decision changes when one changes the weight of factors. If one modifies the weights of factors in Table 4.7, assigning higher importance to factors 4 and 5 (in which alternatives do not differ) and less importance to factors 7 and 9 (in which alternatives differ significantly), then fiberglass and cotton are almost equally preferred. Accordingly, a very high difference in factor 2 (recycled contents) and factor 9 (installation) may get overlooked. In AHP, this type of mistake in the decision-making process is likely to occur because the weighting of factors and attributes are done independently. In CBA, this type of mistake is improbable, since it is difficult (or unsound) to assign a high importance to a very small difference, and certainly impossible to assign a high importance to a non-existent advantage.

Table 4.11 Impacts of assigning high weights to non-differentiating factors in AHP.

Factors:	**1 Recycled contents**	**2 Chemical irritants content**	**3 Density**	**4 Sound privacy**	**5 Insulation capacity**	**6 Recyclability after use**	**7 Fireproof**	**8 Handling material**	**9 Installation**	**Total Score**
AHP factor weights	8%	12%	4%	24%	15%	8%	22%	3%	4%	100%
Contribution to total score cotton	0.06	0.10	0.00	0.12	0.07	0.06	0.06	0.01	0.00	0.49
%	15%	24%	1%	27%	17%	13%	13%	1%	1%	
Contribution to total score fiberglass	0.02	0.01	0.04	0.12	0.07	0.02	0.17	0.03	0.03	0.51
%	3%	3%	8%	27%	17%	5%	38%	6%	8%	

3. AHP Impacts of changing scale of attributes

Third, AHP and CBA differ in that AHP requires the normalization of attributes and that represents a measure of preference, whereas CBA does not require any normalization or weighting of attributes, since the weighting process is done directly using the advantages and expressed in IofAs. For this reason AHP may generate anomalies that are not obvious to the decision maker. For example, changes of numerical scales could affect a decision.

Table 4.12 shows that in AHP the weights of the attributes for recycled contents changes case by case. Case 1 represents the information presented in Table 2, where cotton performs better than fiberglass (0.81/0.19). Cases 2 and 3 represent alternatives that have the same difference but use another scale. In case 2, cotton is preferred infinitely over fiberglass (1/0). In case 3, cotton is preferred over fiberglass with less intensity than in case 1 (0.74/0.26). Finally, case 4 shows that the relative advantage of cotton over fiberglass is reduced to 50%. However, the preferences in AHP remain equal to those of case 1. In both cases 1 and 4, cotton is preferred over fiberglass by a factor of 0.81/0.19.

In CBA the advantage remains the same for cases 1, 2 and 3. In case 4 the advantage is reduced to 0.5, and therefore, the importance should be reduced too, although not necessarily to the same 'value'. This is because CBA does not impose 'value' judgments on the scale of the attributes; instead it has decision makers express those later when they assess the IofA relative to other advantages.

Table 4.12 Impacts of changing scale of attributes in AHP.

	Case 1	**AHP Weight**	**Case 2**	**AHP Weight**	**Case 3**	**AHP Weight**	**Case 4**	**AHP Weight**
Cotton	85%	0.81	65%	1.00	100%	0.74	43%	0.81
Fiberglass	20%	0.19	0%	0.00	35%	0.26	10%	0.19
Difference (CBA Advantage)	65%		65%		65%		33%	

In light of the previous examples, the following seven factors and criteria for evaluation can be described. Table 4.13 summarizes the differences between AHP and CBA according to the observations of comparative case study 2.

1. Transparency on trade-offs inside a factor (Must not assume that attributes can be weighted or normalized)

In AHP assumes linear trade-offs of attributes and is highly dependent on the scale used, as was shown in the third example of the discussion section. Another example is that the design team arrives at a target level within a certain factor (e.g., insulation capacity), which is aligned with the overall system design. In that case, an increment in performance of that factor will not benefit the project.

In CBA the attributes do not need to be normalized and linear trade-offs are not assumed.

2. Transparency on trade-offs between factors (Must not assume linear trade-offs between factors)

In AHP trade-offs between factors are assumed to be linear. However, this is not always true. For example, if designers are considering recycled contents and acoustic performance as two factors, it is not accurate to state that they will always prefer twice more (or any number) an improvement in recycled contents vs. an improvement in acoustic performance. Once designers have reached a satisfactory level in acoustic performance for the interior walls of the hospital, it is not necessary to maintain the same preference ratio. Therefore, forcing a linear representation is inappropriate.

In CBA, trade-offs between factors are not assumed to be linear.

Table 4.13 Differences between AHP and CBA highlighted in comparative case study 2.

Factor (Criteria) for MCDM methods	**Analytical Hierarchy Process**	**Choosing By Advantages**
1. Transparency on trade-offs inside a factor (Must not assume that attributes can be weighted or normalized)	AHP assumes that sustainability factors have zero as a natural scale by normalizing and attributing 'values' to them.	CBA does not assume that attribute scales have an inherent 'value'. 'Value' is only assigned to the differences between alternatives.
2. Transparency on trade-offs between factors (Must not assume linear trade-offs between factors)	AHP assumes that trade-offs between sustainability factors are linear functions.	CBA makes clear what the trade-offs between advantages are, and no pre-assumed trade-off function is required.
3. Focus on differentiating between alternatives (Must help differentiate between alternatives)	AHP may not help in differentiating between alternatives because the weights of factors may not be based on differences between alternatives.	CBA bases judgments on differences between alternatives (advantages).
4. Consistency (The result must not change if irrelevant factors are eliminated from the decision)	AHP changes the result of the decision, or at least the intensity of the preference, when non-differentiating factors, which have same attributes for all alternatives, are eliminated from the analysis.	CBA does not change the result when non-differentiating factors, which have same attributes for all alternatives, are eliminated from the analysis.
5. Collaboration (Must avoid conflicting trade-offs about general ideas)	AHP requires assign weights to factors, which are high order of abstraction concepts (e.g., recycle content, R-value, color, etc.). This exercise may be conflicting.	CBA postpones 'value' judgment until decision makers agree on objective differences between alternatives (advantages), which may minimize conflict among them.
6. Context specific (Must consider a specific context for all judgments)	AHP lacks of context specific judgments when assigning weights to sustainability factors. Sustainability factors may mean different things to different persons in the design team.	CBA makes judgments about the importance of the advantages, which exist only in a given context. Defining an advantage involves knowing the alternatives, the sustainability factors, the attributes of the alternatives and the criterion for judgment.
7. Subjectivity (Must do objective part first and then subjective part)	AHP asks stakeholders to make explicit which factors are more important (subjective task first), without considering the relevant differences between alternatives (objective task).	CBA Highlights the difference between alternatives first (which is an objective task) and then decides what advantages (positive differences) are more important (which is a subjective task).

4. Focus on differentiating between alternatives (Must help differentiate between alternatives)

In AHP it is possible to assign a high weight to factors that do not differentiate between alternatives. Table 4.11 illustrates this possibility.

In CBA the IofA are assigned to real differences between alternatives. Larger advantages are more likely to be more important. However, this is subject to the 'value' that provides the advantage for the design team.

4. Consistency (The result must not change if irrelevant factors are eliminated from the decision)

In AHP the decision can change when a factor that does not differentiate between alternatives (e.g., 'sound privacy') is removed from the decision.

In CBA the decision remains the same if such a non-differentiating factor is removed.

5. Collaboration (Must avoid conflicting trade-offs about general ideas).

In AHP decision makers need to argue about the general importance of factors. For example, asking designers if fire resistance of a material is more important than its acoustic performance does not have a clear meaning and may pose conflicts among stakeholders.

In CBA, decision makers need to argue about specific importance of advantages.

6. Context specific (Must consider a specific context for all judgments)

In AHP decision makers need to decide if recycled contents is more important than installation speed without an explicit context.

In CBA decision makers are tied to the context. They need to decide if the advantage of having 65% more recycled contents (cotton 85% vs. fiberglass 20%) is more important than having an installation speed 2300-2800 ft^2/day/pp faster (cotton 200 ft^2/day/pp vs. fiberglass 2500-3000 ft^2/day/pp)

7. Subjectivity (Must do objective part first and then subjective part)

In AHP the weighting of factors is done first, which is subjective.

In CBA summarizing the attributes of the alternatives (objective) is done first followed by judgments made based on the differences between alternatives (subjective).

4.2.9. Conclusions

In conclusion, CBA is superior to AHP for creating transparency and building consensus. This is because (1) CBA does not require normalizing attributes as AHP does, (2) CBA does not assume linear trade-offs between factors as AHP does, (3) CBA focuses on differentiating between alternatives more than AHP, (4) CBA does not change the decision if non-differentiating factors are taken out of the decision as AHP does, (5) CBA avoids conflicting trade-offs about general ideas and AHP does not, (6) CBA is more closely linked to the context than AHP, and (7) in contrast to AHP, CBA uses objective facts first before moving on to the subjective discussion.

5. COMPARATIVE CASE STUDY 3: WEIGHTING RATING AND CALCULATING vs. CHOOSING BY ADVANTAGES

5.1. Introduction

This chapter compares and contrasts the use of Weighting Rating and Calculating (WRC) with Choosing By Advantages (CBA). Comparative Case Study 3, which examines the selection of the structural system for the Stanford Green Dorm project, was used to discuss WRC and CBA applications. This chapter explores the questions ‘What are the differences between WRC and CBA?’ and ‘What are the impacts of those differences in the decision-making process?’ This case study was used as the basis for a paper that will be presented at the International Group for Lean Construction (IGLC) conference in 2014 (Arroyo et al. 2014b). This comparison adds a broader perspective on value-based methods against CBA, since Analytical Hierarchy Process (AHP) was compared against CBA in Chapter 4. Chapter 9 presents a cross-case analysis comparing WRC, AHP, and CBA.

5.2. Case-Study Background

According to Stanford University (2006a), the Stanford Green Dorm project, formerly known as the Lotus Living Laboratory at Stanford University, was designed to house students and include a lab targeting high sustainability standards. According to Stanford University (2006b), “The design, construction and operation of the building were planned to be an ongoing discovery of sustainable pathways”. According to Fischer and Master (2009), “The Living Lab is not only about the final building for Stanford, but also about research into building technology, design processes, and collaboration.”

The initiative began with a brainstorming session on November 20, 2003, organized by the Department of Civil and Environmental Engineering (CEE) in which faculty, students and professionals developed the initial vision for an ‘evolving,’ ‘influential,’ ‘flexible,’ and ‘desirable’ living and learning facility. The proposal advanced through the work of engineering students and faculty, peer review by outside professionals, and the efforts of several university entities. A design team led by EHDD Architecture was selected in August 2005 to spearhead the feasibility study. In the summer of 2006, the design team presented the schematic design to Stanford’s board of trustees for approval, but the project was suspended due to lack of funding. Construction of the Green Dorm remains on hold because of the financial crisis. However, the decisions during schematic design were well documented, which makes this project a good case study for this research.

5.2.1. Project Team

The project team was the decision-making body for the Green Dorm building. The School of Engineering, and particularly the CEE Department, was leading the user group of the project team, and was responsible for directing the building program and for coordinating fundraising efforts. Other Stanford departments were represented on the project team, or consulted in their area of expertise. These included, among others, the Stanford Woods Institute for the Environment, Stanford Land and Buildings, Stanford

Energy and Water Conservation and Capital Planning and Management. Figure 5.1 shows the relationship among the stakeholders involved in the project. The design team consisted of the following consultant companies:

- EHDD (architecture)
- Tipping-Mar & Associates (structural engineer)
- Taylor Engineering LLC (mechanical systems engineers)
- Davis Langdon PKS (cost estimator)
- Pankow Builders (contractors)
- Integrated Design Associates (electrical engineer)

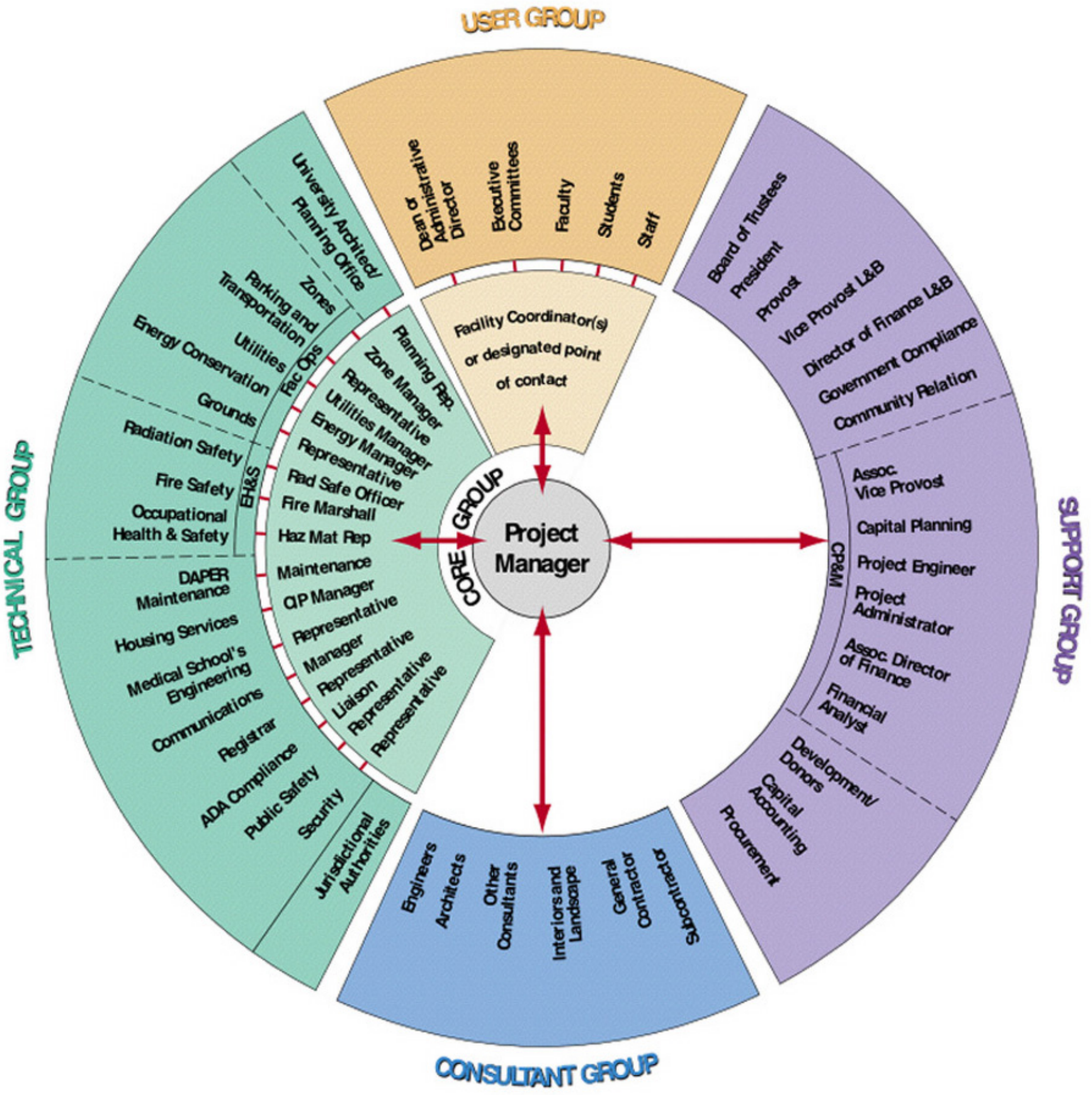


Figure 5.1 Project team diagram (Stanford University 2006b).

Figure 5.2 depicts the project team.

Figure 5.2 Project team of the Stanford Green Dorm project (Stanford University 2006b).

5.2.2. Building

The Green Dorm is to accommodate a 21,150 square foot program in a three-story building. The schematic design includes 47 undergraduate- and graduate-student beds, a building systems laboratory sharing an enlarged ground floor with residential common spaces, and comprehensive building systems. These systems will monitor and measure building performance providing constant feedback to building users. The idea was to develop a flexible design to allow the building systems to evolve over time (e.g., adaptable configuration for wiring and plumbing), making the space a center for experiential education in building systems.

The design idea was to use the whole building as a lab for testing building systems. The physical space was designed to enable a program involving innovation, laboratory research, education, and student housing. Figure 5.3 shows the schematic design.

Figure 5.3 Stanford green dorm schematic design (Stanford University 2006b).

The building design features include (Stanford University 2006b):

- A ground floor laboratory that will serve School of Engineering students and faculty for testing building systems.

- A second floor roof deck that will support experimental green roof testing, solar panels, and outdoor social space.
- A west-facing entry porch.
- An information center where visitors and residents can learn about building systems and access real-time performance monitoring.
- A building orientation to maximize use of the site's unobstructed solar access.

5.2.3. Green Dorm Project Goals

According to the Lotus Living Laboratory or Stanford Green Dorm webpage (Stanford University 2006a), the design team set 4 project goals in the course of their feasibility study. These goals reflected a high performance design target.

1. Provide the most desirable housing on campus

The research components and sustainable strategies of the building will contribute towards making the Green Dorm the most attractive residence on campus. According to the project webpage, "Residential education will be taken to a new level with students engaged in learning about the local and global impacts of their lifestyles on a daily basis. The architectural design of the dorm will complement neighboring row houses. The highest levels of indoor environmental quality and thermal comfort will foster health and happiness amongst residents."

2. Provide a Living laboratory

The building should provide a living lab for the School of Engineering faculty, which will mine project-based data ranging from interior monitoring (e.g., power draw from each outlet, air quality, water consumption and quality) to structural monitoring (e.g., humidity, vibration, and mold within the walls). These data will support research agendas for testing and developing emerging technologies. According to the project webpage, "General topics will include design and construction process, sensing and monitoring, water, materials, structure, building energy, and vehicle energy. The project will provide formal- and informal educational opportunities. Demonstration is a critical goal and will be built into the project through multiple channels." All lifecycle phases of the project will serve as a laboratory. The design and construction process of the building will be studied to assess its impact on the building sustainability performance, as is described next.

3. Obtain Measurable Environmental Goals

The environmental goals include carbon emission, water consumption, and materials selection.

3.1. *Zero Carbon Building Goal:* Zero net carbon emissions due to operational and embodied energy use over the course of a year. The design team defined two performance targets: (1) a 20% reduction in electricity and natural gas compared with the current best row house in Stanford, and (2) use of on site generation of electricity to offset 100% of carbon-based energy consumption.

3.2. *Closing the Water Cycle Goal:* Reduce water use, capture rainwater, and recycle water within the building to ultimately eliminate the import of potable water and the export of wastewater.

3.3. *Material Resources Goal:* Reduce the embodied energy of building through material selection while reducing earthquake losses through high-performance structural design.

4. *Provide Economic Sustainability*

The project team wanted to achieve a cost-neutral sustainable housing (achieve same cost than similar benchmark construction according to their studies) with significantly higher environmental performance and occupant comfort than conventional housing.

5.2.4. Structural System Decision

The design team wanted to choose a structural system that reduced the impact on the environment, and that conformed to the cost and schedule constraints of the project. The design team analyzed both first cost and life-cycle cost of the alternatives.

The intent was to design a structural system that would reduce embodied energy and at the same time achieve a good seismic performance for the lifetime of the building. The design team analyzed alternative structural systems beyond Leadership in Energy and Environmental Design (LEED) rating system requirements. Under LEED, buildings are rewarded with credits for selecting environmentally-friendly materials. However, these credits tend to focus on interior finishes, rather than the overall material flows for buildings that are dominated by structural materials. The LEED 2006 version did not give credit for reducing embodied energy in concrete and other materials used in the structure of a building. It also gave no credit for designing advanced seismic performance, durability or deconstructability.

The design team used set-base design to develop 7 alternative structural systems (Section 5.4 describes these alternatives), and used Weighting Rating and Calculating (WRC) to evaluate the alternatives against 11 factors, which reflected both quantifiable and unquantifiable values. After the evaluation they did a deeper analysis to choose between two structural systems designs that ranked best out of the 7 alternatives. The final alternatives were a wood bearing wall structure and a steel frame with metallic deck and concrete topping. Section 5.4. explains the reason for selecting these two alternatives.

5.2.5. Overall Design Alternatives

With the building design goals set, the design team proposed the use of 26 building systems and design strategies. The design team developed a 'Baseline Green' alternative for the Living Laboratory Green Dorm, which included the first 8 points of the listed sustainable strategies (Table 5.1). The 'Baseline Green' alternative is based on the wood bearing wall structure. In addition, the design team proposed a second alternative named the 'Living Laboratory' that incorporated additional technologies and building systems in order to support performance, research, and educational goals. The 'Living Laboratory' alternative is based on the steel frame structure and incorporates the 26 sustainable strategies (Table 5.2). Figure 5.4 presents the sustainable design strategies (Stanford University 2006b).

Table 5.1 Sustainable design strategies for ‘Baseline Green’ design.

#	**‘Baseline Green’ Wood Structure**
1	Solar orientation for passive solar design, for winter heating, and for summer comfort without air conditioning
2	Sunshades and high performance glazing for energy savings
3	Radiant floor slab heat delivery for energy savings
4	Fly ash/ slag, low-cement concrete for reducing embodied energy
5	Natural ventilation for energy savings and indoor-air quality
6	Efficient and effective light fixtures for energy savings
7	Optimized 24” on center spacing (instead of 16”) for wood framing for reducing material use
8	Dual flush toilets and waterless urinals for water savings

Table 5.2 Additional sustainable design strategies for ‘Living Laboratory’ design.

#	**‘Living Laboratory’ Additional Strategies and Steel Structure**
9	Steel rocking frame for better building performance after an earthquake
10	Bio-composite materials for reducing embodied energy
11	100% daylight interior integrated with electric lighting controls
12	Triple-paned, double low-e windows (super-efficient windows) on residential floors for energy efficiency and thermal comfort
13	Lime plaster & salvaged wood for reducing use of new material and improving the project’s impact on climate and ecosystems
14	Fuel cells for onsite energy generation
15	Ground-source heat pump for reducing HVAC requirements
16	Plug-in electric vehicle fueling
17	Indoor air monitoring for research
18	Rainwater collection for water savings
19	Green roof test beds for research
20	Double piping for water recycling
21	Grey-water recycling including a 5,500-gallon underground storage tank with a filter for use in grey water for toilets, irrigation, and laundry, and heat recovery including shower water heat recovery
22	Membrane bioreactor for water treatment
23	Photovoltaic panels (46 kW photovoltaic array) for onsite energy generation
24	Solar hot water panels (475 ft^2 solar hot water array) for onsite water heating
25	Net-zero storm water discharge for reducing the burden on sewer system
26	Monitoring of all utility systems for research

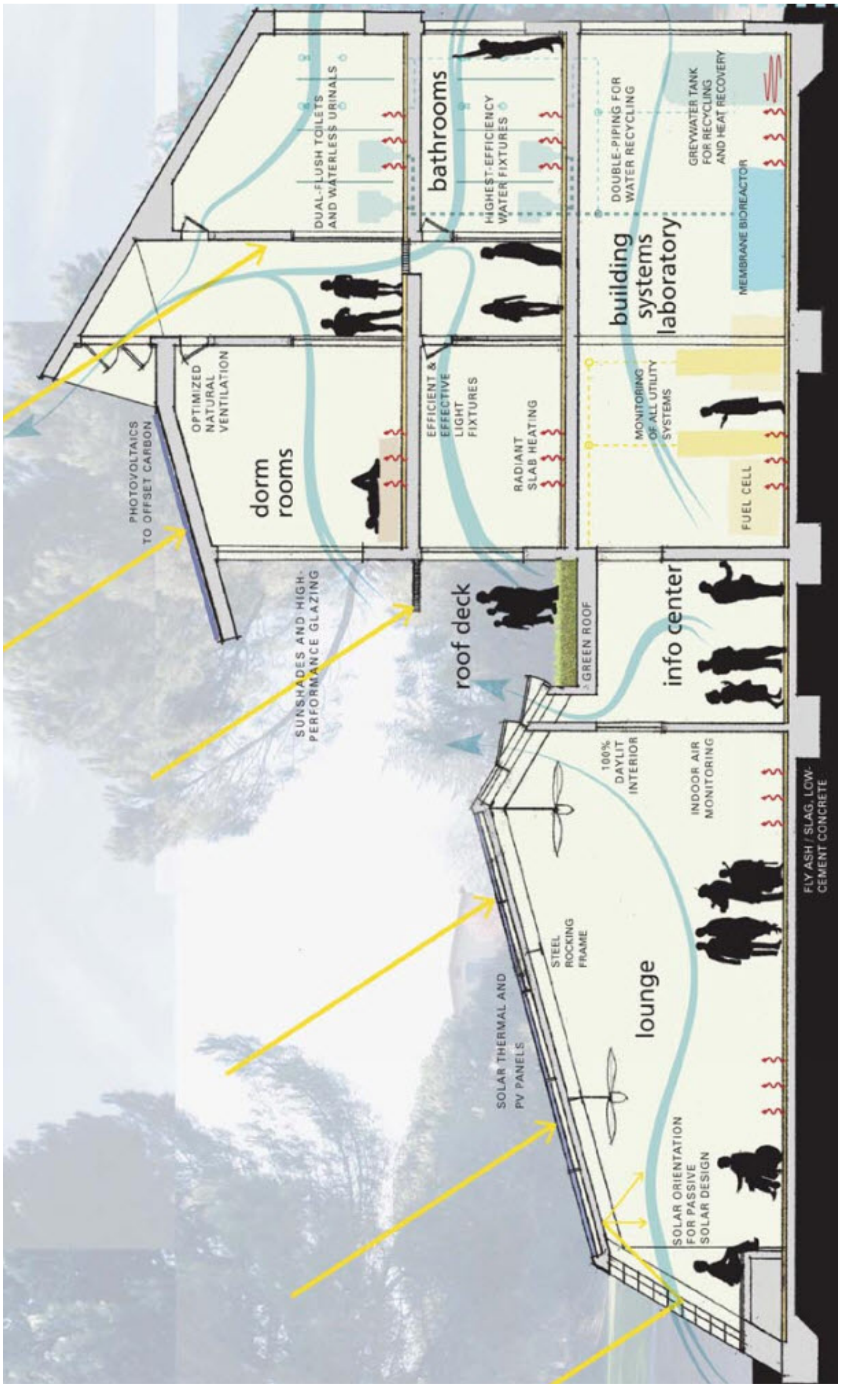


Figure 5.4 Sustainable strategies by EHDD Architecture (Stanford University 2006b).

According to the feasibility report (Stanford University 2006b), the design team came to the following building cost conclusions:

- The 'Baseline Green' building cost is equal in first cost to the benchmark construction cost of $9.65 million. Therefore, sustainable housing at Stanford can be first cost neutral.
- The 'Living Laboratory' construction cost is $12.2 million. Additional costs are directly assignable to items providing research, education, and demonstration opportunities.
- The life cycle cost analysis shows long-term paybacks for many sustainable features. A life-cycle cost analysis shows 30-year payback for the 'Living Laboratory' alternative.

5.3. Case-Study Protocol

The case-study protocol describes the steps that the researcher followed for understanding the use of WRC in the project and how CBA could have being applied.

1. The researcher interviewed David Mar to understand how the decision-making matrix was applied in this project and what the assumptions had been behind the method used for selecting the alternatives. In this interview the decision method and the interdependency between factors were discussed in depth.
2. The researcher obtained public data to understand the project background and the interrelation between the different building systems. This information was obtained through reports (Stanford University 2006b) that explained the rationale behind the WRC method.
3. The researcher was able to identify attributes for applying CBA between two alternatives, wood and steel.
4. The researcher prepared an example of a CBA application, and analyzed the differences between WRC and CBA.
5. The researcher wrote a report with the case study that was sent to the structural engineer to obtain feedback.
6. Finally, the feedback was incorporated in the conclusions.

5.4. WRC Application

The design team used a collaborative decision-making process, where architects, structural engineers, and Stanford faculty were involved. They used WRC, a simple form of value-based method (Section 3.2.2), to make the decision. It is important to mention that the feasibility report (Stanford University 2006b) does not mention the name of the method. As mentioned before, the design team did a ranking of 7 alternatives and then did a deeper analysis to choose between the two best alternatives.

The next sections summarize the application WRC method. However, this was not necessarily a linear process, as the design team required many meetings and probably iterations.

5.4.1. Step 1: Identify Alternatives

The seven alternatives for the structural system of the building were (Stanford University 2006b):

1. Wood bearing wall. Using Forest Stewardship Council (FSC) certified wood, resource efficient framing and plywood shear-walls.
2. Steel frame with metallic deck and concrete topping. Using rocking and restoring system with replaceable fuses including post-tension cables, steel fuses, and Engineered Cementitious Composites (ECC) fuses. The main idea is that these fuses concentrate the building's damage during an earthquake and can be replaced after that.
3. Wood post and beam. Using FSC certified wood, plywood shear-walls, 1.5" concrete or gypcrete topping and Structural Insulated Panels (SIP) skins.
4. Metal stud bearing wall. Using plywood shear-walls, 1.5" concrete or gypcrete topping and plywood floor diaphragm.
5. Concrete slab and walls. Using plywood shear-walls, 1.5" concrete or gypcrete topping and plywood floor diaphragm.
6. CMU bearing wall/wood floor. Using FSC certified wood, resource efficient framing, plywood shear-walls, plywood floor diaphragm and rigid insulation (3") on exterior wall.
7. Straw-bale/wood frame. Using FSC certified wood, resource efficient framing, plywood shear-walls and lime plaster skins.

5.4.2. Step 2: Identify Factors and Criteria for Evaluation

The design team used 11 factors for the decision, and they classified them as life-cycle cost, environmental, and others. The following section presents the rationale behind the factors (Stanford University 2006b).

Life-cycle cost factors: These factors pertain to the impact of the structure in the life-cycle cost of the building.

(1) First cost: It measures the investment or initial cost of the building.

(2) Construction speed: It measures the speed of construction of the different structural systems.

(3) Earthquake losses: It measures the future earthquake (EQ) losses, which are comprised of architectural damage, structural damage, content damage and loss of use—all caused by building drift (the measure of lateral distortion between floors) and accelerations.

(4) Maintenance/durability: It measures the impacts from the maintenance of buildings over their life times. Building maintenance activities like cleaning and repairs are often causes of complaints from building occupants. Therefore, maintenance requirements should be minimized.

Environmental factors: These factors pertain to the impact of the structure on the embodied energy and on the energy required to operate the building.

(5) Embodied energy: It measures the carbon load on the environment needed to produce the building. For example, the carbon impact of every cubic yard of concrete used can be measured as the sum of CO_2 produced in making and transporting the cement and other ingredients.

(6) Thermal mass: It refers to the ability of a material to store heat energy. A large thermal mass will reduce the amount of energy in the use of the building.

(7) Insulation: It refers to the ability of a material to slow down the transfer of heat energy. It measures the insulation capacity of the structure. It also contributes to the net carbon impact, since it affects the carbon quantities produced from operations over the building's lifetime.

Other factors: These factors were aligned with the design goals of the building, especially providing desirable housing and a living laboratory on campus.

(8) Research value: It measures the research potential for the design, the construction and the use phase (performance monitoring) of the structure itself by the structural engineering faculty and students.

(9) Thermal comfort: It measures the qualitative benefit to occupants of the building's mass moderating effect on overheating. This factor is also influenced by other decisions. For example, solar orientation with long north-south building facades will limit the number of rooms with west or east-facing windows, as these are difficult for sun shading control. This will be combined with properly-sized roof overhangs and sunshades to keep the hot sun out in the summer while allowing passive solar gain in the winter.

(10) Deconstructability: It measures how easy it is to deconstruct the structure after its use has come to an end.

(11) Flexibility: It measures how flexible the structure is with respect to future changes. This includes internal spaces and the installation of new building systems.

5.4.3. Step 3: Weigh Factors

The design team assigned weights to the factors using a scale from 1 to 5 for each factor. According to the structural engineer, the rationale behind the weighting of factors was done for this particular project context, including the building location, earthquake probabilities and weather characteristics among others. The weights of factors were agreed among the stakeholder. Table 5.3 presents the weights of factors.

Based on the Stanford University (2006b) feasibility report the rationale for the weight of factors is the following:

- For the life cycle factors: "the weighting was greatest for the factor 'first cost' with 5 on a 1 - 5 scale, this reflects the cost constraints of the project. 'Earthquake losses' had the next largest weight with 3, which is relatively high compared with the rest of the factors. This was justified by the fact that the effects of local seismicity are clearly an issue in the Bay Area. 'Construction speed' was given a weight of 1. 'Maintenance/durability' was given a weight of 1. These four factors together accounted for the building's life cycle cost, with an overall effective weight of 10."

- For the environmental factors: “recognizing the environmental impact of constructing the dorm and lab, ‘embodied energy’ has a relatively large weight of 3. ‘Mass’ and ‘insulation’ were given a weight of 1 each. These relatively low values reflect the minor beneficial impact that added mass and insulation have on the operating costs of the project in light of California’s mild climate. The cumulative carbon impact weight, made up of these three factors, is 5.”
- For the other factors: “The factor ‘research value’ had a weight of 4, reflecting the priorities of the CEE Department. ‘Thermal comfort’ was assigned a weight of 2, representing the qualitative benefit for students due to the building’s mass moderating the effects of overheating. ‘Flexibility’ and ‘deconstructability’ were each given a low weight of 1, since both are benefits that can only be realized in the distant future.”

Table 5.3 WRC Steps 1 to 5 for choosing a structural system (Adapted from Stanford University 2006b).

Structural System Stanford Green Dorm	**Life Cycle Cost Factors (10 points)**				**Environmental Factors (5 points)**			**Other Factors (9 points)**				**Total (Weighted)**	**Total Life Cycle Cost Factors**	**Total Environmental Factors**
	First Cost	**Construction Speed**	**Earthquake Losses**	**Maintenance/Durability**	**Embodied Energy**	**Mass**	**Insulation**	**Research Value**	**Thermal Comfort**	**Deconstructability**	**Flexibility**			
Factors weight (1-5)	5	1	3	1	3	1	1	4	2	1	1			
1. Wood bearing wall	5	3	1	3	5	2	3	1	3	3	2	69	34	20
2. Steel frame/Metallic deck/ Concrete Topping	3	5	4	5	2	4	3	4	4	4	5	83	37	13
3. Wood post and beam	3	3	2	3	5	2	3	1	3	4	4	65	27	20
4. Metal stud bearing wall	4	3	2	5	2	2	3	1	3	1	2	58	34	11
5. Concrete slab and walls	1	2	4	5	1	5	3	4	5	1	4	66	24	11
6. CMU bearing wall/wood floor	3	1	2	4	3	4	3	2	2	2	2	58	26	16
7. Straw-Bale/wood frame	3	3	1	3	4	4	5	2	5	3	1	67	24	21

The weighted factors intent to reflect the collective values of the design team and members of the structural engineering faculty. According to Stanford (2006), they can be subject to further discussion and adjustment as needed.

5.4.4. Step 4: Rate Alternatives for Each Factor

The design team performed different studies in order to understand the performance of each alternative considering the 11 factors. Then using a scale from 1 to 5 (1 least desirable), they determined the rating (attribute's weight) of the alternatives for each factor (Table 5.3). For example, for the factor 'embodied energy', alternative 1 (wood bearing wall) is assigned an attribute weight of 5, since it is the one that has less embodied energy, which is more desirable from the environmental perspective. For this same factor, alternative 5 (concrete slab and walls) is assigned an attribute weight of 1, since it is the least preferred alternative in this regard. It is not clear for the researcher if they assumed or not a linear scale from 1 to 5, meaning that every increment in performance is worth the same.

This section presents the life-cycle cost analysis and the attributes used for rating alternatives 1 and 2, which were studied in more detail by the design team. Attributes of the other alternatives were not available for the researcher. More information may have been available for the design team, however this section is based only on the Stanford University (2006b) feasibility report. It is not clear to the researcher if the rating of attributes represent a quantitative analysis or expert judgment, which may be reasonable to expect at this stage of the design.

5.4.4.1. Life-Cycle Cost Analysis

The design team working with Stanford structural engineering faculty performed a life-cycle cost analysis that includes initial construction costs, the costs of implementing the seismic system, and the possible damages and repairs resulting from earthquake damage. They quantified the effects of local seismicity through life cycle cost analysis. While costs for enhanced, high-performance seismic systems come at a premium above conventional construction costs, they should be thought of as investments against future losses (e.g., additional strength and specially-detailed frames which have self-centering systems and replaceable fusible elements).

According with Stanford University (2006b), seismic loss studies indicate that buildings designed to meet but not exceed current building codes are likely to sustain damage of approximately 15-50% of their construction cost under the cumulative effect of the seismic hazard. This stems from the fact that modern building codes are only meant to ensure life-safety during large earthquakes, not necessarily to control damage to the building structure or the architecture. The aggregate expected damage is significant and the associated repairs and rebuilding should be considered when evaluating design attributes for the Green Dorm.

The design team conducted a life-cycle cost analysis on the following three systems:

1. Wood alternative with lateral resisting system consisting of plywood shear walls and conventional partitions.

2. Steel alternative with conventional partitions.

3. Steel alternative with improved partitions with special detailing to delay their damage.

Systems 2 and 3 include a lateral resisting system consisting of a self-centering rocking brace system.

Table 5.4 summarizes initial costs, expected annual losses from earthquake damage, and annualized life-cycle costs for the three alternatives.

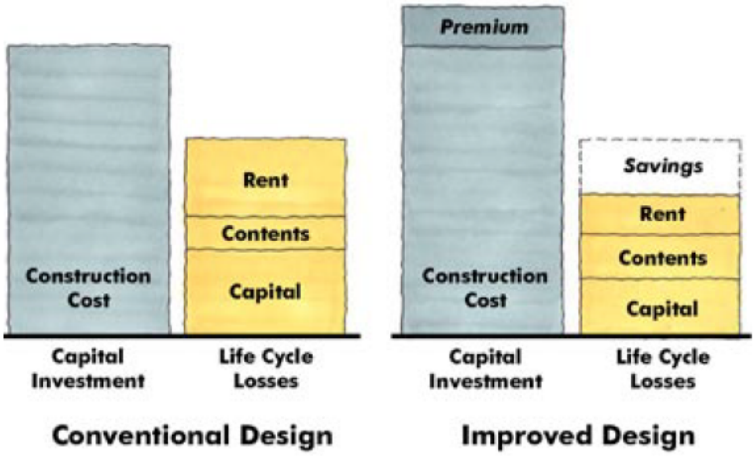


Figure 5.5 Payoff investments of improved structural design (Stanford University 2006b).

Table 5.4 Life-cycle cost of the alternatives considering earthquake losses (Stanford University 2006b).

Scheme	**Initial Construction Cost**	**Cost Premium Compared to Wood**	**Expected Annual Loss from Earthquake Damage**	**Annualized Lifecycle Costs**
Wood with conventional partitions	$6,375,000	$-	$72,141	$199,641
Steel with conventional partitions	$6,605,000	$230,000	$28,244	$160,344
Steel with improved partitions	$6,700,000	$325,000	$22,258	$156,258

According to Stanford (2006), the first alternative is the one with the smallest initial cost, but it is the most flexible system and the one that sustain the largest amount of damage. The third alternative is the most expensive but the one that is likely to sustain the smallest amount of damage. As shown in the last column the option with the smallest annualized life cycle cost is the steel structure using improved partitions.

The initial structural performance investment, or cost premium, of the steel alternative over the wood alternative was $230,000 (Table 5.4). However, the savings of the steel alternative over the wood alternative was $1,964,869, based on the life cycle cost analysis (Table 5.4). The work is based on the site-specific earthquake hazards, performance-based design of the structure, and loss estimation tools developed by CEE structural faculty.

5.4.4.2. Attributes of Alternatives 1 and 2

(1) First cost

The design team estimated that the first cost of the wood structure alternative is lower than the first cost of any of the two steel structure alternatives, as Table 5.4 shows. The wood structure is the one with the smallest initial cost.

(2) Construction speed

The design team estimated that the speed of construction of the steel structure would be faster than the wood structure.

(3) Earthquake losses

The design team estimated that the steel alternative excels in long-term performance for better seismic durability. The lateral strength in the wood alternative comes from plywood-sheathed shearwalls, distributed throughout the building, which are tough and inexpensive. However, under high seismic loads, the wood walls will sustain damage that can be extensive and expensive to repair. In particular, plywood shearwalls will experience some type of damage at interstory drifts (relative horizontal displacement between two consecutive floors) as small as 1⁄2" and will suffer significant amounts of damage requiring replacement at interstory drifts on the order of 2".

The steel alternative can be designed to sustain minimal structural damage and lower levels of non-structural damage. The lateral system can have frames made to stay elastic, except for discrete yielding elements that can be replaced after an earthquake. The frames can also have self-centering capabilities to reduce permanent drift.

(4) Maintenance / durability

The design team estimated that the steel alternative excels in durability and requires less maintenance compared to the wood alternative.

(5) Embodied energy

The design team considered that a building's initial carbon impact is driven by the amount of carbon in the structural materials. To assess this impact for the Green Dorm, the embodied carbon of structural materials was quantified using data extracted from the ATHENA LCA software database (Figure 5.6). The data shows that emissions are around 0.1 lbs of CO_2 per lb of concrete, 1.3 lbs of CO_2 per lb of structural steel, and 0.1 lbs of CO_2 per lb of wood wall stud.

The weight of the material was also considered in the analysis. On one hand aluminum has a very high embodied-carbon per pound (around 9.1 lbs of CO_2 per lb of aluminium), but its total weight in the building is minimal. On the other hand, concrete has low embodied carbon per pound, but dominates the weight of a building, usually being the largest contributor to embodied carbon when considering building materials (Figure 5.7). Thus, the Green Dorm's initial carbon impact is driven by the amount of concrete in the structure.

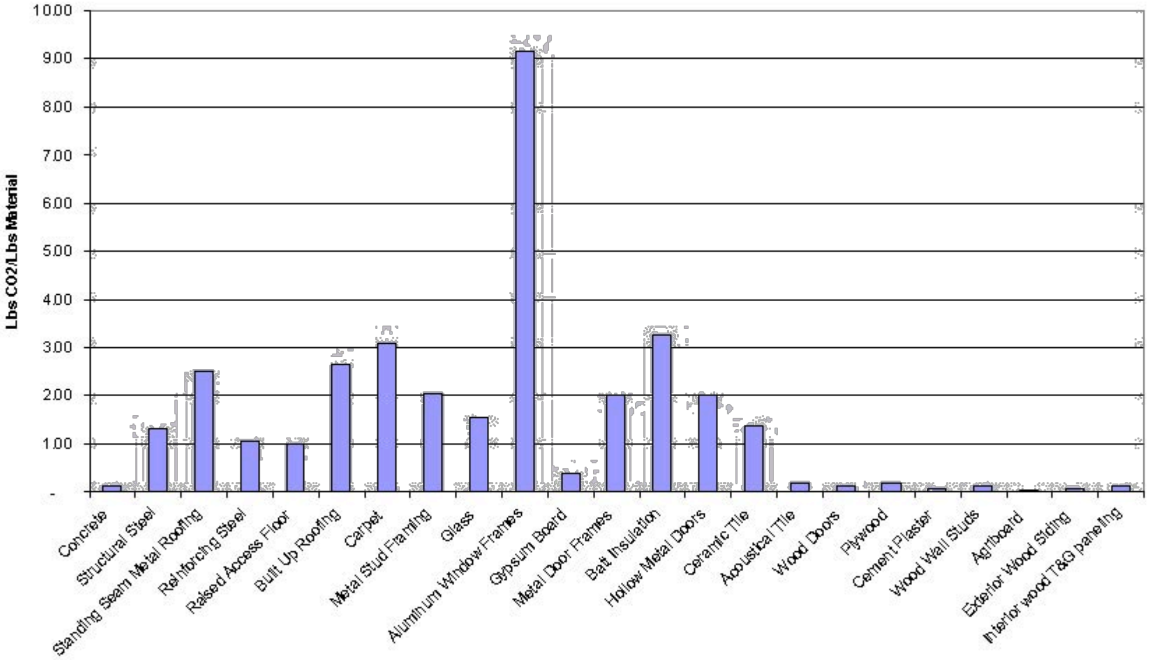


Figure 5.6 Embodied carbon of major materials in lb of CO_2 per lb of material (Figure 5.27 in Stanford University 2006b).

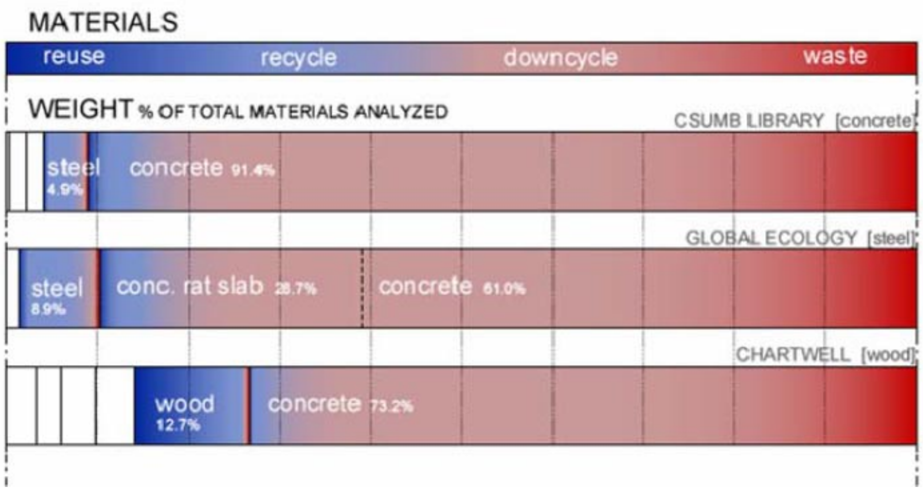


Figure 5.7 Predominance of structural materials in buildings (Figure 5.28 in Stanford University 2006b).

The design team identified the need to reduce the amount of concrete in the design and to make the concrete only as strong as needed. In addition, the design team worked with the Stanford CEE structural faculty to optimize low cement concrete mixes. According to Stanford University (2006b), using cement substitutes, such as slag or fly ash, reduces cement use and can lower the total embodied energy in concrete by over 50% when compared to traditional mixes.

The design team estimated that the wood structure would have a significantly lower carbon impact than concrete because it stores carbon and has a much lower embodied energy.

(6) Thermal mass

The design team estimated that the steel alternative has a higher thermal mass than the wood structure. However, it is not expected to contribute significantly to reducing the operation costs because of the area's mild climate. Much of the 'value' of the thermal mass will be felt through passive cooling in the summer when no air conditioning is provided in any case.

(7) Insulation

The design team estimated that the insulation for alternatives 1 and 2 is expected to be similar.

(8) Research value

The design team estimated that the steel structure presents much richer opportunities for research for the Stanford structural engineering faculty than the wood alternative. Stanford University (2006b) mentions three areas of study related with the steel structure. (1) Evaluating alternative lateral systems based on life-cycle cost as well as first cost. (2) Designing and evaluating the cost effectiveness of a damage resistant building skin and partitions. (3) Evaluating the potential use of self-centering systems, replaceable yielding elements and new high-performance structural materials. These types of frames were being studied by Stanford faculty with assistance from Tipping Mar and Associates.

(9) Thermal comfort

The design team estimated that the steel alternative has a higher thermal mass, with significant potential for improved thermal comfort. This is a qualitative 'value' based on the occupants' comfort from high mass, which reduces the likelihood of overheating.

(10) Deconstructability

The design team estimated that the steel alternative is somewhat better than the wood alternative for potential reuse of the frame after deconstruction. The beams and columns will all be bolted together and can be easily disassembled. The concrete over metal deck cannot be reused without down cycling.

The wood alternative is more difficult to deconstruct because of all the nailing. The plywood sheathing on the floors and shearwalls will most likely be destroyed as will the concrete topping. The framing members can be used again if the nails are removed.

(11) Flexibility

The design team estimated that the steel alternative is a post and beam system that is extremely flexible with a widely spaced grid and few discrete frames. This leaves the plan relatively open for reconfiguring the internal spaces. The steel framed system can accommodate future reconfigurations of the walls, the spaces and their functions.

The wood alternative is relatively inflexible. Almost all of the room walls are shearwalls and most will be bearing walls. This means that any future alterations would be difficult and expensive.

5.4.5. Step 5: Calculate the Value of Each Alternative and Come to a Final Decision

Table 5.3 shows that the wood bearing wall system, alternative 1, had the second best total score of 69 and was chosen for the ‘Baseline Green’ alternative. The steel structure system, alternative 2, had the best total score of 83 and was selected for the ‘Living Laboratory’ alternatives

According to the Stanford University (2006b), the wood alternative scored well for ‘life cycle cost’ factors at 34, with the steel alternative at a slightly higher 37 due to lower ‘EQ losses’ and ‘construction speed’ offsetting higher ‘initial costs’ than the wood alternative. However, this project may have a first cost threshold value, beyond which the project is not viable.

According to Stanford University (2006b), “Reducing the building’s initial carbon impact was a priority, and wood has a significantly lower impact since the material stores carbon.” Wood was suitable for the program and had the lowest first cost. It would likely be the standard market structural system selected for this building type. However, stakeholders decided to consider the impact of future damage due to natural hazards, and the life cycle costs associated with the major repairs that may be required.

According Stanford University (2006b), an initial investment in the seismic safety of a building would significantly reduce life cycle costs, both environmental and financial, over the lifespan of the building.

The analysis performed by the design team showed that steel structure was much more durable and cost effective. Its long-term benefits outweigh the higher initial dollar and embodied energy costs, and it was therefore selected for the Living Laboratory Design.

5.5. CBA Application

The following sections present what the analysis for choosing an alternative might look like if the design team were applying Choosing by Advantages to this problem.

5.5.1. Step 1: Identify Alternatives

The alternatives considered were the two alternatives that were explored in detail, wood and steel structure (alternatives 1 and 2) described in section 5.4.1.

5.5.2. Step 2: Define Factors

The factors would be the same as originally used, but cost will be treated separately in CBA. Cost will be analyzed in step 7 as a constraint for the project. The factors and criteria will judge the potential attributes of the alternatives since the detail design of the 2 alternatives does not actually exist.

5.5.3. Step 3: Define the ‘Must’ and ‘Want to Have’ Criteria for Each Factor

The factors and criteria are summarized in the first column of Table 5.5. The criteria were derived from the report, and were well described by the design team and aligned with the project goals. In CBA cost cannot be a factor, therefore it was separated from the analysis.

5.5.4. Step 4: Summarize the Attributes of Each Alternative.

According to the information provided by the feasibility report, Table 5.5 presents the attributes of the alternatives. The attributes describe characteristics of the two alternatives according to the design team.

5.5.5. Step 5: Decide the Advantages of Each Alternative

The design team can obtain the advantages by applying the criteria and comparing the attributes of the alternatives (Advantages in Table 5.5). In this case it is clear that the steel structure alternative has advantages in every factor except for embodied energy and insulation.

5.5.6. Step 6: Decide the Importance of Each Advantage

Table 5.5 presents the complete CBA table, showing steps 1 to 6. In this case the values of IofA were assigned by the researcher, based on the project data, and not by the design team for the purpose of exemplifying the use of CBA.

The process of deciding the Importance of Advantages (IofAs) is subjective. However, CBA provides a clear guide to make trade-offs using the attributes of the alternatives in the context of the decision. In a real application of CBA, the design team would need to agree on the IofAs.

The researcher’s rationale for choosing the IofA scores is explained here:

- According to the data it appears that the most important advantage is that the steel structure presents much richer opportunities for research than the wood structure. As specified by the design team, this was one of the goals of the building and the steel structure has an important advantage compared to the wood structure. Accordingly, the researcher assigned 100 points to this advantage. This is the paramount advantage, which is used as point of comparison to score other advantages.
- The embodied energy advantage is important since wood production and transportation have a significantly lower carbon impact than steel and concrete, but this seems somewhat less important than the paramount advantage. At the same time, a steel structure has significantly less EQ losses than the wood structure and seems equally important to the embodied carbon advantage that wood has over steel and concrete. Therefore, the researcher assigned 80 points to both advantages.

Table 5.5 CBA steps 1 to 6.

Factor (Criterion)	**Alternative 1: Wood Bearing Wall Structure**		**Alternative 2: Steel frame /Metallic deck/ Concrete Topping**	
1. Construction Speed	Att.: Slow when constructed on site.		Att.: It is fast to construct.	
(The faster, the better)	Adv.:	Imp.:	Adv.: *Faster to construct than wood structure*	Imp.: 10
2. Earthquake Losses	Att.: It will presents significant architectural, structural, and content damage.		Att.: It will presents moderate architectural, structural, and content damage.	
(The lower EQ losses, the better)	Adv.:	Imp.:	Adv.: *It has significantly less EQ losses than wood.*	Imp.: 80
3. Maintenance/ Durability	Att.: It requires frequent cleaning and repairs.		Att.: It will require sporadic cleaning and repairs.	
(The less maintenance required, the better)	Adv.:	Imp.:	Adv.: *Steel frame is easier to maintain than wood.*	Imp.: 30
4. CO_2 Emissions - Embodied energy.	Att.: Wood stores carbon and has a low embodied energy, and it is light.		Att.: Steel and concrete have high-embodied carbon.	
(The less CO_2 emissions, the better)	Adv.: *Wood emits significantly less CO_2 than steel and concrete.*	Imp.: 80	Adv.:	Imp.:
5. Thermal Mass	Att.: It will have only thin concrete or gypcrete topping slabs on the floors providing little thermal mass.		Att.: The exposed concrete over metal deck and floors provides exposed thermal mass.	
(The more thermal mass, the better)	Adv.:	Imp.:	Adv.: *The steel alternative has a higher expected thermal mass.*	Imp.: 20
6. Insulation	Att.: Good insulation material		Att.: Good insulation material	
Criterion: The higher insulation, the better	Adv.: -	Imp.:	Adv.: -	Imp.:
7. Research value	Att.: Not so valuable for research.		Att.: Very interesting for research.	
(The more interesting for research, the better)	Adv.:	Imp.:	Adv.: *Steel is more interesting for research than wood.*	Imp.: 100
8. Thermal Comfort	Att.: It has low thermal mass, which is less effective in reducing overheating.		Att.: It has a high thermal mass, which reduces the likelihood for overheating.	
(The higher thermal mass, the better)	Adv.:	Imp.:	Adv.: *Steel reduces the likelihood for overheating when compared to wood.*	Imp.: 30
9. Deconstructability	Att.: Difficult to deconstruct because of all the nailing.		Att.: Bolted beams and columns are easy to disassemble. Concrete over metal deck requires down cycling.	
(The easer to deconstruct, the better)	Adv.:	Imp.:	Adv.: *Slightly easier to deconstruct than wood structure.*	Imp.: 30
10. Flexibility	Att.: It is relatively inflexible. Most room walls are bearing walls. This means that any future alterations would be difficult and expensive.		Att.: It has a post and beam system that is extremely flexible. It has a widely spaced grid. It can easily accommodate future reconfiguration.	
(The more flexible, the better)	Adv.:	Imp.:	Adv.: *Considerable more flexible than wood.*	Imp.: 50
Total IofAs		80		350

- The advantage of the steel structure being considerably more flexible than the wood structure seems to be of medium importance compared to the paramount advantage. Therefore, the researcher assigned 50 points.
- The advantages of the steel and concrete structure being more durable, less likely to cause overheating, and being somehow easier to deconstruct than the wood structure seem to be on the same level of importance. While these advantages provide a gain in 'value,' they are not as important as the paramount advantage, and thus the researcher assigned 30 points to each of the advantages.
- The advantage that the steel structure has a higher expected thermal mass than wood is not that important since it is not going to provide a huge difference in terms of energy savings as explained in the project feasibility report. Therefore, the researcher assigned it 20 points.
- The advantage that the steel and concrete wall would be faster to construct than wood wall, does not seem to be important for the overall goal of the project. Therefore, researcher assigned only 10 points to this advantage.
- Finally, none of the alternatives has an advantage with regard to insulation value.

Finally, the total IofA for alternative 1 is 80 and for alternative 2 is 380.

5.5.7. Step 7: Evaluate Cost Data

Comparing the IofA with first cost and lifecycle cost, decision makers need to decide which alternative to use.

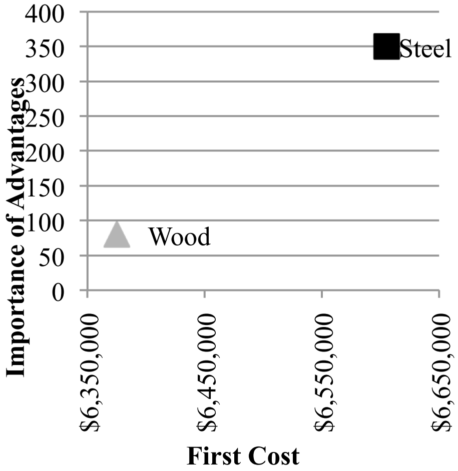


Figure 5.8 IofA vs. first cost.

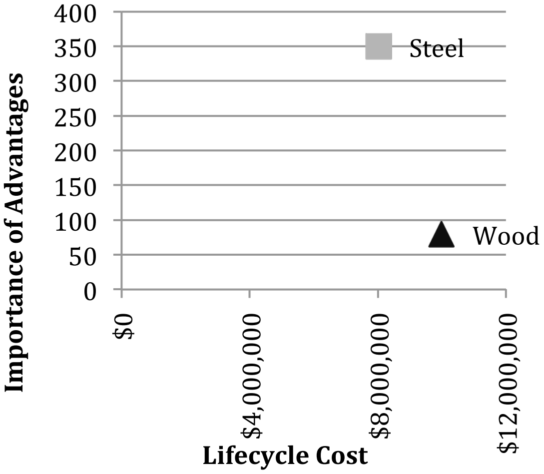


Figure 5.9 IofA vs. lifecycle cost.

From Figure 5.8 the design team should ask if it is worth paying $230,000 ($6,605,000 – $6,375,000) for obtaining 350 instead of 80 IofA points. It is evident that by choosing the wood-bearing wall the design team will be sacrificing important advantages for saving around 3-4% of the initial cost of the project. The three most important advantages being sacrificed would be the steel structure with much richer opportunities for research than the wood structure, the steel structure with significantly less EQ losses than the wood structure, and the steel structure with considerable more flexibility than the wood structure. It seem, that even from a short-term monetary perspective, the design team should choose the steel structure, if they have the available funds.

Figure 5.9 shows that in the long term the steel structure is better with regards to cost and IofAs. Therefore, it should be selected. In context of this project, this decision makes sense since Stanford University will realize the benefits in the long term.

5.6. Discussion

Mar (2012b) expressed confidence that they made the right decision, and he stated that they conducted a rigorous analysis to assign numbers in the decision matrix (WRC Table 5.3). He emphasized that the analysis considered earthquake losses in the sustainability perspective. This case was interesting for the researcher to study because the design team took the time to document their decision-making process, which is not a common practice in the industry. However, the goal of this chapter is to compare WRC and CBA, and both methods have important differences in the way the information is presented and summarized. Even when the final decision in this case seems to be obvious using both methods, CBA presents the information in a more clear and transparent fashion. Some differences are presented next.

1. Double Counting Cost

WRC allows mixing cost with ‘value’ of the alternatives. In this case cost was incorporated as a factor with all the others. In contrast, CBA treats cost as a resource. In this way the design team can describe the advantages of the alternatives and the ‘value’ they provide (Figures 5.9 and 5.10), and then evaluate if they have the resources or if they need to seek more funding.

2. Weighting Factors and Attributes vs. Weighting Advantages

Figures 5.11 and 5.12 present a visual illustration of WRC and CBA. In WRC decision makers had to debate the general importance of factors. For example, deciding if ‘research value’ is more important than ‘thermal mass’ and then ‘value’ the attributes in order to calculate and overall score. In contrast, in CBA decision makers need to discuss the relative importance of specific advantages.

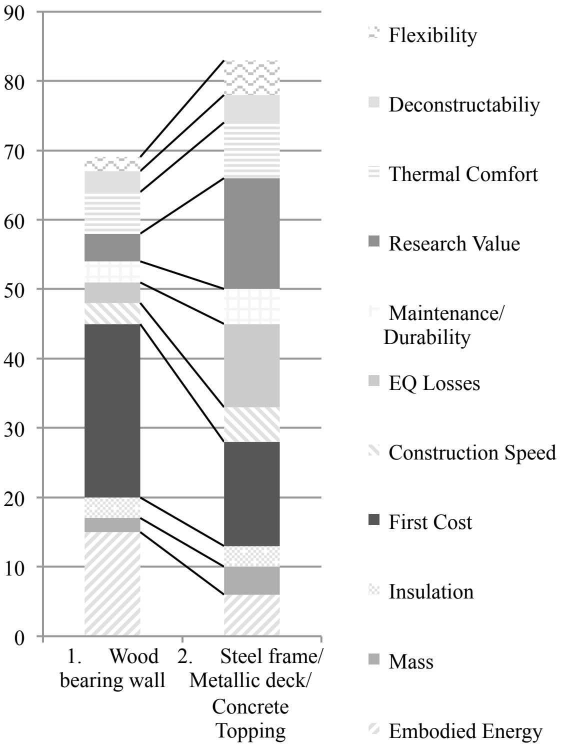


Figure 5.10 WRC scores.

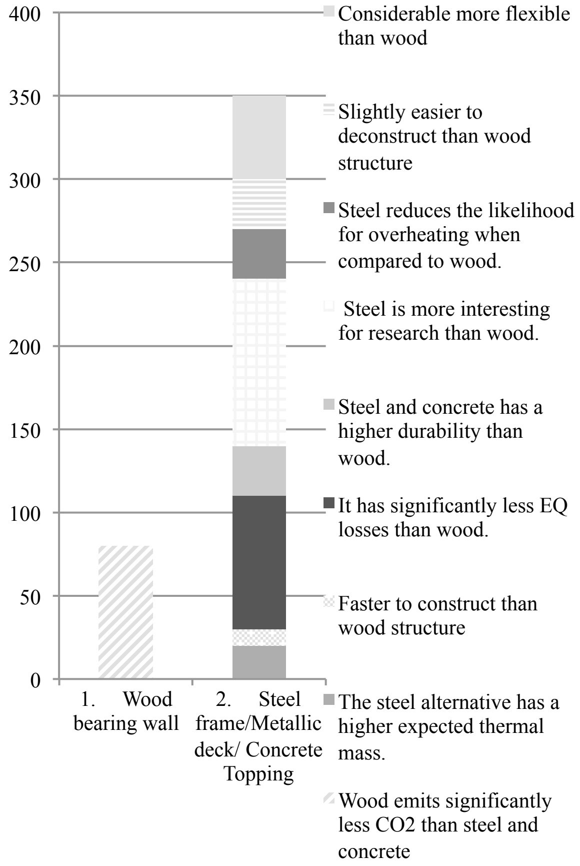


Figure 5.11 CBA IofAs.

3. Impacts of removing non-differentiating factors

In this case the factor 'insulation' does not differentiate between steel and wood alternatives. The effect of removing that factor from the decision has different consequences in WRC and CBA. In CBA the decision remains the same if 'insulation' is removed because none of the alternatives has an advantage. In contrast, in WRC the final decision does not change, but the intensity of the preferences does change (Table 5.6).

If 'insulation' is removed from the list of factors, wood would have 66 points and steel 80 points (case II in Table 5.7), in comparison with 69 vs. 83 in the original case (case I in Table 5.7). As Table 5.6 shows, the percentage between the preferences of the alternatives changes slightly. This may not be relevant for this decision, but stakeholders may have done that to other factors with high scores in WRC and the differences would have been bigger.

Table 5.6 Impacts of removing insulation factor in WRC.

Dorm/Common Lab spaces	**Life Cycle Cost Factors (10 points)**				**Environ-mental Factors (4 points)**		**Other Factors (8 points)**						
	First Cost	**Construction Speed**	**EQ Losses**	**Maintenance/Durability**	**Embodied Energy**	**Mass**	**Research Value**	**Thermal Comfort**	**Deconstructability**	**Flexibility**	**Total (Weighted)**	**Total Life Cycle Cost Factors**	**Total Environmental Factors**
Factors weight (1-5)	5	1	3	1	3	1	4	2	1	1			
1. Wood bearing wall	5	3	1	3	5	2	1	3	3	2	66	34	17
2. Steel frame/Metallic deck/ Concrete Topping	3	5	4	5	2	4	4	4	4	5	80	37	10

Table 5.7 Final preferences when removing insulation factor in WRC.

	Case I	**%**	**Case II**	**%**
Wood	69	45.4%	66	45.2%
Steel	83	54.6%	80	54.8%

Next section summarizes the differences between WRC and CBA. Table 5.8 presents a summary of the characteristics of WRC and CBA.

1. Transparency on trade-offs inside a factor (Must not assume that attributes can be weighted or normalized)

WRC assumes linear trade-offs of attributes. This means than every increment in performance within a factor is equally valuable. Would this be the case when analyzing construction speed? Does every day of reduction have the same importance? Is there a range in which it is not acceptable to trade-off a day for any other attribute? Is there a range in which saving one more day is not valuable anymore?

In CBA the attributes do not need to be described in a scale, CBA uses the original units from the attributes. In CBA linear trade-offs are not assumed. The criteria represent a guideline to make judgments, but it does not require every increment in performance to be valued equally.

Table 5.8 Differences between WRC and CBA highlighted in comparative case study 3.

Factor (Criterion) for MCDM methods	**Weighting Rating and Calculating**	**Choosing By Advantages**
1. Transparency on trade-offs inside a factor (Must not assume that attributes can be weighted)	WRC assumes that all increments in attribute performance are equally valuable.	CBA does not assume that attribute scales have an inherent value.
2. Transparency on trade-offs between factors (Must not assume linear trade-offs between factors)	WRC may assume that trade-offs between sustainability factors are linear functions.	CBA makes clear what the trade-offs between advantages are, and there is no assumed trade-off function.
3. Focus on differentiating alternatives (Must help differentiate the alternatives)	WRC May not help in differentiating alternatives because it is not based on differences of attributes.	CBA bases judgments on advantages.
4. Analyzing Cost (Must be treated separately from value)	Cost can be a factor and be mixed with the intrinsic value of the alternative.	Cost is not a factor. It is treated separately from value.
5. Consistency (The result must not change when removing non-differentiating factors)	In WRC the intensity of the preferences changes when irrelevant factors are removed. If factors must add up to a given total, then rank order may be reversed when irrelevant factors are removed.	In CBA the decision does not change if irrelevant factors are removed.
6. Collaboration (Must avoid conflicting trade-offs between high-order of abstraction concepts)	WRC requires weighting factors, which are high-order of abstraction concepts, possibly hard to agree upon because of their abstraction.	CBA requires agreement on (more objective) advantages and postpones value judgment until later, which may minimize conflict.
7. Context specific (Must consider a specific context for all judgments)	WRC lacks context specificity when weighting factors.	CBA judges the importance of the advantages, which exist only in a given context.
8. Subjectivity (Must do the more objective part first and then the more subjective part)	WRC asks stakeholders to make explicit which factors are more important (a more subjective task first), without considering relevant differences between alternatives (a more objective task). In group decision making, this may lead to premature argument about value judgments.	CBA highlights the difference between the alternatives first (a more objective tasks) and then decide what advantages (positive differences) are more important (a more subjective task).

2. Transparency on trade-offs between factors (Must not assume linear trade-offs between factors)

If the weight of factors remains constant in WRC, designers may assume linear trade-offs between factors. For example, increasing research value will always be more valuable than decreasing embodied energy. However, is it true that they would always prefer an alternative with very high 'research value' and high 'embodied energy' over an alternative with high 'research value' and low 'embodied energy'? The probably do have some limits to those trade-offs, but this method does not help designers to highlight those limits. In addition, many assumptions and trade-offs that were agreed to are not explicitly shown or explained. The researcher found it difficult to understand the weighting of factors, and the 'value' assigned to each alternative. The table does not display all analyses and information. The researcher could not understand the rationale of the decision by just looking at the table, but the feasibility report provided the explanations for assigning weights to factors.

In CBA trade-offs between factors are not assumed to be linear. The trade-offs are based on the differences between attributes of the alternatives.

3. Focus on differentiating between alternatives (Must help differentiate between alternatives)

In WRC it is possible to assign a high weight to a factor that do not differentiate between alternatives. In fact, insulation does not differentiate between steel or wood structures, yet both alternatives have a score for that. Therefore, the advantages of the alternatives are not highlighted. For example, alternative 7 (straw-bale/wood frame) has the higher advantage in insulation while all other alternatives were assigned with the same value. However, this fact is mixed with the weights of factors and attributes, making it difficult to determine how it affected the decision.

In CBA the IofA are assigned to real differences between alternatives. Higher advantages are more likely to be more important. In this case steel has a big difference in terms of the research value over wood structure. In CBA it is clear that the steel structure is better than wood in every aspect except for embodied energy and insulation where no difference exist.

4. Analyzing Cost (Must be treated separated from value)

In WRC the stakeholders' 'value' judgments with technical data and cost is mixed. This makes it hard to make trade-offs between cost and 'value'. The disposition of cost is not transparent.

In CBA, the attributes, which are objective data, are treated separately from stakeholders' values, which are expressed in the importance of the advantages. Finally, the cost of the advantages is contrasted with the importance of the advantages. This method makes the disposition of cost more transparent.

5. Consistency (The result must not change if irrelevant factors are eliminated from the decision)

In this case the factor 'insulation' does not differentiate between steel and good alternatives. The effect of removing that factor from the decision has different consequences in WRC and CBA.

In WRC the final decision does not change, but the intensity of the preferences changes (Table 5.7).

In CBA the intensity of the preferences between wood and steel alternative remains the same if the 'insulation' factor is removed.

6. Collaboration (Must avoid conflicting tradeoffs between high-order of abstraction concepts)

In WRC decision makers had to debate the general importance of factors. For example, deciding if 'research value' is more important than 'thermal mass'. This decision may cause conflict between the faculty and managers who are responsible for the operation and cost of the building inside the university. Unfortunately, the researcher has no data or evidence about the discussions that existed in the weighting the factors. From the interview, it seems that the architects were in charge of giving the weights of factors according to what they thought would represent the values of the owners and users.

In CBA decision makers need to discuss the specific importance of advantages. In this case the difference in 'research value' between steel and wood structures was the most important advantage. However, that does not mean that the factor 'research value' will be more important than all the other factors if the attributes of the alternatives change.

7. Context specific (Must consider a specific context for all judgments)

In WRC decision makers decided if 'first cost' is more important than 'earthquake losses', 'embodied energy', or any other factor, which is very abstract. However, most projects are constrained by cost. Should designers be relying heavily on cost even before considering the differences between alternatives? Or should the designers set a target cost to produce alternatives within specific cost constraints? Lastly, should designers seek more funding if the alternative they want is considerably better than another, but more expensive?

In CBA decision makers are tied to the context when assigning weights to advantages. They need to decide if one advantage is more important than another. A relevant questions would be 'Is the advantage of steel structure presenting much richer opportunities for research than the wood alternative more important than the advantage of wood having a significantly lower carbon impact than steel structure?'

8. Subjectivity (Must do objective part first and then subjective part)

In WRC the weighting of factors (subjective) may be done before rating the attributes of the alternatives (more objective), and without understanding the performance of the alternatives. This may not be the case in this project since the process was iterative. However, the WRC method allows for it.

In CBA summarizing the attributes of the alternatives (objective) is done first followed by judgments, which are made based on the differences between alternatives (subjective).

5.7. Conclusions

In conclusion, CBA helps more in creating transparency than WRC because (1) CBA does not assume that every increment in performance within a factor is equally valuable as WRC may assume; (2) CBA does not assume linear trade-offs between factors as WRC may assume; (3) CBA focuses on differentiating between alternatives more than WRC; (4) CBA does not mix 'value' and cost as WRC does; and (5) CBA does not change the intensity of preferences if irrelevant factors are removed from the decision as WRC does. In addition, CBA helps more in building consensus than WRC because (6) CBA avoids conflicting trade-offs between high-order of abstraction concepts and WRC does not; (7) CBA is more closely linked to the context than WRC; and (8) CBA first considers objective facts before moving on to more subjective discussion in contrast to WRC.

6. TEST CASE 1: CHOOSING A SUSTAINABLE CEILING TILE USING CBA

6.1. Introduction

Test case 1 applies Choosing By Advantages (CBA) to a real project and was used as the basis for a paper presented at the International Group for Lean Construction (IGLC) conference in 2013 (Arroyo et al. 2013).

The objective of this case is to demonstrate the applicability of CBA in a real design project, and obtain feedback from practitioners about CBA implementation. In addition, section 6.7 explores how the use of rhetoric may help CBA application.

6.2. Case-Study Background

The project studied used a Design Bid Build (DBB) delivery system. The client was a global information technology company wanting to renovate their offices in multiple locations around the world, while seeking Leadership in Energy and Environmental Design (LEED) gold certification. A large architectural firm needed to expeditiously provide a consistent design for all locations. They designed the client´s San Francisco location first and this design in turns as a prototype for the other locations around the world. Other cities included in this case study were New York, Sydney, Dublin, and Tokyo because these were thought to be representative of strategic locations in the world. The most expensive interior design items were the carpet, ceiling tile, and furniture. The researcher analyzed the availability of specific products for different locations and conducted a deeper analysis on choosing ceiling tile alternatives considering one global manufacturer, since finding the best alternative was not obvious. The design team wanted to study a single global manufacturer since this simplifies the complexity of the supply chain management. The design team wanted to ensure that materials would be available in all project regions and within acceptable lead times (less than 3 weeks). However, other manufactures can be used if they meet ‘or-equal’ product’s specifications of selected materials.

In this case study the decision makers were the design team comprising the architect, interior designer, project manager, and sustainability specialist. In addition, the acoustic consultant and the manufacturer provided information for the decision-making process. The design team considered the interests of the stakeholders including the owner, users, general contractor, and architect, as well as environmental impacts.

6.3. Case-Study Protocol

The case-study protocol describes the steps that the researcher followed for applying CBA in this project.

7. Mastered the CBA system, read all relevant literature and attended a 2-day CBA workshop (Koga 2012).
8. Obtained access to project background information including the details leading to decisions. In this case, the researcher had access to the design team through an internship.

9. Understood the requirements for product selection (in this case ceiling tile), in terms of lead times, availability, LEED credits, aesthetics, installation procedures, etc. The researcher obtained information by direct communication with the design team.
10. Identified competitive alternatives and gathered relevant information from manufacturers and designers, including Environmental Product Declaration (EPD) reports. From there, the design team selected relevant factors and criteria for evaluating the alternatives.
11. Prepared a CBA training session for the design team that covered the following points: importance of the decision-making process, description of the CBA method, an example of a CBA application, and discussion session.
12. Discussed alternatives with the design team. In addition, the researcher presented the relevant information for the decision-making process, the process for obtaining the information, and assumptions behind the data presented.
13. Led and videotaped a decision session, so the interaction between the design team could be analyzed later. The design team was asked about the procedure, what worked well and what did not.
14. Documented the decision-making process and wrote recommendations for choosing ceiling tiles. This document was sent to the design team for feedback.
15. Analyzed the process and the results of the decision in a post-decision meeting to gather further insights about the method, barriers for implementation, and future applications in the firm.
16. Finally, sent a post-study report to the design team for feedback. The design team recognized the benefits of using CBA, though they expressed that they may not always have the time to analyze decisions at this level of detail. Whether or not this is a legitimate concern will be discussed later.

6.4. Step-by-Step CBA Application

The step-by-step CBA process is not linear as described here. However, the researcher explains the CBA steps linearly to provide clarity to the reader. Steps must be reiterated as new information is gathered during the design process or as new perspectives emerge.

6.4.1. Step 1: Identify Alternatives

For this case study, the design team looked at only one manufacturer (Armstrong), but it could have compared products from different manufacturers. However, different manufacturers may present different data for their products, which makes comparison harder. Table 6.1 shows the alternatives considered. Aesthetically all alternatives are the same and all can be installed with the same system (Tegular). All ceiling tiles are available in 2’x2’ and 3’x4’ sizes.

Table 6.1 Ceiling tiles alternatives

Alternative	**Optima**	**Ultima**	**Optima PB**	**Optra**
Material	Fiberglass	Mineral fiber	Fiberglass with plant based binder	Biosoluble glass wool
Manufacturing location	Hilliard, OH	Pensacola, FL. Marietta, PA. Munster, Germany. Shanghai, China.	Hilliard, OH	Shanghai, China.

6.4.2. Step 2: Define Factors

In step 2, the design team needs to identify factors that will help differentiate between alternatives. In CBA, it is not about which factor is most important. Which factor has an impact on the decision will change depending on the attributes of the alternatives, and the importance assigned to the alternatives' advantages. Many factors were not considered in the decision-making process (Figure 6.1) since the alternatives have similar (or the same) attributes for them (e.g., all alternatives have the same fire resistance rating). This is due to CBA method is focused in differentiating between alternatives. In addition, the design team merged some factors that had the same purpose. For example, recycled content, energy use, locally-sourced material, were all contained in the Global Warming Potential (GWP) factor, which represents a more holistic view of the environmental impacts.

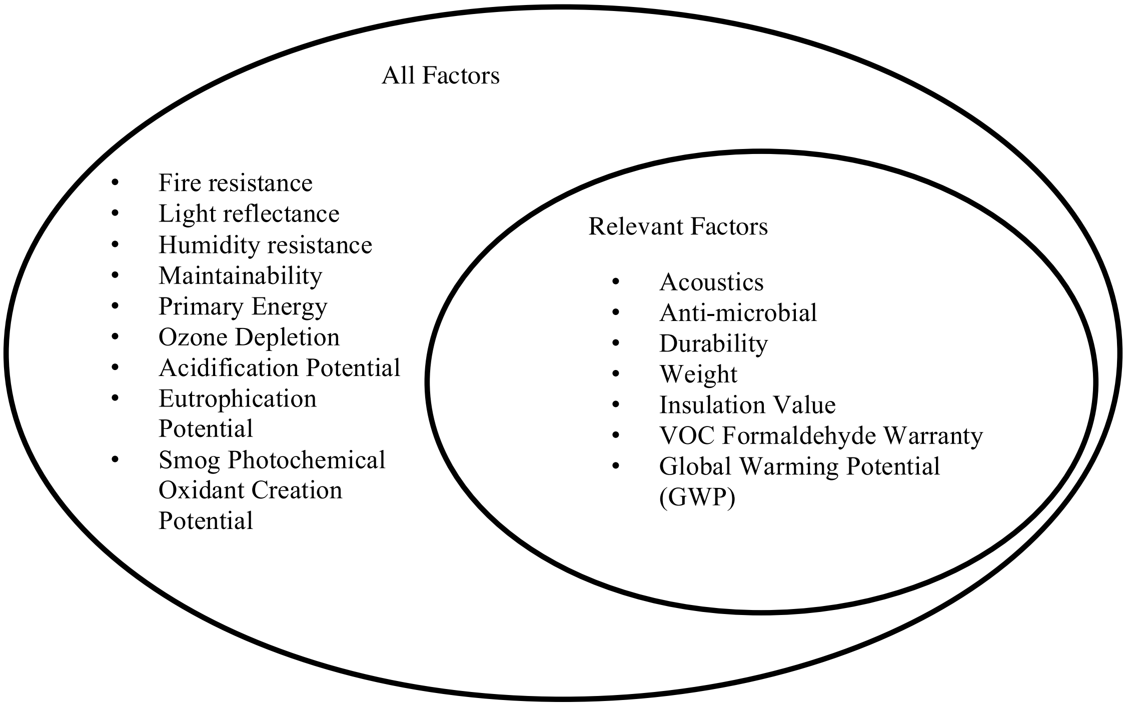


Figure 6.1 Identified factors and relevant factors used in the decision-making process.

The CBA process of researching attributes of the alternatives and looking for relevant factors in an interactive manner helped in differentiating between alternatives. In this case, no one in the design team came up with the idea of diminishing the replacement frequency of ceiling tiles as a criterion. However, this appeared as a factor (durability) when the design team realized that the attributes of the alternatives were different in that regard.

6.4.3. Step 3: Define the 'Must' and 'Want to Have' Criteria for Each Factor

For each factor, the design team needs to agree on criteria on which to judge alternatives. A criterion can be a 'must have' or a 'want to have'. In this case, defining the criteria for each factor was easy to agree with the design team. The factors used for this choosing problem had attributes with a standard evaluation in which case it is easy to establish a criterion. In other cases defining a criterion for a subjective factor, such as athletics, could be more difficult. This section explains what the design team understood by each factor and their criteria for evaluation. Table 6.2 presents the summary of factors and criteria for this decision.

Table 6.2 Factors and criteria.

Factor	**Criterion**
1. Acoustics NRC (Noise Reduction Coefficient)	The higher the NRC value, the better. The minimum acceptable is 0.7 for open spaces.
2. Anti-microbial barrier	The more anti-microbial resistance, the better.
3. Durability	The more resistant to scratches and impacts, the better.
4. Weight	The lighter, the better.
5. Insulation Value	The higher the R-value, the better.
6. VOC Formaldehyde	The less added formaldehyde, the better
7. Warranty	The more years of warranty, the better
8. Global Warming Potential	The less CO_2 emissions, the better

(1) Acoustics: The design team decided that the Noise Reduction Coefficient (NRC) would be important due to the high percentage of open spaces. NRC is a measure of the average percentage of noise that a material absorbs in the mid-frequency range. Therefore, the criterion for this factor is the higher NRC value, the better. The minimum acceptable NRC value (a 'must have') is 0.7 for open spaces.

(2) Anti-Microbial Barrier: This factor accounts for the ceiling tile's resistance against the growth of mold and mildew. For fiberglass tiles this is not an issue because they do not contain organic compounds. However, for mineral fiber tiles an antimicrobial treatment on the face and back is required to obtain acceptable performance. The mold and mildew resistance can be tested using the ASTM D 3273 procedure. The criterion for this factor is the more microbial resistance, the better.

(3) Durability: This factor accounts for the ceiling tile's resistance against impact and scratching. The impact resistance can be tested using the falling ball impact test

(procedure similar to ASTM D 1037), which accounts for surface impact, and the scratch resistance can be measured using the Hess Rake Test. The Hess Rake Test evaluates surface scratch resistance by dragging spring steel shims (or feeler gauges) across the ceiling surface as various levels of force are exerted. The test proceeds until surface scratching is observed. In this case, ceiling tiles will be removed frequently for plenum access. Therefore, the design team agreed that surface scratch resistance is desirable. The criterion for this factor is the more resistant to scratches and impact, the better.

(4) Weight: The design team decided that a lighter material would be better, because it would be easier to install or remove for plenum access than a heavier material. The criterion for this factor is the lighter, the better.

(5) Insulation Value: This factor accounts for a material resistance to heat transfer. It is measured using the R-Value, in which a higher value indicates a higher thermal resistance, however, the R-Value requirement for ceiling tiles needs to be aligned with the rest of the design. The criterion for this factor is the higher R-value, the better.

(6) Volatile Organic Compounds (VOC): This factor accounts for the indoor air quality that will result from the selection of ceiling tile. The design team agreed that low VOC materials (materials without added formaldehyde) are desirable. Exposure to formaldehyde is a significant consideration for human health. The design team agreed that materials must comply with California Department of Health Services (CHPS) Standard Practice for the testing of VOC emissions and qualify for 'low-emitting' material. In addition, the materials should comply with LEED v3 environmental quality credit 4.1 (low emitting adhesives and sealants). The criterion for this factor is the least added formaldehyde, the better.

(7) Warranty: The design team defined that having more years of warranty is desirable. However, this depends on how long the client plans to stay in the same office building. The criterion for this factor is the more years of warranty, the better.

(8) Global Warming Potential (GWP): This factor accounts for the environmental impact of the materials. Here the design team decided to use the Environmental Product Declaration (EPD) provided by the manufacturer. EPDs account for CO_2 (equivalent) emissions using a Life Cycle Assessment (LCA), encompassing raw material production, transport of raw materials to production facility, manufacturing of ceiling panels, packaging, transportation to job site, use phase, and end-of-life including disposal or recycling (Figure 6.2). The criterion for this factor is the less CO_2 (equivalent) emissions, the better.

In CBA the criteria represent the design team's preferences for each factor. The design team does not need to assign weights to factors or represent trade-offs between them. It is important to highlight that CBA does not assume linear trade-offs inside a criterion. For example, the criterion "the more years of warranty, the better" does not mean that the design team will 'value' every year of warranty equally. The evaluation of the alternatives regarding factor (7), warranty, will depend on the context of the project, the attributes of the available alternatives in all the factors and the design team's values.

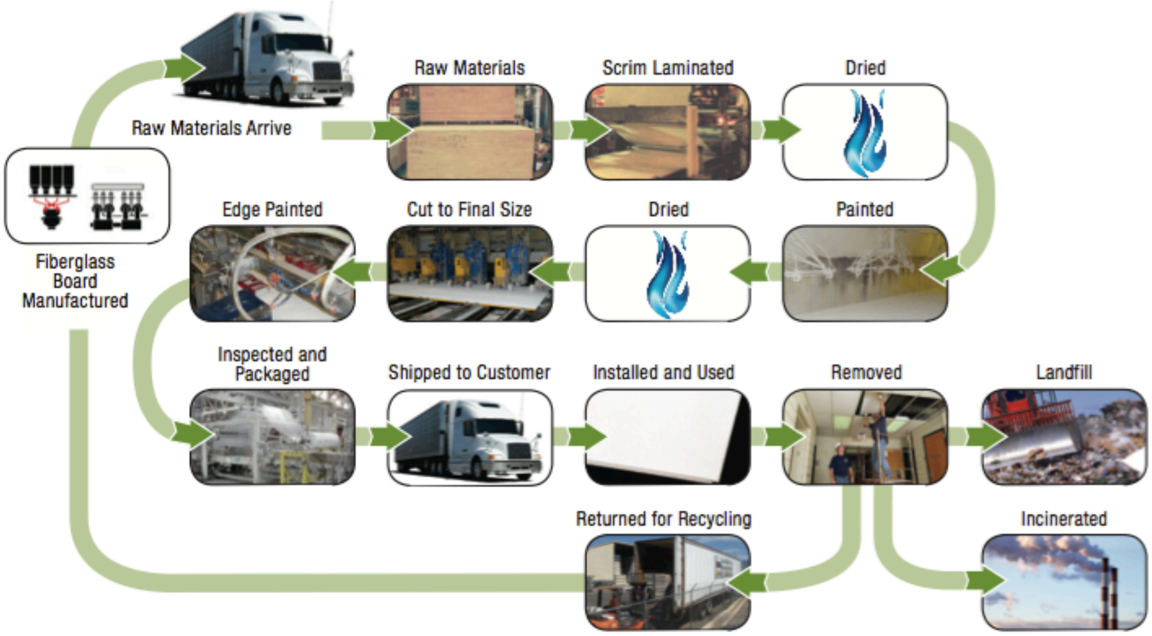


Figure 6.2 Life cycle of ceiling tile (Armstrong 2012).

In addition, when considering factors and criteria, the design team should avoid sub-optimizing. They need to think about criteria in a holistic manner, and consider the interaction among different building systems. For example, the sound privacy performance of the ceiling tiles need to be aligned with the whole room design (including walls and floor systems) and with the activities that will take place in the room. In this case study, the acoustic consultant recommended to use a minimum acceptable value of 0.7 for NRC to be aligned with the rest of the design and the purpose of the building. Collaboration among the design team in setting the factors and criteria is important in order to avoid sub-optimization.

6.4.4. Step 4: Summarize the Attributes of Each Alternative

The researcher found the attributes of each alternative in the manufacturer's technical documents and EPD reports. For the GWP factor the researcher adjusted the transportation to job site portion of the LCA, since the manufacturer data assumes 500 miles of transportation from manufacturing plant to site, and most sites are not located within that range (Table 6.3). The adjustment also considered the transportation mode (truck or vessel) according to manufacturer's information. Therefore, the attributes of factor GWP will vary according to the project site, transportation mode and manufacturing plant location.

Table 6.3 Distance from manufacturing plant to site.

Product	**Location**	**San Francisco**	**New York**	**Dublin**	**Tokyo**	**Sydney**
Optima	Hilliard, OH	2,111 mi	467 mi	3,577 mi	6,545 mi	9,462 mi
Ultima	Pensacola, FL	2,066 mi				
	Marietta, PA		141 mi			
	Munster, Germany			687 mi		
	Shanghai, China				1,093 mi	6,145 mi
Optima PB	Hilliard, OH	2,111 mi	467 mi	3,577 mi	6,545 mi	9,462 mi
Optra	Shanghai, China			5,434 mi	1,093 mi	6,145 mi

In addition, the quantity of ceiling tiles required in each location varies. This will affect the GWP factor. Table 6.4 shows the area of ceiling tiles required in each project.

Table 6.4 Estimated area of ceiling tiles required in different project location.

Project Location	**San Francisco**	**New York**	**Tokyo**	**Sydney**	**Dublin**
Ceiling tiles area	410,000 ft^2	71,340 ft^2	85,280 ft^2	32,800 ft^2	98,400 ft^2

In this case all attributes can be measured with objectivity, in other words, they can be described using inherent characteristics based on a standard way of measuring performance. However, not all attributes have a natural scale such as weight. For example, the scales for measuring NRC and R-Value are convention systems; therefore, the scale of attributes cannot be used to represent an objective ‘value’. Only a difference between attributes of two alternatives and their impact on the design has a meaningful ‘value’.

Table 6.5 summarizes the attributes of the alternatives. The least preferred attributes are underlined and will be used as comparison points to describe advantages.

Table 6.5 CBA steps 1 to 6.

Factor (Criterion)	**Alternative 1: Optima (Fiberglass)**		**Alternative 2: Ultima (Mineral Fiber)**		**Alternative 3: Optima Plant Based (Fiberglass)**		**Alternative 4: Optra (Fiberglass)**	
1. Acoustics NRC	Att.: 0.90		Att.: 0.70		Att.: 0.95		Att.: 0.90	
(Higher is better)	Adv.: 0.20 Higher noise resistance	Imp.: 100	Adv.:	Imp.:	Adv.: *0.25 Higher noise resistance*	Imp.: 100	Adv.: 0.20 Higher noise resistance	Imp.: 100
2. Anti-microbial	Att.: Inherent		Att.: It has BioBlock+		Att.: Inherent		Att.: Inherent	
(Higher is better)	Adv.: *Better Anti-Microbial*	Imp.: 15	Adv.:	Imp.:	Adv.: *Better Anti-Microbial*	Imp.: 15	Adv.: *Better Anti-Microbial*	Imp.: 15
3. Durability	Att.: Scratch resistance Impact resistance		Att.: Scratch resistance Impact resistance		Att.: Scratch resistance Impact resistance		Att.: No Scratch resistance No Impact resistance	
(Higher is better)	Adv.: *More resistant to Scratches and impact*	Imp.: 25	Adv.: *More resistant to Scratches and impact*	Imp.: 25	Adv.: *More resistant to Scratches and impact*	Imp.: 25	Adv.:	Imp.:
4. Weight	Att.: 0.55 (lbs/ft^2)		Att.: 1.14 (lbs/ft^2)		Att.: 0.55 (lbs/ft^2)		Att.: 0.48 (lbs/ft^2)	
(Lighter is better)	Adv.: 0.59 (lbs/ft^2) lighter	Imp.: 50	Adv.:	Imp.:	Adv.: 0.59 (lbs/ft^2) lighter	Imp.: 50	Adv.: *0.66* (lbs/ft^2) *lighter*	Imp.: 50
5.Insulation Value	Att.: R-value 4.0 Btu		Att.: R-value 2.2 Btu		Att.: R-value 4.0 Btu		Att.: R-value 3.0 Btu	
(Higher is better)	Adv.: *1.8 Btu higher*	Imp.: 45	Adv.:	Imp.:	Adv.: *1.8 Btu higher*	Imp.: 45	Adv.: 0.8 Btu higher	Imp.: 40
6. VOC Formaldehyde	Att.: Low Formaldehyde - less than 13.5 ppb		Att.: Free of Formaldehyde		Att.: Free of Formaldehyde		Att.: Low Formaldehyde - less than 13.5 ppb	
(Less is better)	Adv.:	Imp.:	Adv.: *Free of Form.*	Imp.: 90	Adv.: *Free of Form.*	Imp.: 90	Adv.:	Imp.:
7. Guaranty	Att.: 30 Year Guarantee		Att.: 30 Year Guarantee		Att.: 30 Year Guarantee		Att.: 15 Year Guarantee	
(Longer is better)	Adv.: *15 More Years of Guarantee*	Imp.: 90	Adv.: *15 More Years of Guarantee*	Imp.: 90	Adv.: *15 More Years of Guarantee*	Imp.: 90	Adv.:	Imp.:

8. CO2 Emission SF	Att.: 275 t CO_2eq		Att.: 392 t CO_2eq		Att.: 275 t CO_2eq		This alternative is not available in SF	
(Lower CO2 emission is better)	Adv.: *7 t CO_2 less*	Imp.: 30	Adv.:	Imp.: 0	Adv.: *7 t CO_2 less*	Imp.: 30		
8. CO2 Emission NY	Att.: 44 t CO_2eq		Att.: 58 t CO_2eq		Att.: 44 t CO_2eq		This alternative is not available in NY	
(Lower is better)	Adv.: *14 t CO_2 less*	Imp.: 35	Adv.:	Imp.:	Adv.: *14 t CO_2 less*	Imp.: 35		
8. CO2 Emission Tokyo	Att.: 54 t CO_2eq		Att.: 70 t CO_2eq		Att.: 54 t CO_2eq		Att.: 56 t CO_2eq	
(Lower is better)	Adv.: *15 t CO_2 less*	Imp.: 35	Adv.:	Imp.:	Adv.: *15 t CO_2 less*	Imp.: 35	Adv.: 14 t CO_2eq less	Imp. :35
8. CO2 Emission Sydney	Att.: 22 t CO_2eq		Att.: 30 t CO_2eq		Att.: 22 t CO_2eq		Att.: 23 t CO_2eq	
(Lower is better)	Adv.: *8 t CO_2 less*	Imp.: 30	Adv.:	Imp.:	Adv.: *8 t CO_2 less*	Imp.: 30	Adv.: 7 t CO_2eq less	Imp. : 30
8. CO2 Emission Dublin	Att.: 61 t CO_2eq		Att.: 80 t CO_2eq		Att.: 61 t CO_2eq		Att.: 68 t CO_2eq	
(Lower is better)	Adv.: *19 t CO_2 less*	Imp.: 35	Adv.:	Imp.:	Adv.: *19 t CO_2 less*	Imp.: 35	Adv.: 12 t CO_2eq less	Imp. : 35
Total IofAs SF		355		205		445		
Total IofAs NY		360		205		450		
Total IofAs Tokyo		360		205		450		240
Total IofAs Sydney		355		205		445		235
Total IofAs Dublin		360		205		450		240

6.4.5. Step 5: Decide the Advantages of Each Alternative

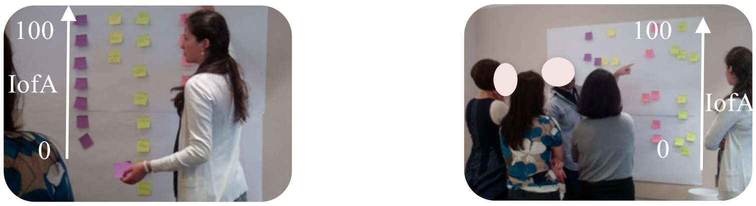
Once the attributes are summarized, the criteria are applied to identify the advantages. In this case, the advantages were easily found since decision makers had already agreed on the criteria for evaluation.

Table 6.5 presents the advantages of each alternative. The GWP factor is shown for each location, considering the area of ceiling tiles required in each office, and the correction of the LCA data for distance and transportation mode used to ship ceiling tiles to site. Note that for each factor at least one alternative does not have an advantage because it has the least preferred attribute in that factor. In addition, Table 6.5 shows in italics the most important advantage for each factor. Until this step of CBA the design team did not have any issue with agreeing on criteria or advantages, since all factors can be represented by objective attributes. The following Section 6.4.6 explains the process for deciding the importance of the advantages.

6.4.6. Step 6: Decide on the Importance of Each Advantage

The process is collaborative and decisions are reached through discussion within the design team. The client vision was also considered in every trade-off that is made.

The recommended procedure to weight advantages in CBA is to first identify the most important advantage for each criterion (in italics in Table 6.5) and then choose the most important advantage for all factors, which in CBA is called paramount advantage. A practical way of assigning Importance of Advantages (IofAs), that was used in this case study, is to write them in post-it notes, then draw a scale from 0 to 100 (or any other convenient scale, as defined by the paramount advantage), and finally place the post-it notes according to their importance relative to others (Figure 6.3).



List the advantages of each alternative

Discuss the importance of each advantage

Figure 6.3 Deciding collaboratively on the importance of the advantages.

In this particular case decision makers decided that the 0.25 higher value in the NRC rating (0.95 of Optima PB – 0.70 Ultima) was the paramount advantage, because it will make an important difference in the user experience. Therefore, decision makers assigned 100 IofAs to this paramount advantage. Next, the design team assigned an importance score to the most important advantages for each criterion (the ones in italics in Table 6.5) by comparing them with the paramount advantage. In this case the advantage ‘free of added formaldehyde’ was the second most important advantage (90 IofAs), with 15 years of guarantee (90 IofAs). Finally, the design team assigned importance points to the other advantages. Once all advantages have been assigned IofAs, the total importance of each alternative is computed. In this way it was easy to compare which alternative provides a higher IofA score (Table 6.5).

It is important to mention that decision makers did not necessarily assign IofAs linearly. For example, they assigned a value of 100 IofA to the advantages of Optima and Optra over Ultima, which is a 0.20 higher value in the NRC rating (0.90 of Optima – 0.70 Ultima and 0.90 of Optra – 0.70 Ultima) as well as to the paramount advantage, which is a 0.25 higher value in the NRC rating (0.95 of Optima PB – 0.70 Ultima).

The process of deciding IofA was mostly straightway agreed among the design team. In just one instance someone disagreed about an IofA. That person was trying to assign a higher IofA to the GWP advantage of Optima. Her argument was that the GWP factor was the most important for her due to the importance of climate change, but when she realized that the difference between GWP attributes of the alternatives were not that big compared with the paramount advantage, she and the design team agreed in assigning an IofA of 30 for San Francisco.

The final IofA score represents the 'value' of the alternatives. This is a subjective evaluation. How assertive this 'value' representation is depends on how well the design team used the data for differentiate between alternatives and represented the preferences of the stakeholders. Communication plays an important role in understanding stakeholders' 'values'. If a decision does not have the right persons involved, the 'value' judgments will probably be inadequate or incomplete.

Understanding the 'value' of an advantage may not be simple and it must not be confused with its cost or price. For example, when evaluating the IofA of the advantage more resistant to scratch and impact (for Optima, Optima PB, and Ultima over Optra) the design team should avoid be influenced by the cost impact of this advantage (e.g., less money used for replacement of ceiling tiles). Here the decision makers should think if 'value' having a more resistant ceiling tile, not in terms of cost but for example in terms of convenience, the process of replacement may be annoying for the organization when the building is in operation. If this is a 'value', then this should be reflected in the IofA. If it is not a 'value', then durability should not be a factor and it should be reflected in a life cycle cost vs. IofA analysis.

6.4.7. Step 7: Evaluate Cost Data

To evaluate cost data, the design team plots the total IofA score for each alternative against the local cost (Figure 6.4). Then this data is used for making decisions. For example, in this case Optima PB has and advantage over Ultima, which is 0.95 vs. 0.7 NRC. The 'value' of this advantage, which in CBA is called IofA, will depend on the owner/users values. Then the relevant question is how much the owner/user will be willing to pay for obtaining this advantage (in this case Optima PB is more expensive than Ultima PB in all regions). In CBA cost and 'value' are totally different concepts, which are not related at all. That is why is important to separate them in the analysis. Optima PB will not be less valuable if it cost less, it maybe less likely to be chosen if the owner does not 'value' that advantage enough for paying more for it.

In this example, choosing Ultima for Japan, Sydney or Dublin does not make sense since Optra costs less and it has advantages that are more important. The decision, then, is whether or not to spend more money on an alternative that provides more advantages. This depends on the client and other investment choices they face. In the short term, Optra is a cheaper option than Optima or Optima PB. However, stakeholders will be losing important advantages if they select Optra over Optima PB, including using a product with vs. without formaldehyde, getting 15 vs. 30 years of guarantee and no vs. some scratch and impact resistance.

For New York and San Francisco Optra is unavailable in the market, so the alternatives are reduced. Recommending the selection of Optima vs. Optima PB is not difficult because Optima PB does not have formaldehyde, which has an IofA of 90, and costs only

$0.25 more per ft^2 However, the decision of using Ultima vs. Optima PB will depend on the budget of the project ($0.25 more per ft^2 may not be available).

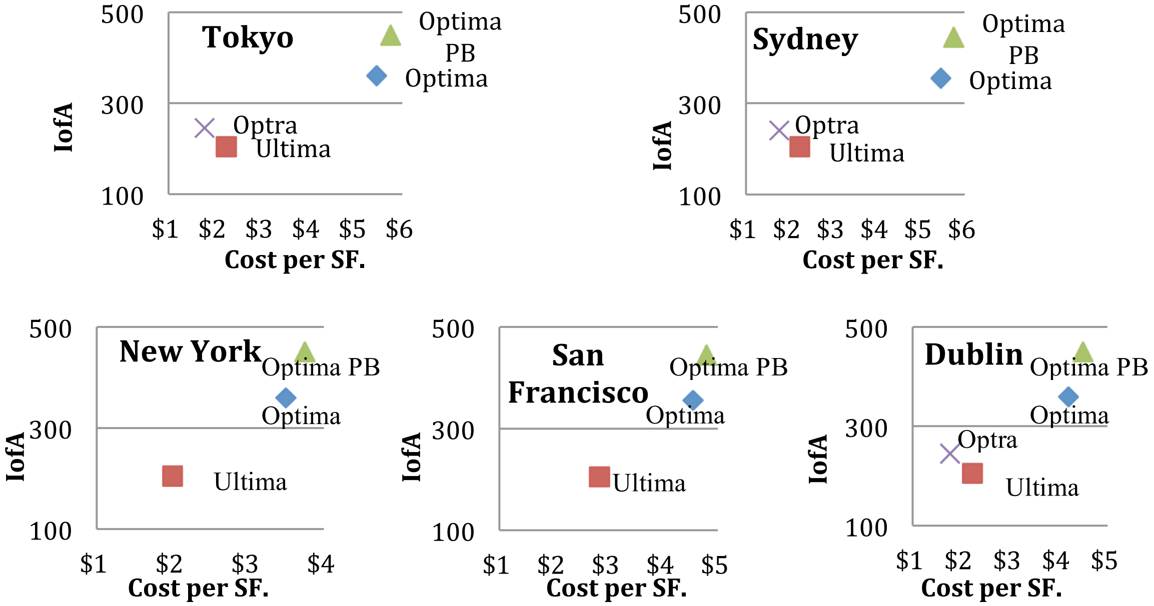


Figure 6.4 CBA results for the different locations.

At the end of the application of the CBA method, the design team is able to provide clear rationale for their decisions. In addition, they can use their CBA tables and IofA vs. cost plots to learn from project to project.

6.5. Discussion

Through this exercise the researcher realized that CBA helped to organize data for decision making in a transparent manner. The design team could incorporate multiple locations for the same products, and see how the alternatives' attributes changed. This made it easy to find the advantages of the alternatives depending on the location and assess their importance.

The researcher identified the following issues regarding the implantation of formal decision-making methods:

1. Gathering all relevant stakeholders

Due to the nature of the project (Design Bid Build), it was not possible to get all relevant stakeholders together for the decision. In this case a representative of the owner or final user was not present at the time of the decision. Therefore, architects and interior designers assigned the importance of advantages, representing the client's values as they understood them. A representative of the contractor was not present at the time of the decision. Perhaps in a more collaborative environment, such as in an IPD project delivery system, more stakeholders' perspectives could be considered.

2. Collecting data

The researcher devoted substantial time for data collection. The attributes of the alternatives were not just taken from previous experiences. The researcher had to gather the attributes communicating directly with the manufacturers. This helped to understand what the differences were between the alternatives. However, collecting data would be required for making an informed decision using any MCDM method.

The researcher notice that not all manufactures have an Environmental Product Declaration (EPD) and a Health Product Declaration (HPD) for their products, and if they did, a single standard for comparison did not appear to exist.

3. Training to apply CBA

The application of CBA required time for training the design team. The researcher had to explain the CBA method and vocabulary and gather the design team together to conduct a workshop. The time commitment may be a barrier for CBA application, although it is something that the design team will be able to apply to future decisions.

4. Timing of the whole decision-making process

The time spent for the whole decision-making process exceeded the expectation of the team for choosing materials. Even when the experiment was useful, the design team would not use their time to research the attributes of the alternates in a way that the researcher did for choosing every building material for the project. An extensive analysis may be appropriate for other projects where the owner demands a rationale for the decision.

6.6. Conclusions

Through this case study, the researcher was able to prove that CBA is applicable in practice for choosing a sustainable alternative. Even when the studied decision was not very complex, it helped the researcher to assess how difficult it is to apply CBA in practice and how useful it is.

Obtaining data for decision making requires time and effort. However, it is also the only way to ensure that the decision considers all relevant information. CBA required training for the design team. However, it can be seen as an investment for future decisions and for reducing time in future iterations.

The researcher believes that CBA helped to present information in a transparent manner and build consensus because of its structure, which presents attributes first and then compares advantages and asks stakeholders to discuss IofAs. In addition, the information obtained and the analysis of IofA vs. cost can be used for continuous learning.

In terms of creating transparency CBA was helpful in:

- Identifying advantages that were relevant for making trade-offs between alternatives.
- Differentiating between alternatives in a transparent manner.
- Separating the ‘value’ of the alternatives and the cost of alternatives, making it easier to decide trade-offs between ‘value’ and cost.
- Organizing factors that had different attributes depending on the location. CBA supported the incorporation of the supply chain portion of the decision. In this case

the life cycle CO_2 emissions of the four ceiling tiles alternatives changed depending on the transportation mode and distance from manufacturing plant to site, and also depending on the manufacturing plant itself.

In terms of building consensus, CBA was helpful in:

- Integrating multiple stakeholders' perspectives.
- Identifying relevant sustainability factors applicable for the decision context.

In terms of continuous learning, CBA was helpful in:

- Providing documentation for the decision-making rationale. A person not present when the decision was made and who subsequently reads the CBA report, may not understand why one advantage has a higher importance than another, but will understand what the group valued most and the advantages of the alternatives. A thoroughly documented CBA process will help in providing a good understanding for the stakeholders after the decision was made.

Finally, the researcher thinks that if designers use CBA to select materials, it would be easier for them to choose more 'sustainable' materials according to their values, compared to making decisions using less structured methods. In addition, if designers use CBA, it would be less conflicting for them compared to making decisions using methods that require weighting factors. At the same time, this information can be transformed into market feedback, especially for manufacturers, so their new product development is aligned with what the industry is asking for, and in the long term, produce more sustainable materials.

6.7. Choosing By Advantages and Rhetoric

This section explores the following questions: 'Is rhetoric present during CBA decision-making?' and 'How can the use of rhetorical tools improve the CBA decision-making process?'

In order to answer these questions the researcher reviewed the literature on the use of rhetoric in design, rhetorical tools of persuasion (Section 2.13.2). In addition, the researcher used this case-study videotape to analyze discussions and interactions among design team members while discussing the IofA in CBA. The discussions were analyzed to look for the natural use of rhetoric. This analysis was used as the basis for a paper that will be presented at the International Group for Lean Construction (IGLC) conference in 2014 (Arroyo et al. 2014).

6.7.1. Evidence of the Use of Rhetoric in CBA

During the application of CBA the researcher could observe the use of rhetorical arguments:

1. Acoustic performance factor

In the process of summarizing attributes, describing advantages and assigning importance to them, all three types of rhetorical proofs were used:

An example of logos in CBA is the design team's requirement to assess advantages based on attributes of the alternatives. In other words, design teams describe alternatives using their inherent and quantitative characteristics. For example, the design team can use the advantage that Optima PB has 0.25 higher NRC points for noise resistance than Ultima (Optima PB 0.95 NRC vs. Ultima 0.7 NRC) for arguing in favor of Optima.

An example of ethos is the design team believing the information provided by the acoustic specialist about the level of acceptable performance for the ceiling tiles. That specialist had the authority and knowledge to influence the decision. In this case, the acoustic consultant recommended using a minimum acceptable value of 0.7 for NRC to be aligned with the rest of the design and the purpose of the building. This information was used for setting the criterion for the factor acoustics.

An example of pathos was that a designer made an argument appealing to user experience. He argued that the difference in acoustic performance of Optima PB vs. Ultima would affect the users in how they would feel about the space. This argument was enough to convince the rest of the team that the advantage of Optima PB vs. Ultima in acoustic performance was the most important advantage. In this case, he was using empathy with the user in order to convince other decision makers.

2. A change in perspective from thinking about importance factors to thinking about importance of advantages.

In one instance, a designer disagreed with an IofA score. She argued that the team should assign the highest IofA to the advantage of Optima vs. Ultima in terms of Global Warming Potential (GWP). Her argument was that the GWP factor was the most important to her due to its importance of climate change. The researcher reminded the design team that in CBA decisions are based on the differences between the alternatives instead of the general importance of the factor. When looking at the differences, the design team realized that the differences between the GWP attributes of the alternatives (275 t CO_2eq vs. 392 t CO_2eq difference between Optima PB and Ultima respectively) were not that significant compared with the paramount advantage (0.95 vs. 0.7 NRC difference between Optima PB vs. Ultima respectively). Finally, the design team agreed to assign an IofA of 30 to the advantage of Optima vs. Ultima in GWP.

The change of perspective in CBA, in which decision makers analyze the particular advantages instead of the general ideas about the importance of factors, makes the design team more connected with the context. This provides more 'strong' arguments since the decision makers can appeal to data that is relevant to this particular decision instead of data that is abstract or ambiguous.

3. Deciding the importance of the advantages

The CBA process of deciding the importance of the advantages is highly collaborative and decisions are reached through discussion within the design team. Rhetorical tools are used in many comparisons between advantages including facts (logos), and expert opinion (ethos). The designers often appeal to the client vision or to the user experience (pathos) in order to argue in favor of an advantage. However, not all the members of the design team are aware of the tools they can use to build arguments. A person with better rhetorical skills can dominate the decisions.

6.7.2. Discussion

Even when the design team has no formal training in the use of rhetoric, the use of rhetorical tools appeared naturally during the discussion and argumentation phase of the decision, especially when deciding the IofAs.

As Aristotle thought, designers can improve their rhetorical skills to discover and develop better arguments. The better the arguments that are discovered, the better the design outcome can be. Some questions that may contribute to the discovery of new arguments are:

1. Using Logos

In CBA the use of logos is encouraged by requiring the design team to describe the advantages of the alternatives based on their attributes; the design team needs to summarize the attributes of each alternative. These assessments influence the decision.

The design team needs to think of all available arguments, which favor a particular alternative, for example:

What data or facts can support an advantage?
What other factors may be considered?

2. Using Ethos

Considering the arguments from people who have authority or relevant knowledge (Superiority).

Who can speak for making a credible statement about one advantage? Who has relevant knowledge for this decision context?
The specialist's role in the AEC process, their attitude and words will impact the decision. Have all relevant specialists been given the option to speak?
A tool for developing a more credible speech is to show a variety of sources. This may be applied by involving all relevant specialists and having the 'right people' in the design room with the authority to judge (the right status).

3. Using Pathos

Considering arguments that appeal to the people who will be affected by the decision (e.g., users, environment, etc.). (Inferiority)

Designers can appeal to emotion in many ways. Some relevant questions are:

How will this advantage impact the user experience?
How will this advantage impact the environment?
How can previous experiences relevant to this context be used?

6.7.3. Conclusions

In conclusion, the case study confirmed the use of rhetoric in CBA applications including conscious and unconscious use of rhetoric. This analysis provides insights about the use of rhetoric in CBA by providing questions that the design team should ask in discovering new arguments.

The researcher thinks that CBA provides the right framework to ask questions and find arguments to influence decisions. The score behind every IofA should be analyzed using logos (the facts and differences between alternatives), ethos (the opinion of the relevant specialists about the impact of the advantage) and pathos (the sense of how this advantage will affect others). In other words, the alternatives should be judged based on how they work, how they are perceived by expert judgment, and how they appeal to the users.

More research in needed in order to understand how best to consciously apply rhetoric in the CBA process and what the benefits are.

7. TEST CASE 2: CHOOSING AN HVAC SYSTEM FOR A NET ZERO ENERGY MUSEUM USING CBA

7.1. Introduction

Test case 2 applies Choosing By Advantages (CBA) to a real project, in this case choosing an HVAC system for a Net Zero Energy (NZE) museum in San Francisco, California. At the time of this study, the actual decision regarding HVAC had already been made. Therefore, this case retrospectively considers how the CBA decision-making method could have been applied. The researcher conducted several interviews to understand the project context and to obtain feedback from the design team, building operator and users about their design decision.

The objective of this case is to demonstrate the applicability of CBA in a real design project. This case study is more complex than test case 1, because it concerns choosing a building system, which has several interdependencies with other building systems. In addition, the researcher had the opportunity to interview the people in charge of operating the building since the project was finishing construction when the research was done.

7.2. Case-Study Background

This test case is based on the context of the Exploratorium's move from its home in the Palace of Fine Arts to Piers 15 and 17 on San Francisco's Embarcadero. The Exploratorium is a famous museum in San Francisco, and is known for pioneering in innovation. When it opened in 1969, it was one of the first interactive science museums, a model that has since become the norm for many museums in the US and around the world. This project has received substantial publicity, because it is the largest NZE museum in the US, and also for the revolutionary way that it demonstrates green building to the public as part of the museum exhibits.

7.2.1. Project Team

The design team consisted of a multidisciplinary group, which supported the project's goals including the constraints of working in an historical building and ensuring the requirements of a structural retrofit. The design team was composed of the following organizations/individuals:

- Owner, Exploratorium, led by Kristina Woolsey.
- Architect, EHDD, led by Marc L'Italien.
- Contractor, Nibbi Brothers, led by Joe Mazzetti.
- Solar Energy Provider, SunPower, led by Bill Kelly.
- Mechanical Engineers, Integral Group, led by Peter Rumsey.
- Lighting Design, Dave Nelson and Associates, led by David Nelson.
- Electrical Design, Camissa and Wipf, led by Robert Boyd.
- Historical Architects, Page and Turnbull, led by Carolyn Kiernat.
- Structural Engineers, Rutherford & Chekene, led by Patrick Ryan.
- Furniture Designers, Teknion, led by Meredith Wylie.

- Food Operators, Bon Appetit, led by Fedele Bauccio.
- Landscape, GLS Landscape Architecture.

7.2.2. Building

The new Exploratorium campus size is 330,000 ft^2 including indoor and outdoor exhibit space, and 1.5 acres of freely accessible public space. The project required a major retrofit of the long and narrow Pier 15. The new building retained the existing building's steel superstructure and concrete cladding. The Bay Observatory was the only new structure added to the site. It is a glass-enclosed structure with an unobstructed view of the San Francisco Bay. The project cost $220 million. Figure 7.1 shows the final design of the Exploratorium campus, including the exhibits housed in and around Pier 15, which extends over 800 ft into the Bay. The indoor and outdoor spaces are divided into six galleries, each highlighting a specific content group. Many exhibits are mobile, and move among different galleries. The building also offers two cafes, a theatre, more than a dozen classrooms and teacher training rooms, wood- and metal workshops, two retail stores, offices, and a large outdoor plaza.

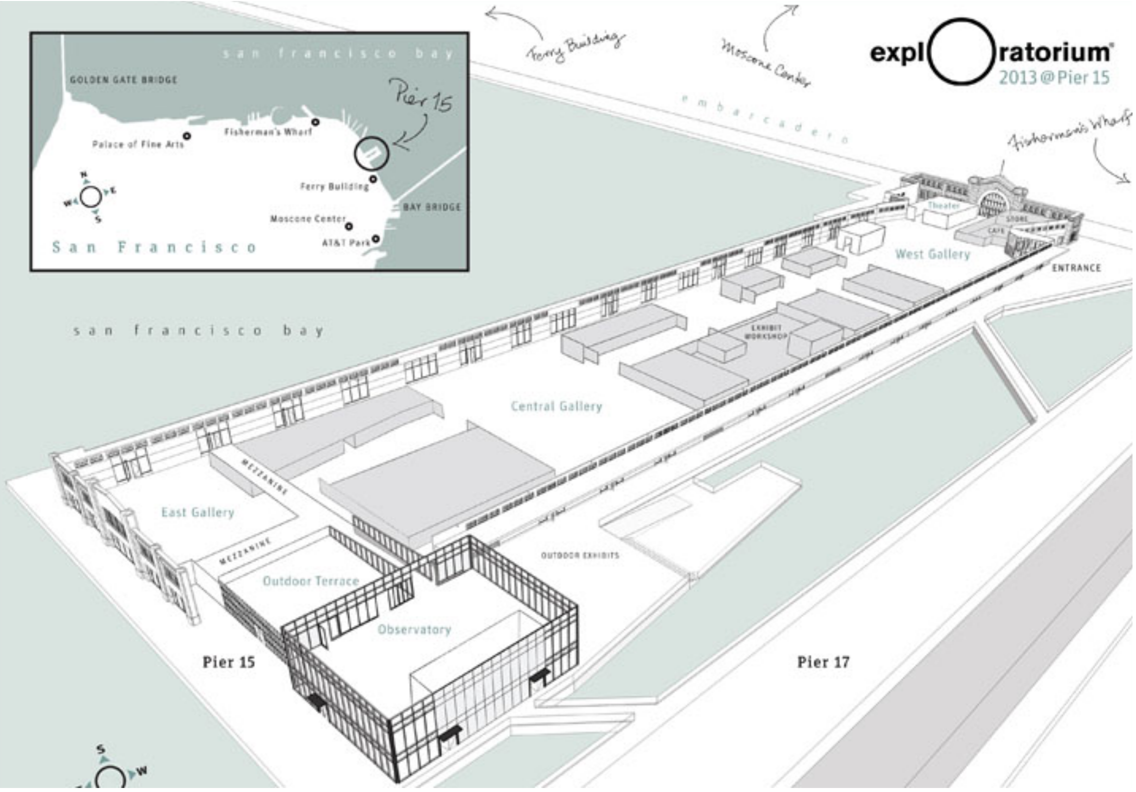


Figure 7.1 Exploratorium Campus (Exploratorium 2013).

In order to achieve the goal of NZE, which means that the building produces as much energy as it consumes when measured on site on a yearly basis, the Exploratorium installed a 1.3-megawatt solar system in the roof (Figure 7.2) to offset the new facility's energy needs (Boyer 2013).

PV PANELS ON THE ROOF WILL SUPPLY 100% OF THE BUILDINGS ENERGY NEEDS.

Figure 7.2 Schematic design of the roof system (Exploratorium 2013).

7.2.3. Design Goals and Building Features

According to Woolsey's book (2010), the project has several goals that were incorporated into the design as result of the evaluation of design alternatives. For example, the building was not originally planned as an NZE project, but ongoing design team discussion revealed an opportunity to achieve an NZE building. Some of the highlighted goals and building features incorporated in the final design are described as follows.

(1) Energy Efficiency Goal: Net Zero Energy

The design team targeted NZE. It sets a goal of producing as much energy as it consumes on site in a year (Net zero site energy building according to Marszal et al. 2011 definitions). The final building design uses bay water for heating and cooling, and solar panels for generating power.

(2) Water Usage Goal

The design team wanted to minimize the water usage. The final building design uses a bay-water heating and cooling system. The design team estimated that it will circulate about 74,000 gallons of water per hour throughout the facility (Woolsey 2010). The cold temperature of the bay water will be used to cool the building. Heating will be achieved by passing water through electric heat pumps. The design team estimated that the system would save an estimated 2 million gallons of water per year by avoiding the use of evaporative cooling towers (Woolsey 2010). Additionally, rainwater will be collected from the building's roof to be used for toilet flushing.

(3) Educating About Energy-Efficient Design

The design team wanted to educate visitors about energy-efficient design and the museum itself was designed to serve as an interactive exhibit. "This project combines an effort to both innovate and think critically about the impact science can have on the world. Our net-zero goal is, in part, a way to reduce our global footprint and help improve the community we've been a part of for more than 40 years… Net-zero is a process – and an opportunity for the public to learn with us." said Dennis Bartels, the Exploratorium's executive director, in a press release (Boyer 2013). The final building design includes exhibits and guided tours to show how the HVAC system, photovoltaic (PV) panels, and water-saving systems work.

(4) Location

The design team wanted to move the Exploratorium to a location that is easily accessible by mass transit. Pier 15 (the new location) is close to the Embarcadero Bay Area Rapid Transit (BART) station, as well as the ferries that land at the nearby Ferry Building, making it easier for both locals and tourists to visit the museum.

(5) Building Capacity

The design team wanted to increase the Exploratorium capacity for exhibits and research projects. The new location triples display spaces and increases visitor capacity by 100%. The museum eventually plans to expand into the adjacent Pier 17.

(6) Reduced Energy Load

The design team wanted to reduce the energy load to facilitate achieving the NZE goal. The final design includes exhibits that require less energy than they use to. The challenge was to combine the excellence in the museum exhibits, which is the main reason why visitors want to go to the museum, and the energy usage constraints. A New York Times article (2013) stated, "Yet the new Exploratorium remains eccentrically original. Technology is scarce. There are few video screens. There are fewer computers. There are circuits but no evident circuit boards. Woodworking and metalworking take place on the museum floor. There are more than 600 exhibits, but the emphasis remains on the laws of physics and motion, elementary principles of perception, and elegantly designed machines that conceal nothing."

7.3. Case-Study Protocol

The following case-study protocol describes the steps that the researcher followed for testing the use of CBA retrospectively on this project.

1. Obtained public data to understand the project background.
2. Conducted interviews with several stakeholders including: Kristina Woolsey Project director of the Exploratorium representing the Owner, Peter Rumsey from Integral Group representing the mechanical engineers, Chuck Mignacco in charge of operating the building and Jesse MacQuiddy, a colleague of Mr. Mignacco.

The interviews were done to better understand the perspectives that went into the general decision-making process and to identify a specific design decision that could be used as a test case. The researcher showed the interviewees examples of CBA applications to assist them in identifying opportunities where applying this method might have been valuable for the project.

3. Decided to study the HVAC system because the decision was relevant for the project, involved multiple stakeholders, and impacted multiple building systems.
4. Obtained access to alternative HVAC systems originally considered, and their interaction with other building systems. In this case, the researcher had access to analyses and presentations provided by the Integral Group.
5. Identified attributes for applying CBA between three HVAC alternatives.
6. Prepared an example of a CBA application using the information available.
7. Wrote a report with the case study that was sent to the mechanical engineer to obtain feedback.
8. Incorporated feedback in the CBA application and conclusions.

7.4. How Were Project Decisions Made?

Figure 7.3 presents the organizations involved in the decision-making process. The lines in this case represent contractual relationships.

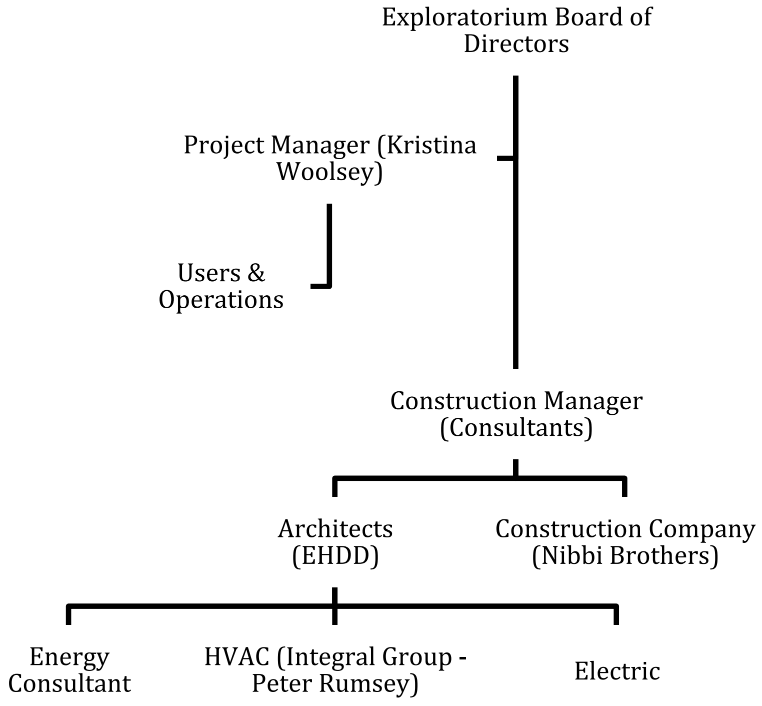


Figure 7.3 Project structure.

During the interview process it was clear that the design team was not using a specific process for making decisions. Many of the interviewees did mention that there had been collaboration during the design process including users' participation. However, it was not clear that they were using any particular method for making decisions. Some decisions were documented through presentations to the board of directors and other meeting documents.

This research proposes the use of CBA for providing a transparent manner of making decisions, for supporting the design team to build consensus, and for providing a basis for continuous learning. This case study demonstrates how CBA might have been implemented in this project.

7.4.1. Owner's Perspective

In order to gather the owner's perspective, the researcher interviewed Kristina Woolsey. As Project Director of the Exploratorium from 2009 to 2013, she coordinated the Exploratorium's move to Pier 15/17. Her previous experience with the Exploratorium (at the Exploratorium's Institute for Inquiry and the Center for Informal Learning and Schools) and her familiarity with the Exploratorium's culture were invaluable in assisting with the move.

When Ms. Woolsey assumed overall responsibility for the project, major design decisions had already been made, including going for NZE. Her major role was to serve as custodian to ensure proper implementation of the design decisions. In the interview she mentioned that many specialists who were hired, especially the architects (EHDD Architecture) influenced the decision and goals for the design. The architects were leading the project to obtain a result that conformed to the desires of the owner. As Belton and Stewart (2002) state, the desires and aspirations were revealed through the design process. There were no previous design alternatives or conceptions. Most decisions were based on the experience of consultants and designers. She also stated that there was a commitment from the organization to make the building green and that they were willing to pay an extra fee (around 5%) for having a more sustainable design.

Many of the decisions were also constrained by regulatory agencies. Given the historic importance of the building, the designers had to comply with many restrictions. For example, they could not remove many of the structural trusses of the building.

With regard to collaboration and interaction with the users, she stated that there were many meetings in which she was coordinating different groups to make decisions. The dynamic was usually to present one design and discuss what people liked or disliked about it (evidently not following the CBA method, in which only advantages of the alternatives are discussed). Usually designers made changes and then a new meeting would be arranged for discussing further changes. For example, the location of the administrative offices was one of these participative decisions in which Exploratorium administrative staff were involved.

Despite the efforts for collaboration early in the design, the design team made many changes later in the design process and even post construction.

7.4.2. Operation's Perspective

In order to gather the building-operation's perspective, the researcher interviewed Chuck Mignacco, the Exploratorium's building-operations manager, and Jesse MacQuiddy, the Exploratorium's senior building-operations technician.

The building operators are in charge of building operations, maintenance, and repair. They were directly involved during the construction phase, and they also participated in some design meetings. Regarding collaboration, Mr. Mignacco stated that he participated in many meetings, but he was not aware of which decision-making method was employed, who participated in the final decision or the timing of the decisions. He was responsible for providing designers with the operation perspective, such as how equipments can be accessed or how reliable they are in the long term. He mentioned that many times in the AEC industry decisions are not documented because of possible litigation if a decision results in a failure. Through these interviews the researcher had the opportunity to look back into the design process from the construction and operation perspectives, and evaluate opportunities for improvement.

The researcher acknowledges that it is easier to look at problems and ways of overcoming them in retrospective, than avoid them before they happen. With the purpose of analyzing problems, the researcher asked the interviewees for examples in which design decisions were changed later during the construction phase, or were implemented without considering impacts for construction, operations or maintenance. The gathered examples are:

- *Exterior painting selected was not adequate for the marine environment:* The design team decided to use low VOC paints for exterior façade with the purpose of avoid contaminating the air and obtaining LEED points. However, this was not aligned with the project context, considering the fact that they were in a marine environment. The paint was peeling off before finishing the painting process. Ultimately, they had to repaint using an epoxy paint product.
- *Coil system was not designed for easy replacement:* The coil system for air conditioning was designed to stay permanently inside the building. If coil replacement were required, demolition of a substantial section of the building would be needed.
- *Design of HVAC mechanical room is not optimal for maintenance:* The competition for space inside the building led to a reduction in size of the HVAC mechanical room, which may pose challenges for future maintenance purposes.
- *Water filters selected required replacement earlier than planned:* The selected filters for marine water were not working well and some pieces did not resist the harsh marine environment. This led to the replacement of water filters after only 3 months of operation. At the time of the interview, the design team was working on the problem and looking for a solution to redesign the marine-water pumps, so the equipment can last longer and be easy to maintain.
- *Door system decision lacked coordination among different subcontractors:* The software installation requirement for selected door system was not compatible

with other door systems (e.g., automatic openers). These design decisions was made without proper coordination among subcontractors.

After talking about these examples, the interviewees and the researcher discussed how these problems could have been avoided. The interviewees mentioned that the involvement of appropriate stakeholders (specially contractors, subcontractors and maintenance specialists) at the right time might have help. Finally, after the researcher presented an application of the CBA method, the interviewees agreed that the use of a more formal decision-making method would have benefit the design process. This is not to say that CBA would have prevented all these problems, but suggest that it is important to understand and study the design process in building, including the decision-making method.

7.4.3. Architect’s Perspective

Unfortunately, it was not possible to have an interview with the architects in charge of the project. The researcher had only limited public information regarding the architect´s perspective on the building.

According to the EHDD Architecture (2012) press release, “the complexity of the program was matched by the challenge of rehabilitating an existing historic structure in the most energy efficient manner possible. To that end, the building takes advantage of the original Pier’s natural lighting and bay water for cooling. In addition, it must use materials that are both sustainable and durable enough to withstand a maritime climate.”

From this information it is unclear how the architects were leading the decision-making process and if they were implementing any specific decision-making method. However, it seems from the other interviews that a clearly predefined decision-making process was lacking.

7.4.4. Mechanical Engineer’s Perspective

In order to gather the mechanical engineering perspective, the researcher interviewed Peter Rumsey, Principal at Integral Group, and in charge of designing the HVAC system.

His view was that the decision-making process in this project was not as well established when compared with other Integrated Project Delivery (IPD) projects he has worked under using CBA.

The HVAC system selection was especially important for the project given the NZE goal. This decision generated many meetings and discussions during the design process, which created substantial documentation.

In practice the board of directors made this decision. Peter Rumsey had to present alternatives (Section 7.5.1) in front of the board of directors to explain technical differences. Usually, alternatives were analyzed presenting advantages and disadvantages (Different from CBA where only advantages of the alternatives are analyzed). Peter Rumsey advocated for the use of bay water coupled with PV panels for heating and cooling the building because he thought it that was ‘the right way’ of doing it considering sustainability issues. The documentation of the process was given by presentations explaining the advantages and disadvantages of the alternatives systems. Integral Group also reviewed other cases in which water was used as a heat sink for buildings (e.g., Hong Kong for commercial buildings, and Monterey aquarium in California). Finally, Integral group provided cost estimations of the alternatives and developed an analysis to compare the CO_2 emissions associated with each alternative.

7.5. Step-by-Step CBA Application to Choose an HVAC System

The following sections present how the analysis for choosing an alternative would look if the design team were applying Choosing by Advantages to this problem.

7.5.1. Step 1: Identify Alternatives

Choosing an HVAC system is composed of many decisions (Lechner, 2008). The design team needs to choose the primary energy source for heating systems (e.g., gas or electricity), the distribution system (e.g., radiant slab or fan coil unit), and the heat sink for pumping heat from the building (e.g., the outdoor air or a body of water).

This case study analyzes three different but interdependent decisions, (1) the energy source for the heating system, (2) the energy source for the cooling system, (3) and the sink to pump heat from the building (bay water or air using a cooling tower). Table 7.1 shows the alternatives that were considered by the design team.

Table 7.1 Design alternatives for energy sources and heat sink.

	Alternative 1	**Alternative 2**	**Alternative 3**
Heating Source	Natural gas boilers	Bay water-coupled electric heat pumps sourced by utility company	Bay water-coupled electric heat pumps with PV panels
Cooling Source	Electric chiller source by utility company	Bay water-coupled electric heat pumps sourced by utility company	Bay water-coupled electric heat pumps with PV panels
Heat Rejection	Cooling tower	Bay water	Bay water

All options include 3 inches roof insulation, energy efficient lighting and basic day-lighting controls. In addition, Integral Group recommended the use of a radiant floor system as a distribution system for all alternatives. Figure 7.4 shows an example of a radiant floor system installed in the Pier 1 building in San Francisco, California.

Figure 7.4 Radiant system (WSP Flack and Kurtz 2007).

The following presents the description of the three alternatives considered in this test case.

Alternative 1: Natural Gas boiler and chiller system with a cooling tower.

This alternative is commonly used in commercial buildings, and is considered the standard way of designing HVAC systems. In this case the heating source is a natural gas boiler, and the cooling source is an electric chiller (Figure 7.5). Heat rejection is done through a cooling tower (Figure 7.6).

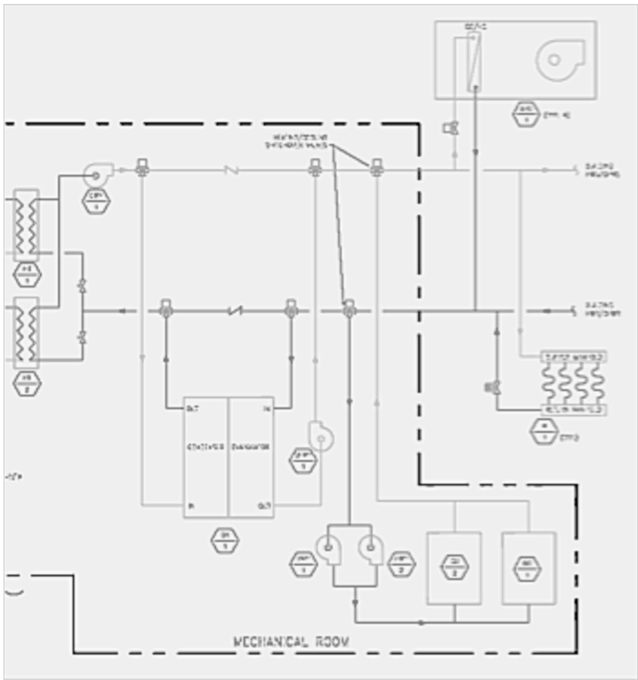


Figure 7.5 Gas boiler and chiller system piping schematics (Integral Group 2007).

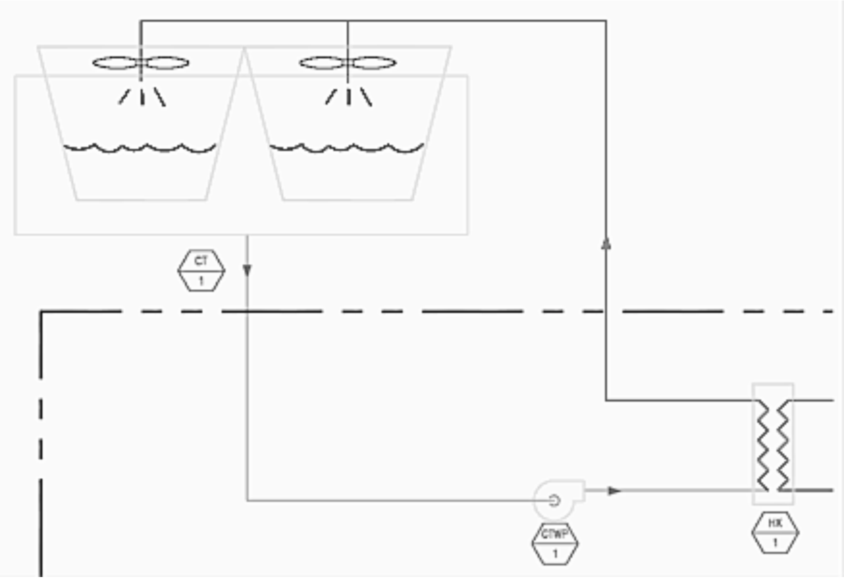


Figure 7.6 Cooling tower schematics (Integral Group 2007).

Figure 7.7 shows an example of a cooling tower in Pier 1 on The Embarcadero Street in San Francisco. The cooling tower requires extra space and is noisier when compared to using the bay water-cooling option.

Figure 7.7 Cooling tower Pier 1 (Integral Group 2007).

Alternative 2: Electric heat pump sourced by utility company with bay water.

This alternative takes advantage of the position of the building to use bay water for cooling and heating. Figure 7.8 shows the bay water-cooling concept for the Exploratorium building. The idea is to exchange heat between the cooler bay water and the hot water coming from the building, after the bay water is released.

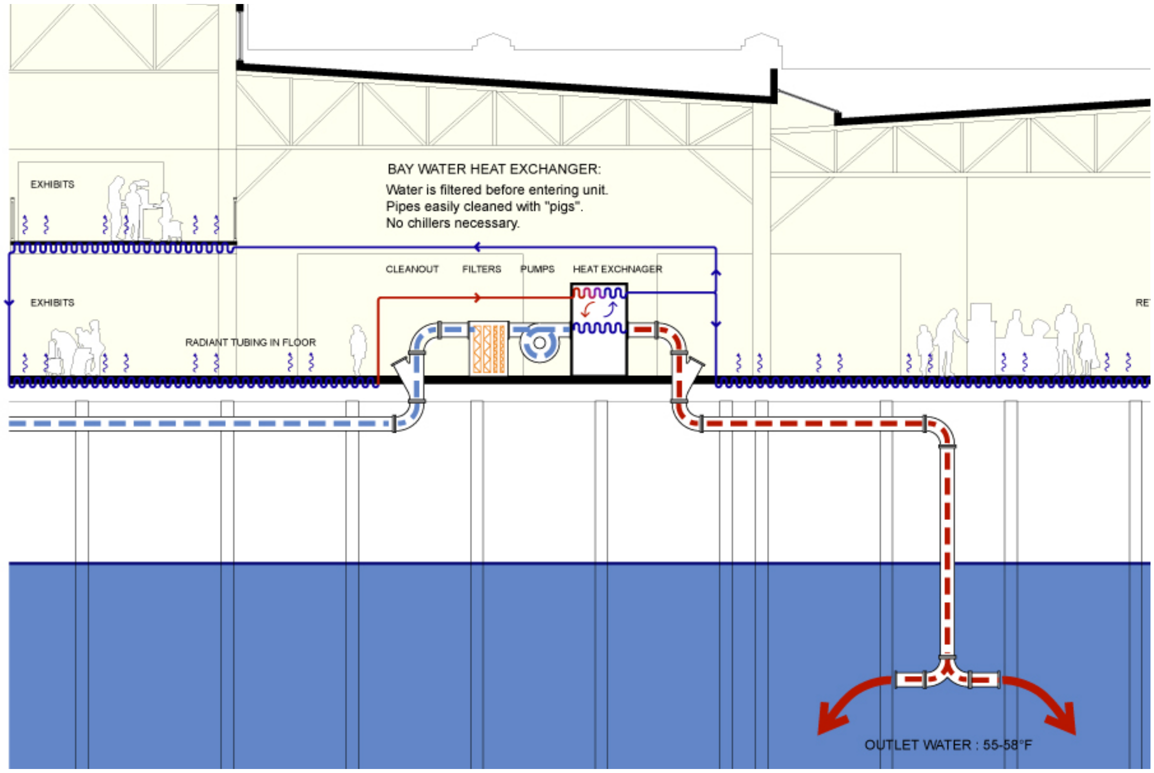


Figure 7.8 Bay water cooling concept (Integral Group 2007).

In this case the heating and cooling source will be bay water coupled with electric heat pumps (**Error! Reference source not found.**Figure 7.9) connected with a local utility company. Heat rejection is accomplished though bay water recirculation (Figure 7.10).

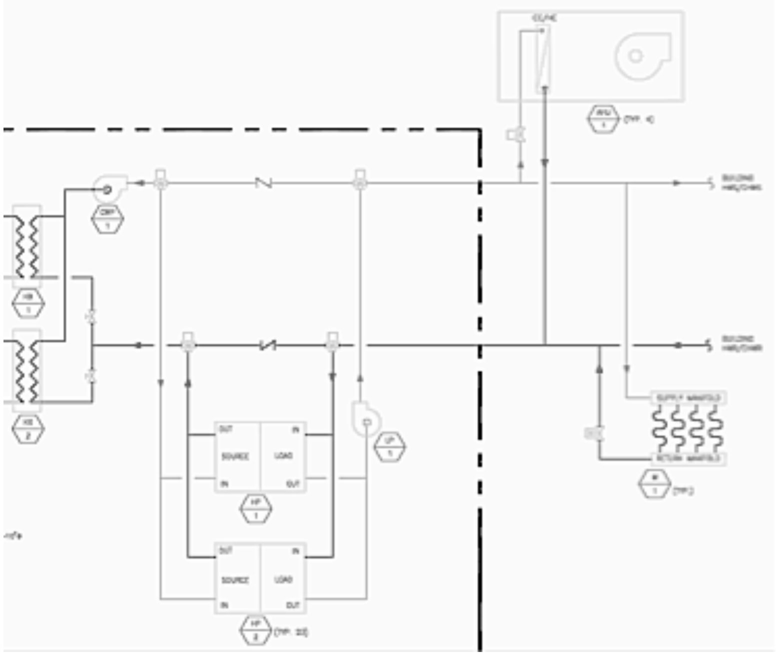


Figure 7.9 Electric heat pump system schematics (Integral Group 2007).

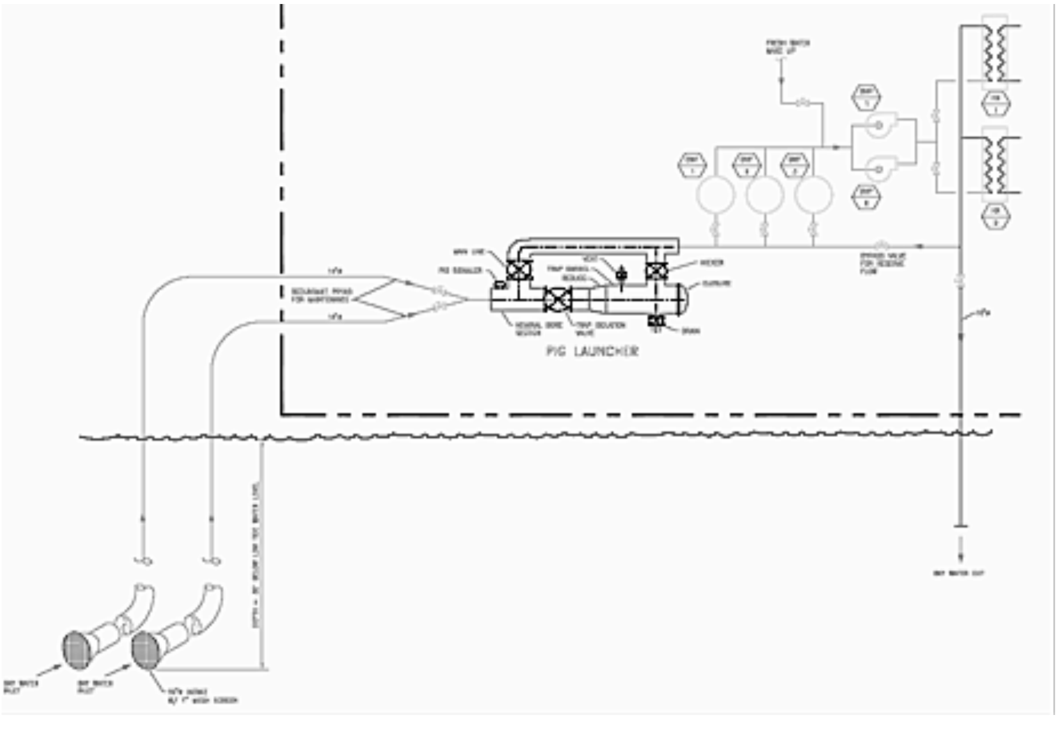


Figure 7.10 Bay water piping schematics (Integral Group 2007).

According to Integral Group estimations, bay water can meet the entire cooling load of the building 65% of the year, when bay water temperature is 60º F or below. However, a chiller system will still be required to meet peak loads in the months of July, August, September and October when bay water temperature is over 61º F (Figure 7.11).

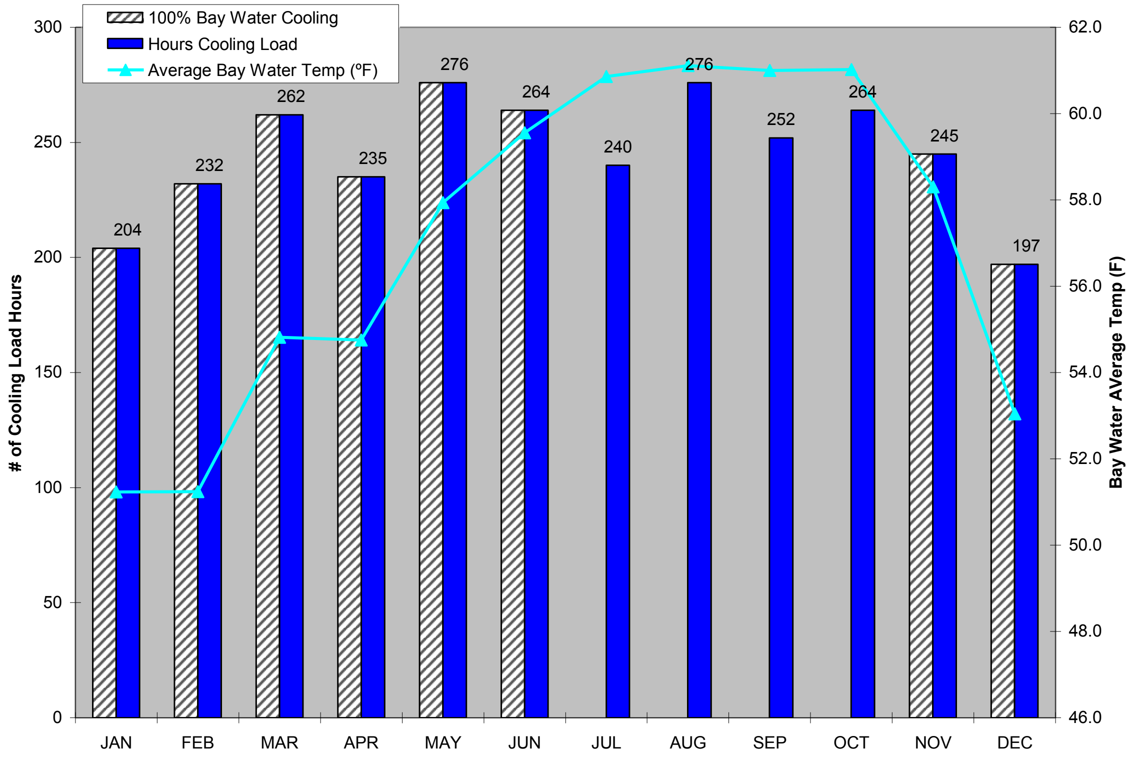


Figure 7.11 Estimated building cooling loads vs. bay water temperature (Integral Group 2007).

Alternative 3: Electric heat pump sourced by PV system with bay water.

In this case the heating and cooling source will be bay water coupled with electric heat pumps (**Error! Reference source not found.**same as alternative 2) connected with a PV system as energy source instead of the local utility company. Heat rejection is accomplished though bay water recirculation (**Error! Reference source not found.**same as alternative 2).

The design team did a photovoltaic study to see the potential energy that could be provided by the PV panels. Using solar data from a NASA satellite for lat. 37°47’27” N, long. 122°23’05 W, they could estimate the average daily radiation per month (Figure 7.12). The annual average solar incoming radiation for the Exploratorium location is 4.69 kWh/m^2/day and the clearness index is 0.570.

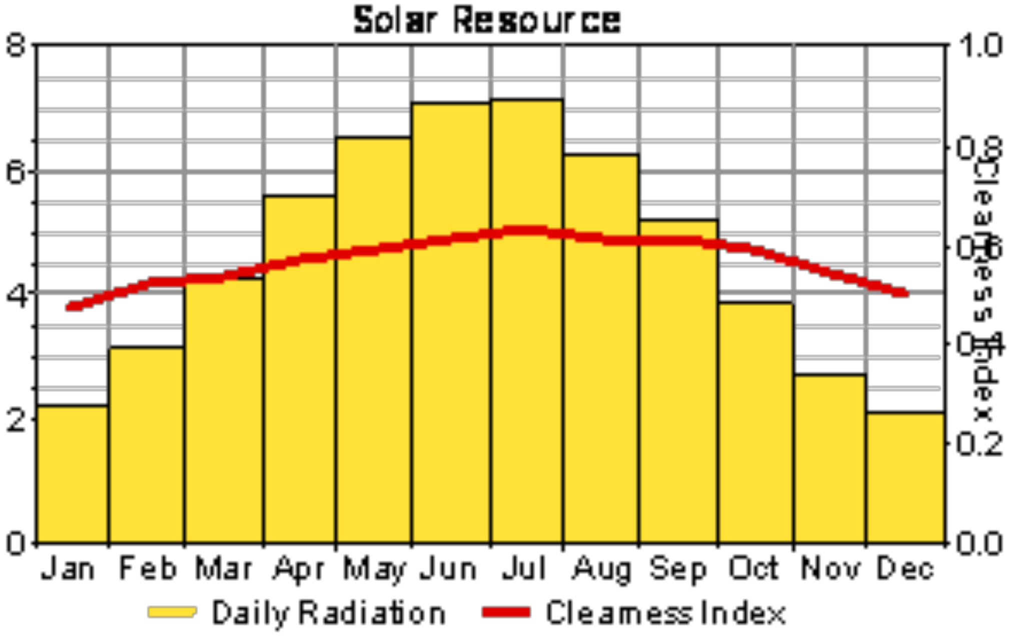


Figure 7.12 Average solar incoming radiation at the Exploratorium (Integral Group 2007).

The actual PV array is also a design decision and many alternatives were considered (e.g., possible roof area used, positioning PV system in Pier 15 or Pier 17, tilting positions of the PV panels, and panels type). The study included the optimal and possible roof areas based on building sections and plans provided by EHDD Architecture. The design team considered 80% area efficiency to account for walkways, running wiring and mounting hardware. They also accounted for 10% losses for temperature, dirt & grime on the panels, and degradation over time. The final design for this alternative consisted a PV array to cover 100% of the annual energy use, which can produce 1.3-megawatt, using 5,874 solar panels (Sunpower A-300 solar cells with a panel efficiency of 13.5 W/ft^2). By using this alternative the design team also expects to sell surplus power generated by the array to Pacific Gas and Electric's (PG&E) grid. This also provides a practical scientific teaching opportunity by informing visitors of the current output of the array.

In order to compare these 3 alternatives, Integral Group did an analysis to better understand what the impacts were in terms of energy use, CO_2 emissions and costs. Figure 7.13 shows the annual CO_2 emissions for the 3 alternatives during the operation phase.

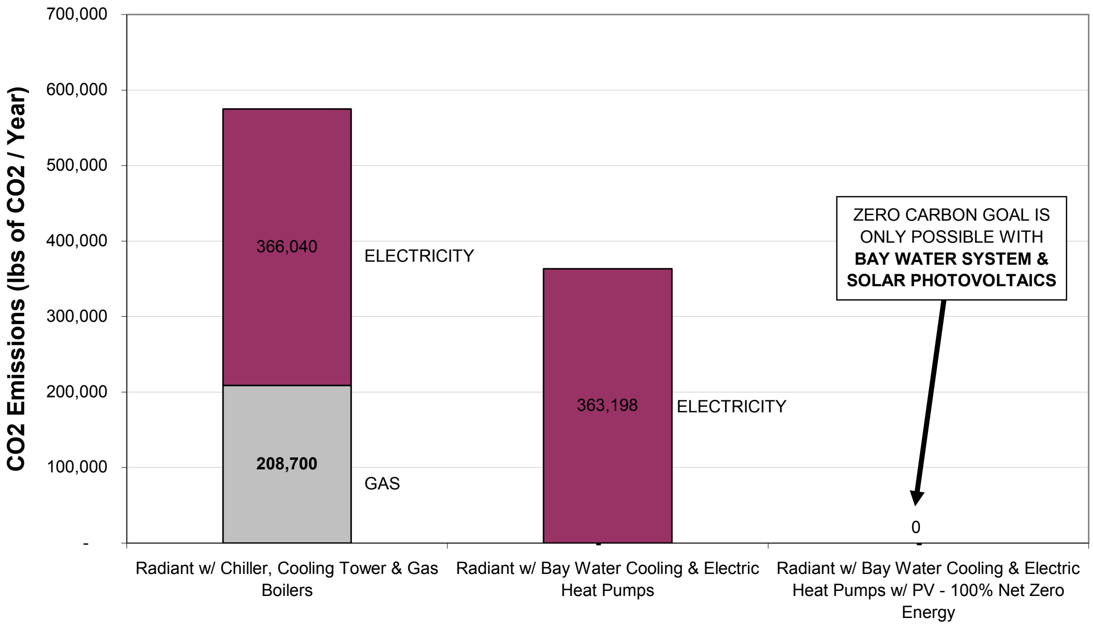


Figure 7.13 Annual CO2 emissions (Integral Group 2007).

Finally, Table 7.2 presents the initial- and life cycle costs of these 3 alternatives.

Table 7.2 Initial- and lifecycle cost of the 3 alternatives (Integral Group 2007).

	Alternative 1: Natural gas boiler and chiller system with cooling tower	**Alternative 2: Electric heat pump sourced by utility company w bay water.**	**Alternative 3: Electric heat pump sourced by PV panel system with bay water.**
Initial Cost	$1,154,250	$1,654,250	$6,173,399
Annual Operation Cost of Energy	$269,754.78	$245,145.57	$0
Annual Maintenance Costs	$1,500	$6,000	$6,000
Replacement Costs HVAC (every 40 years)	$912,500.00	$596,250.00	$596,250
Life Cycle Cost (50 years)	$15,857,614	$14,956,841	$7,218,712

All 3 options include a radiant floor system, 3” roof insulation, energy efficient lighting and basic day-lighting controls. In addition, the PV cost calculations include available incentives from PG&E ($0.37/kWh for 5 years which equals $3.25 million for alternative 3). This amount is approximate and the exact incentive depends on the timing of the project, and the type and layout of PV installed.

7.5.2. Step 2: Define Factors

In CBA, the design team needs to identify factors that will help differentiate between alternatives. The process of identifying factors may be iterative, since the design team may find new information when they develop a more detailed design of the alternatives. Based on the interviews and the available data, the researcher identified 7 factors that help to differentiate between alternatives. The factors represent the views of the owner, the architect, the mechanical engineer, the operation manager and users. The factors and the rationale for selecting them are as follows:

(1) Experience in using HVAC systems: The alternatives have important differences in how often they are utilized. The majority of commercial buildings use cooling towers and water-based systems are infrequently utilized. This is important in order to have a proven and reliable system.

(2) Space requirements: The alternatives have important differences in space requirements due to the requirement of having (or not) a cooling tower. Space is scarce and can be use for the museum displays instead of a cooling tower.

(3) Contribution to goal of NZE: The alternatives are different in how they contribute to the goal of NZE, e.g., using a PV panel system allows for onsite generation vs. natural gas needs to be sourced elsewhere.

(4) Water usage: The alternatives are different in their requirements for municipal fresh water. The cooling tower recirculates fresh water and loses significant quantities in evaporation vs. the bay-water system, which does not require precious fresh water from public sources.

(5) Maintainability: The alternatives are different in terms of maintenance requirements, e.g., using a bay-water system poses special challenges for maintenance vs. using standard maintenance procedures for a cooling tower.

(6) CO2 emissions: The alternatives have important differences in terms of CO_2 emissions during the operation and maintenance phase (Figure 7.13).

(7) Noise: The alternatives differ in terms of noise due to airflow movement, e.g., a cooling tower emits noise vs. bay-water system, which does not require cooling tower.

7.5.3. Step 3: Define the 'Must' and 'Want to Have' Criteria for Each Factor

For each factor, the design team needs to agree on criteria to judge the alternatives. Some attributes have a standard evaluation in which case it is easy to establish a criterion (e.g., for CO_2 emissions, the criterion may be the lower the CO_2 emissions the better). In other cases, the design team needs to describe what they want (e.g., for experience using the HVAC systems, the criterion may be the more reliable the system is, the better.). The criteria do not represent a trade-off. CBA does not assume that every increment of performance is equally valuable. Table 7.3 presents the factors and criteria considered in this decision in the first column.

7.5.4. Step 4: Summarize the Attributes of Each Alternative

In order to obtain the attributes of each of the alternatives, we used data available from Integral Group and also from the interviews. Table 7.3 summarizes the attributes of the alternatives. The least preferred attributes are underlined and will be used as comparison points to describe advantages.

Table 7.3 CBA steps 1 to 6 for choosing an HVAC systems for the Exploratorium building.

Factor (Criterion)	**Alternative 1: Natural Gas boiler and chiller system with a cooling tower**		**Alternative 2: Electric heat pump sourced by utility company with bay water.**		**Alternative 3: Electric heat pump sourced by PV panel system with bay water.**	
1. Experience using this HVAC system	Att.: Typically used in commercial buildings. This is the standard way.		Att.: It is not that common to use bay water for HVAC systems unanticipated problems may arise.		Att.: It is not that common to use bay water for HVAC systems unanticipated problems may arise.	
(The more reliable the system is, the better)	Adv.: *It is more reliable than alt. 2 and 3.*	Imp.: 50		Imp.:	Adv.:	Imp.:
2. Space requirements	Att.: Cooling tower uses a lot of space. 370 ft^2 approximately.		Att.: The condenser occupies the least amount of space		Att.: The condenser occupies the least amount of space	
(The less space the HVAC system uses, the better)	Adv.:	Imp.:	Adv.: *It saves around 370 ft^2*	Imp.: 20	Adv.: *It saves around 370 ft^2*	Imp.: 20
3. Contribution to goal of NZE	Att.: It requires external energy by using natural gas and electricity from the grid. It does not allow for NZE.		Att.: Lower power consumption than air-cooled systems, especially at peak load. It requires external energy by using natural electricity from the grid. It does not allow for NZE.		Att.: Lower power consumption than air-cooled systems, especially at peak load. It allows the building to produce the same energy that it consumes.	
(The more the alternative contributes to achieve the NZE target, the better)	Adv.:	Imp.:	Adv.: slightly better than alt. 1.	Imp.: 20	Adv.: significantly better than alt. 1. Allowing for NZE	Imp.: 100

4. Water usage	Att.: It requires the use of evaporative cooling towers, which uses an estimated 2 million gallons of fresh water per year		Att.: Used water is returned to the bay		Att.: Used water is returned to the bay	
(The less water the system uses, the better)	Adv.:	Imp.:	Adv.: *It saves 2 million gallons of fresh water per year.*	Imp.: 35	Adv.: *It saves 2 million gallons of fresh water per year.*	Imp.: 35
5. Maintainability	Att.: Easy standard maintenance		Att.: Hard maintenance. Bio Fouling will be produced		Att.: Hard maintenance. Bio fouling will be produced	
(The easier to maintain, the better)	Adv.: *maintenance is easier and less frequent than alt 2 and 3.*	Imp.: 60	Adv.:	Imp.:	Adv.:	Imp.:
6. CO_2 emissions	Att.: 574,740 lb CO_2 per yr.		Att.: 363,198 lb CO_2 per yr.		Att.:	
(The lower the CO_2 emissions, the better)	Adv.:	Imp.:	Adv.: Avoids 211,542 lb CO_2 per yr.	Imp.: 40	Adv.: *Avoids 574,740 lb CO_2 per yr.*	Imp.: 80
7. Noise	Att.: It may produce noise problems associated with high airflow required for air-cooled systems.		Att.: it is a quiet system		Att.: it is a quiet system	
(The less noise, the better it is)	Adv.:	Imp.:	Adv.: *Less noisy than alt 1.*	Imp.: 10	Adv.: *Less noisy than alt 1.*	Imp.: 10
Total IofAs		110		125		245

7.5.5. Step 5: Decide the Advantages of Each Alternative

Once the attributes are summarized, the design team needs to apply the criteria to identify the advantages. Table 7.3 presents the advantages (Adv.) of each alternative for each factor

7.5.6. Step 6: Decide the Importance of Each Advantage

This part of the process is collaborative and decisions are reached through discussion within the design team. In this case the subjective values of Importance of Advantages (IofAs) were assigned by the researcher and not by the design team for the purpose of exemplifying the use of CBA. Table 7.3 presents the IofAs (Imp.), the most important advantage for each factor is shown in italics.

The rationale for choosing the IofA scores is explained here:

- The most important advantage seems to be that alternative 3 is significantly better than alternative 1 in terms of contributing to the NZE goal. Actually, only alternative 3 allows for achieving a NZE building. This is one of the main purposes of the building and also allows for teaching sustainability concepts to visitors. In addition, alternative 2 is slightly better than alternative 1 with regards to contributing to NZE because it does not require natural gas. However, that seemed less important when compared to the paramount advantage, so the researcher assigned an IofA of 20.
- Alternative 3 avoids 574,740 lbs. of CO_2 per year when compared to alternative 1. This seems important so the researcher assigned an IofA of 80. At the same time alternative 2 avoids 211,542 lbs. of CO2 per year when compared to alternative 1, so the researcher assigned an IofA of 40.
- Alternative 1 has two advantages over alternative 2 and 3. First, it is more reliable than alternatives 2 and 3, which seems important, but not that much when compared with the paramount advantage. Accordingly, the researcher assigned 50 IofA. Second, alternative 1 maintenance is easier and less frequent than alternatives 2 and 3, which is also important, so the researcher assigned an IofA of 60.
- Lastly, alternatives 2 and 3 have 3 equal advantages over alternative 1. First, alternatives 2 and 3 save approximately 370 ft^2. when compared with alternative 1, because they do not require a cooling tower. This advantage seems relatively unimportant when compared with the paramount advantage, therefore the researcher assigned an IofA of 20. Second, alternative 2 and 3 save 2 million gallons of fresh water per year when compared to alternative 1. This seems somewhat important when compared to the paramount advantage, so the researcher assigned an IofA of 35. Third, alternative 2 and 3 are less noisy than alternative 1, which does not seem very important when compared to the paramount advantage, so the researcher assigned an IofA of 10.

7.5.7. Step 7: Evaluate Cost Data

The design team can plot total IofAs against first cost (Figure 7.14) and total IofAs against lifecycle cost (Figure 7.15) for the 3 alternatives.

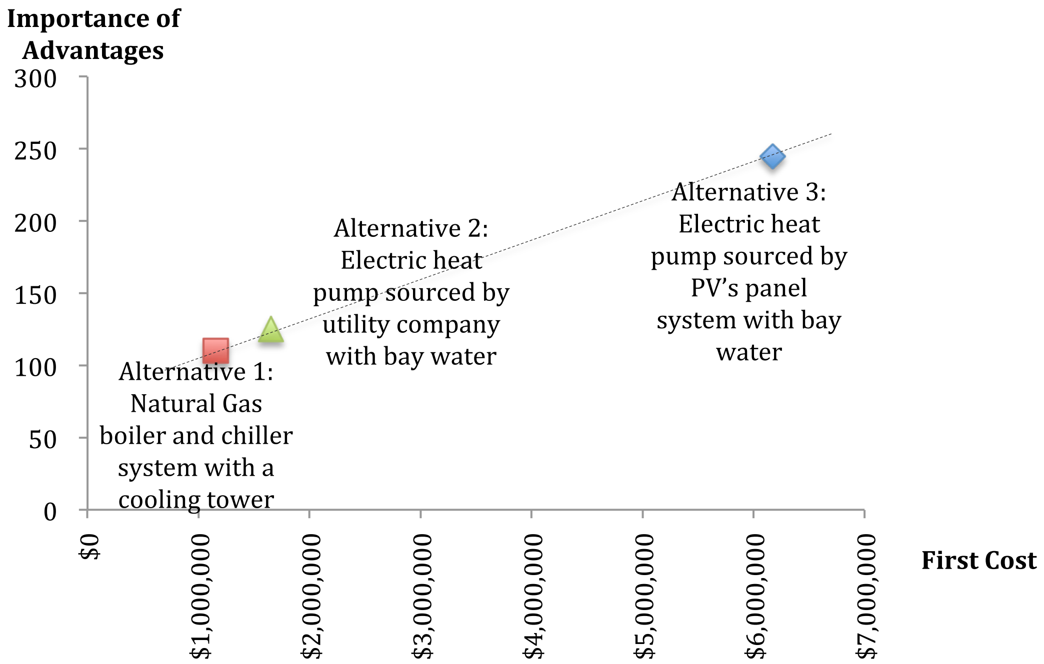


Figure 7.14 IofA vs. first cost.

Figure 7.14 shows that the first cost follows almost a linear curve with IofAs. The design team needs to decide if they can and are willing to pay more for getting alternative 3 with the highest IofA.

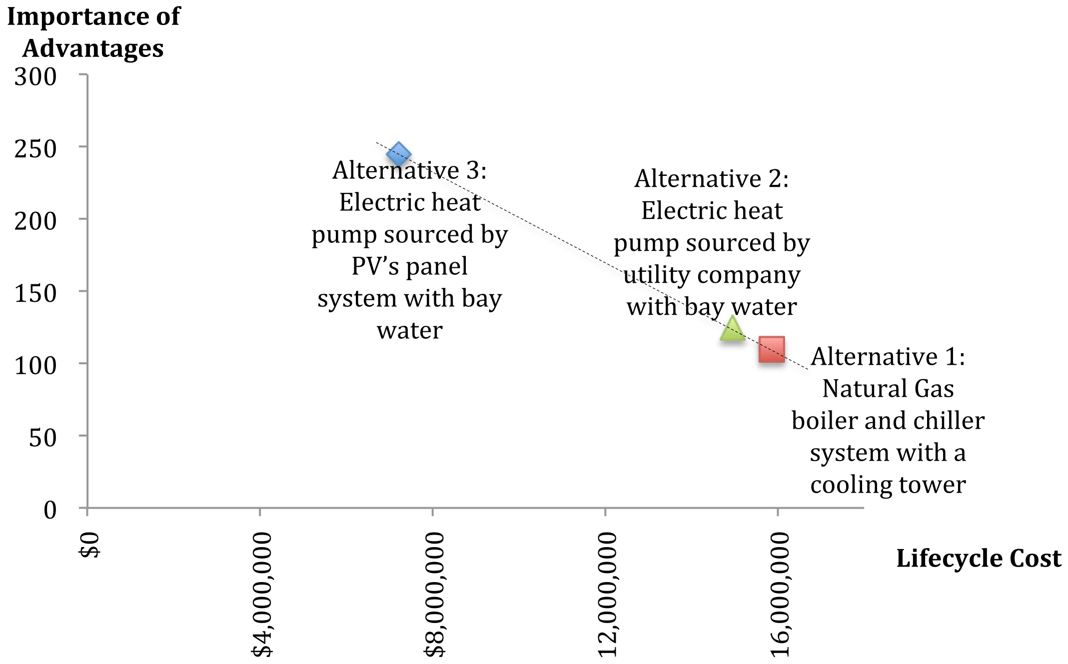


Figure 7.15 IofA vs. lifecycle cost.

Figure 7.15 shows that alternative 3 is better long term in lifecycle cost and IofA than alternatives 1 and 2. Since alternative 3 has the advantage of achieving NZE goal and reduces CO_2 emissions to almost zero (for the operation of the HVAC system), it makes sense for the design team to select alternative 3.

7.6. Discussion

It seems that the design team made the decision in agreement with the CBA analysis by choosing alternative 3 as the final design alternative for the Exploratorium since it provided more IofA and the least lifecycle cost compared to alternatives 1 and 2. However, this may have been influenced by the available information. Some questions arise in terms of what other factors should have been evaluated, and how realistic the calculated life cycle costs were.

This test case shows how CBA can be used for organizing the information in a way that is easy for the design team to make subjective judgments and then present trade-offs of cost vs. 'value'. CBA helps in documenting the rationale behind the decision-making process. This can help designers in learning from past experiences, and to improve designs for future projects. In addition, documenting decisions with CBA helps in retaining knowledge of the project in case people leave the design team.

The CBA method creates a transparent framework, and builds consensus within a design team with multiple perspectives (e.g., owner, architects, mechanical engineer, operation manager, and users). Different perspectives can be discussed, using factors, criteria, attributes, and understanding of the advantages before estimating the IofAs. The major challenge in building consensus is when the design team has to agree on the IofAs. CBA helps the design team in avoiding base decisions on assumptions or previous experiences. Instead, the design team needs to understand the differences between the alternatives in the particular decision context, decide which alternative has advantages for each factor, understand how important these advantages are compared to each other, and finally, decide on the importance of the advantages.

7.7. Conclusions

The researcher believes that applying CBA would have helped the design team in making a more transparent decision than originally made, by providing a clear method for expressing the trade-offs. CBA provides a clear structure for the design team to present alternatives based on its advantages. Using advantages only and not advantages and disadvantages (as it was presented for the board of directors) makes the process more transparent and easy to understand. CBA allows incorporating perspectives from different stakeholders, and provides a basis for discussion.

The researcher thinks that building consensus on a decision and understanding the impacts of each alternative can be supported by the use of CBA. The design team made decisions based on the information they had. They gave more importance to the advantages of the 'electric heat pump sourced by a PV panel system with bay water' alternative, mainly due to significant savings in energy, water, and CO_2 emissions than the other two alternatives. However, the advantages of discarded alternatives provided valuable information for discussion also. For example, the ‘natural gas boiler and chiller system with a cooling tower’ alternative is more reliable and easier to maintain than the chosen alternative. Trade-offs between the advantages required a common understanding and also can guide actions in the design. The design team can ask how to incorporate the advantages of the discarded alternatives into the chosen one, making the design of the chosen alternative more reliable and easy to maintain.

The researcher also believes that using CBA systematically for other building decisions would make it easier to document and track them and their rationale. This would allow the team to learn through the different iterations. For example, the design team may have used CBA for choosing the PV panels’ array and that could provide a way of evaluating multiple decisions by aggregating the IofAs. CBA can support the comparisons of IofA across different decisions by comparing the importance of paramount advantages of the different decisions, and then rescaling the advantages. Other decisions regarding light fixtures, roof insulation, and daylight options were also related with the HVAC system alternatives and may have been documented using CBA. Chapter 8 explores in more depth how different decisions may be aggregated using CBA.

8. TEST CASE 3: CHOOSING A BUILDING DESIGN FOR A NET ZERO ENERGY LIBRARY USING CBA

8.1. Introduction

Test case 3 applies Choosing By Advantages (CBA) to decisions that the design team made in the design of a Net Zero Energy (NZE) library in Berkeley, California. The actual decisions were already made without the use of CBA. Therefore, this case analyses how CBA could have hypothetically been applied to the design process. The objectives of the case were to understand how decisions were made, apply CBA to one decision, and see how CBA could have been used in multiple interrelated decisions. The researcher interviewed the architect in order to have his perspective on the use of CBA.

8.2. Case-Study Background

This test case pertains to the West Branch of the public library, located in the city of Berkeley, California (Figure 8.1). The new West Branch replaces a library building formerly located on the same quarter-acre site on University Avenue near the corner of San Pablo Avenue. The design team aimed to achieve NZE, and possibly a net-positive energy performance using passive design techniques. This would make the building the first NZE library in Berkeley.

Figure 8.1 Final design Berkeley West Branch Library (Harley Ellis Devereaux 2013).

The estimated completion date for the project was August 2013, but the actual completion date was December 2013. The researcher conducted interviews with the architects from March 2013 to May 2013, when the construction was already advanced.

8.2.1. Project Team

The design team consisted of a multidisciplinary group, which worked collaboratively since early stages of the design. The design team was composed of individuals from the following organizations:

- Client: City of Berkeley, California.

- Architect, sustainability consultant, commissioning agent: Harley Ellis Devereaux, GreenWorks Studio
- General contractor: West Bay Builders
- Mechanical, Electrical, and Plumbing (MEP) engineer: Harley Ellis Devereaux
- Structural engineer: Tipping Mar
- Civil engineer: Moran Engineering
- Landscape architect: John Northmore Roberts and Associates
- Cost estimator: Cumming Corporation.

In addition, the project benefited from early collaboration between the City of Berkeley, specifically the Office of Energy and Sustainable Development, Harley Ellis Devereaux and representatives of the ‘savings by design’ program of Pacific Gas and Electric (PG&E) Company (Corbeil 2012).

8.2.2. Building

The project consisted of a new 9,500 ft^2. building with an estimated construction cost of \$5.5 million, but an actual cost of \$6 million. Figure 8.1 shows the final design of the West Branch Library. The new branch has space to accommodate library and adult literacy programs. Features include a quiet study room, teen room, comfortable seating for adults and children, and increased space for computer access and improved access to collections compared with the previous library.

8.2.3. Design Goals and Building Features

The project had several design goals that were used for guiding decisions. Some of the highlighted goals that were achieved in the final design, but may need to be measured after operations begin, are:

1. Net zero energy target

The design team’s goal was to achieve net-positive energy performance (supplying power back to the city’s electrical grid) and a carbon-neutral footprint. The team had to apply passive design in order to achieve this goal. This includes making extensive use of natural day light, system-controlled natural ventilation for fresh air and cooling, zoned radiant floor heating with hot water from solar panels, and a solar photovoltaic (PV) system for electric power. The building also makes extensive use of energy-efficient LED lighting, and special control features to help reduce secondary electrical loads from computers and other equipment. Table 8.1 shows the final design projected energy performance of the building.

Table 8.1 Final design projected energy performance.

Electricity generation and load	
Total renewable energy generation	17.4 kBtu/ft^2/year
Photovoltaic panels	15.4 kBtu/ft^2/year
Solar thermal panels	2.0 kBtu/ft^2/year
Total building electrical load	17.4 kBtu/ft^2/year
Lighting	3.8 kBtu/ft^2/year
Heating	3.5 kBtu/ft^2/year
Cooling (heat pumps)	2.2 kBtu/ft^2/year
Plug load	6.3 kBtu/ft^2/year
Hot water	0.9 kBtu/ft^2/year
Ventilation fans	0.7 kBtu/ft^2/year
Net energy consumption	**0 kBtu/ft^2/year**

2. *Daylight*

The design team goal was to provide adequate light for all the activities inside the library (e.g., reading or using computers) while minimizing energy consumption in the building. The final design utilizes daylight through a series of skylights and a large glass curtain wall on the main façade. The team minimized the amount of electrical lighting in the building, such as in the back office areas. When the library closes for the day, the entire facility will essentially go dark to reduce energy use.

3. *Ventilation*

The design team's goal was to provide adequate air quality in the building while minimizing energy consumption. To achieve this, the team used Computational Fluid Dynamics (CFD) to design a natural ventilation scheme.

4. *Low building loads in balance with programming*

The design team's goal was to minimize building electrical loads without compromising the desired library program. The new library has a larger square footage than the previous one and has multiple use spaces with an improved patron flow. According to Gerard Lee, associate and project manager with Harley Ellis Devereaux, "we had to find the sweet spot between what the building wanted to be from a program standpoint and what it should be from an energy-performance standpoint." (Barista 2013)

5. *Harmonize with the surrounding architecture and invite visitors*

The design team's goal was to provide a building that is in harmony with the surroundings and invites visitors to the library. The final design features an arbor at the entry with hanging wisteria and public exterior seating areas. The final design also facilitated pedestrian and bicyclist access by providing additional bicycle racks.

6. *Saving water*

The design team's goal was to minimize water usage in the building, as well as the runoff water effect. The final design includes water efficient fixtures and site improvements that meet bay friendly landscaping guidelines such as the use of native plants and planters that divert runoff water through an infiltration system.

7. Cost paradigm shift

The design team wanted to demonstrate that it was possible to design a NZE building that is also economically feasible and meets a client's needs. A NZE building does not need to cost more. In fact, Mr. Lee (2013) stated that the first cost of this building was close to a regular non-NZE building.

8.3. Case-Study protocol

The case-study protocol describes the steps the researcher followed for testing the use of CBA retrospectively in this project.

1. Identified and reviewed the literature about the project to understand the background, the decisions made and the alternatives considered.
2. Conducted an interview with the architect in charge of the project, Gerard Lee. This interview was key in understanding the design motivations, the design process and how decisions were made in the project.
3. Obtained data about alternative designs. The architect provided data about the analysis and alternatives that were analyzed for this project. The researcher reviewed in detail the specific data relating the building's layout decision.
4. Developed a prototype of how CBA might have worked in this project and how decisions might have been made or supported. The researcher developed a complete CBA application for the building's layout decision.
5. Conducted a second interview with Mr. Lee in order to present the CBA method application. The researcher gathered his comments and perspectives regarding the potential use of CBA in this project.
6. Wrote a report and sent it back to the architect for further feedback.

8.4. How Were Project Decisions Made?

This information is based on the two interviews with Mr. Lee and design documents that showed alternatives and analysis of different building systems.

According to Mr. Lee (2013), it was not easy to isolate a single design decision from the design process. Moreover, the design team was studying multiple design decisions at the same time. During the design process the decisions were interrelated and the design team tried to analyze them from a holistic perspective and judge how they would impact the whole building performance. The researcher developed Figure 8.2 for illustrating the interrelation among different design decisions, according with the interviews and information gathered. For example, the decision about which building layout to use impacts the ventilation design and the skylight design. At the same time, the roof height impacts the building layout and the ventilation system. Therefore, the application of CBA to a single design decision may not be realistic if it is not accompanied by the application of CBA to other interrelated decisions at the same time. The challenge in trying to use

CBA, or any other decision-making method, for each individual system is that (1) design alternatives of other related systems may not be known, (2) the impact of the design alternatives may not be well understood by analyzing each system, (3) many iterations may be required. The actual order in which decisions were made or if the design team analyzed combinations of alternatives was not clear to the researcher. The decision-making process was iterative and not every step was documented. In addition, one of the architects that started with the building design process left the project; therefore, information about decisions he made was not available for the researcher.

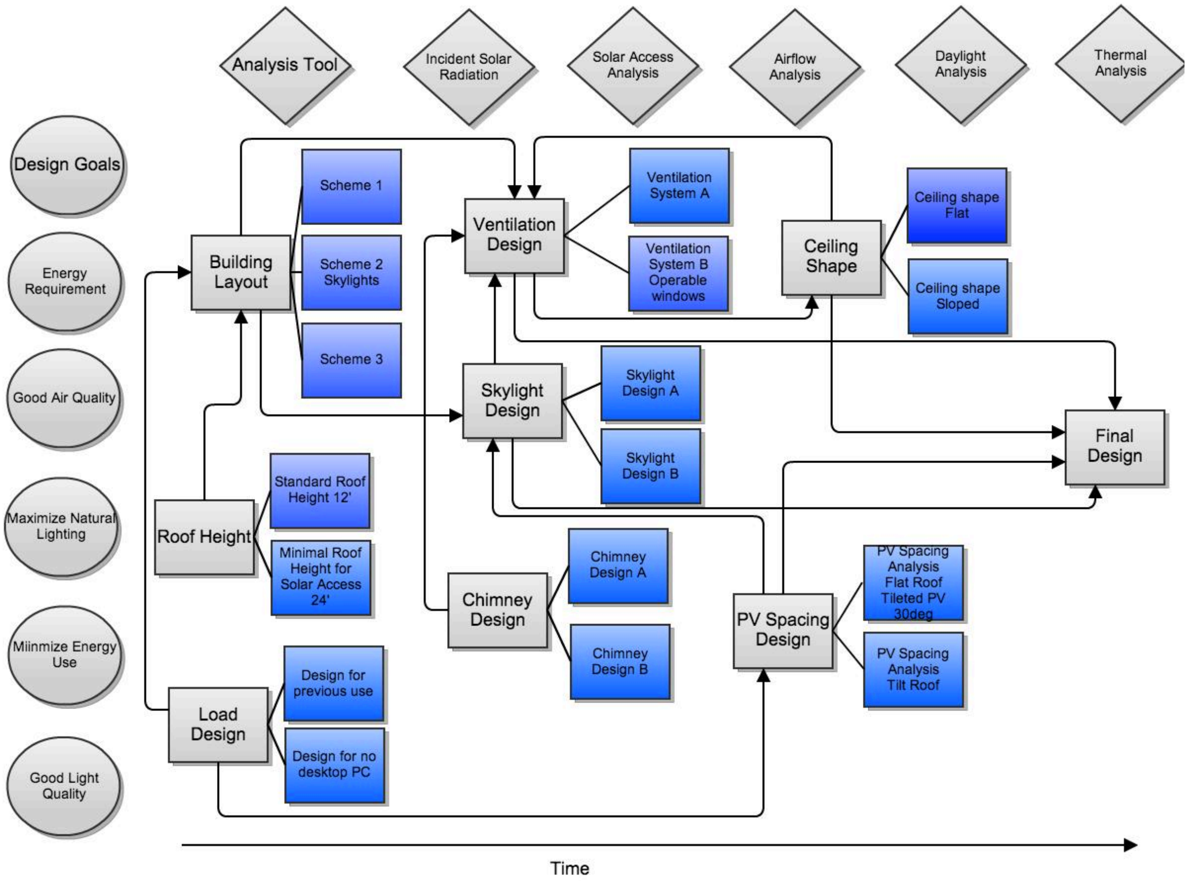


Figure 8.2 Decision interrelations.

In order to manage the interrelationships among building systems, the design team ran simulations to estimate the overall outcomes in terms of energy use, energy generation, light quality, and air quality for the whole building. This was done collaboratively with the different design specialists including architects, engineers and consultants (PG&E). At the same time the design team was trying to maintain consistency between the design and the constructability. The design team documented a number of alternatives that were not part of the final design, and the attributes of those alternatives. However, the design team did not use a standard or systematic decision-making method to make decisions using the available information. It was not clear to the researcher how they made trade-offs during the design process.

The following are some of the alternatives and analyses the design team studied.

8.4.1. Roof Height Design

In collaboration with its partner, PG&E, the design team was able to make a solar axis study for the rooftop solar installations according to the project site. The goal was to optimize the amount of energy generated by the PV and solar thermal panels and to minimize shading from other buildings, including a three-story hotel to the east (Figure 8.3).

Figure 8.3 Project site and orientation (Harley Ellis Devereaux 2013).

Figure 8.4 shows the solar access analysis for two alternatives, a 12 foot high roof (the standard roof height for a one story building in Berkeley), and a 24 foot high roof (the minimal roof height for solar access at this site). According to Michael Bulander, associate with Harley Ellis Devereaux, “the starting point for the entire design was actually the building’s roof” (Barista 2013).

Through the modeling, the design team determined that the optimal design consisted of a compact, rectangular roof, 24 feet high in order to avoid shading. It is not clear to the researcher if the design team estimated only two alternatives (12’ and 24’) or a wider set of alternatives.

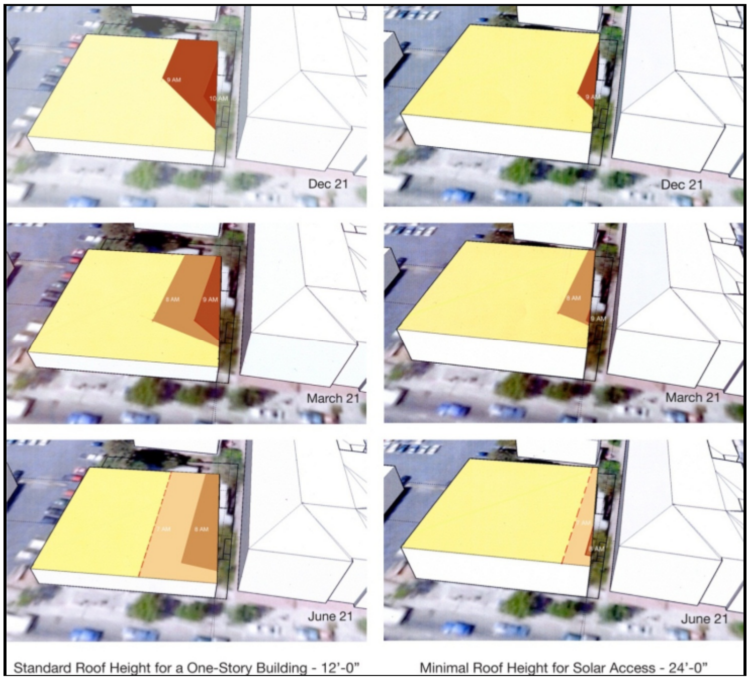


Figure 8.4 Solar access analysis for 12' and 24' high roofs (Harley Ellis Devereaux 2013).

8.4.2. Building Layout

The design team considered three layout options or, at least, three were documented (Figure 8.5, Figure 8.6, and Figure 8.7).

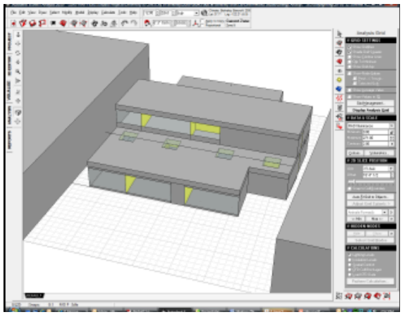


Figure 8.5 Alternative A: Long high windows (Harley Ellis Devereaux 2013).

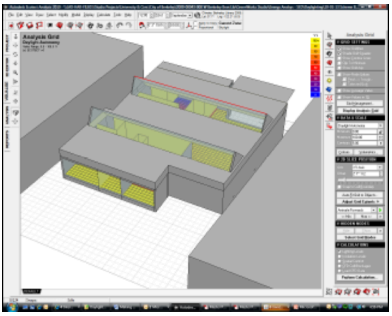


Figure 8.6 Alternative B: Skylights (Harley Ellis Devereaux 2013).

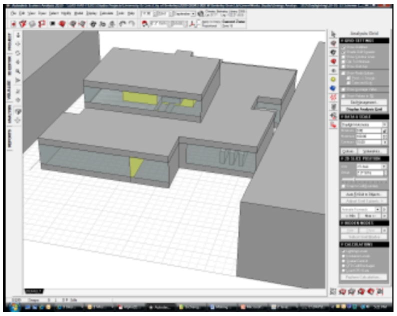


Figure 8.7 Alternative C: Long window and atrium (Harley Ellis Devereaux 2013).

The design team did an analysis to estimate the incident solar radiation associated with the three layout alternatives (Figure 8.8, Figure 8.9, and Figure 8.10).

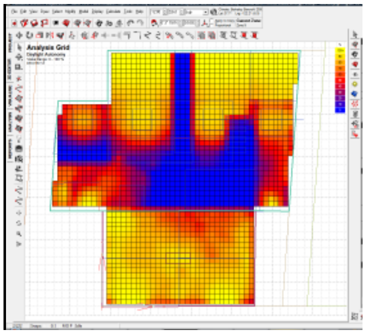


Figure 8.8 Incident solar radiation for alternative A (Harley Ellis Devereaux 2013).

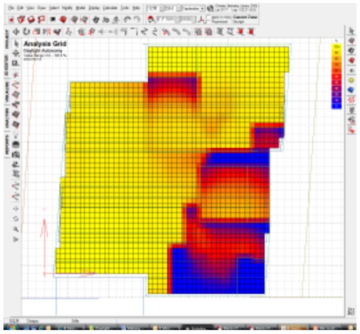


Figure 8.9 Incident solar radiation for alternative B (Harley Ellis Devereaux 2013).

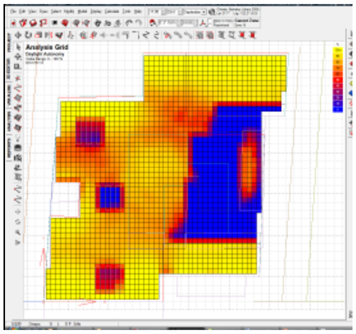


Figure 8.10 Incident solar radiation for alternative C (Harley Ellis Devereaux 2013).

The final design was to include the skylight alternative, given the higher incident solar radiation it obtained compared to the other two design alternatives. Unfortunately, the researcher did not have access to the exact results.

8.4.3. Skylight Design

The design team considered the skylight's design by comparing the annual energy saving (considering lighting, cooling and heating) vs. the skylight to floor ratio (Figure 8.11).

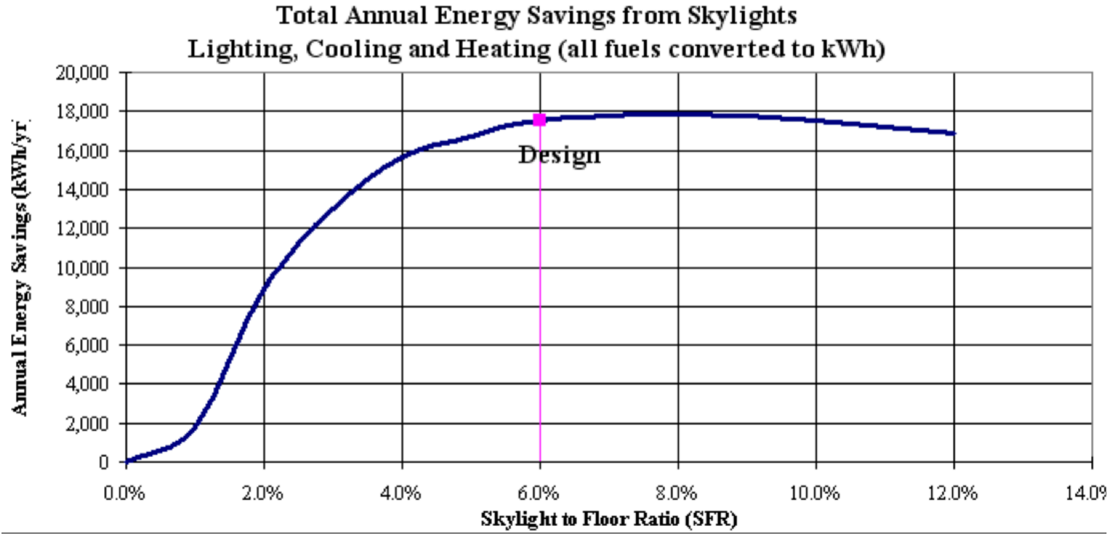


Figure 8.11 Trade-off between daylight vs. thermal conditioning (Harley Ellis Devereaux 2013).

The final design consisted of 3 rows of skylights, with a skylight to floor ratio of 6%. According to PG&E (2013), the placement of the skylights and the solar PV panels was designed to avoid any shading of the PV panels by the skylight shafts while at the same time giving the skylights the maximum 'view' of the sky, which is the source of daylight.

8.4.4. PV Array Design

The design team modeled the roof design to maximize the number of solar panels that could be installed on it. In addition, the rooftop solar panels had to compete for space with three rows of skylights that were designed to provide adequate day lighting to the building. And, of course, the roof configuration had to meet the programmatic requirements for the library.

In addition, the design team studied different spacing and tilting options for the PV panels. Figure 8.12 and Figure 8.13 show the different alternatives analyzed and the estimated generation per square foot considering three options (flat roof with horizontal panels, flat roof with panels tilted at a 30º angle facing north, and sloped roof tilted at a 30º angle facing north).

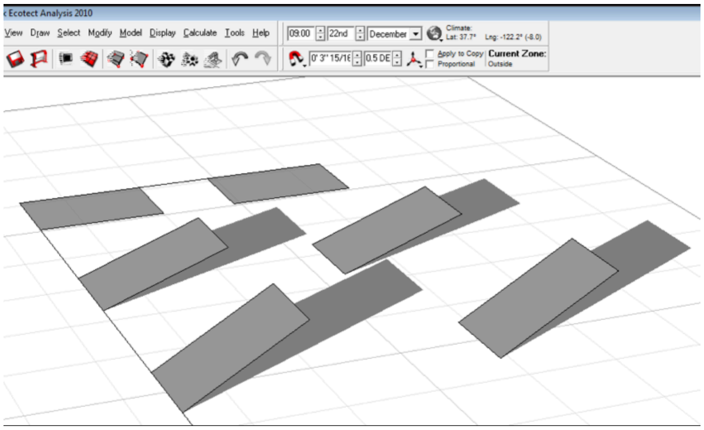
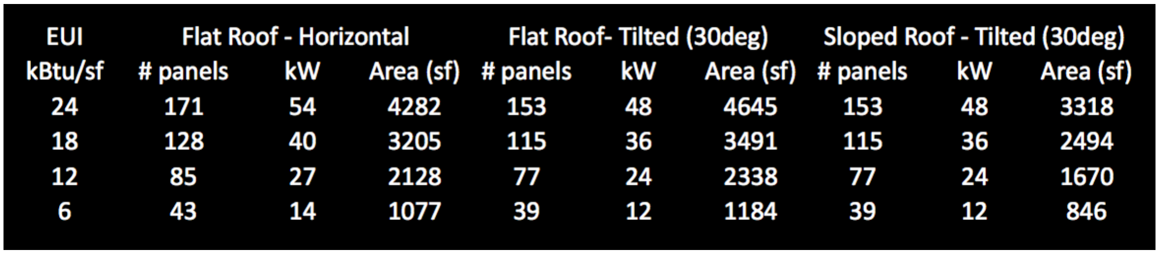


Figure 8.12 PV design alternatives (Harley Ellis Devereaux 2013).



EUI	Flat Roof - Horizontal			Flat Roof- Tilted (30deg)			Sloped Roof - Tilted (30deg)		
kBtu/sf	# panels	kW	Area (sf)	# panels	kW	Area (sf)	# panels	kW	Area (sf)
24	171	54	4282	153	48	4645	153	48	3318
18	128	40	3205	115	36	3491	115	36	2494
12	85	27	2128	77	24	2338	77	24	1670
6	43	14	1077	39	12	1184	39	12	846

Figure 8.13 PV spacing analysis (Harley Ellis Devereaux 2013).

The final design consists of horizontally oriented solar panels, stacked three high at a 20º angle. The panels are divided into four arrays, which are interspersed between the three rows of skylights. The design team estimated that a total of 120 panels would generate 75,050 kWh/year with a final system efficiency of 93.8%. In addition, 16 solar thermal panels are located in two arrays at the northeast corner of the roof.

According to Mr. Lee. “The PV panels are angled and located to avoid casting shadows on the skylights, and the same can be said for the skylights.” (Barista 2013).

8.4.5. Load Design

Once the design team established the roof design, they could accurately calculate the amount of solar energy that would be harvested. The idea was to design the building to minimize the Energy Use Intensity (EUI) to match the renewable energy supply. The EUI is expressed as energy per square foot per year. This is calculated by dividing the total energy consumed by the building in one year (in this case, measured in kBtu) by the total gross floor area of the building. According to Mr. Bulander "Our EUI is very low in relation to other projects—just 17 kBtu/ft^2/year. By comparison, the average office building has an EUI of 193 kBtu/ft^2/year; hospitals can exceed 500 kBtu/ft^2/year." (Barista 2013). Figure 8.14 shows the EUI target compared with a baseline building.

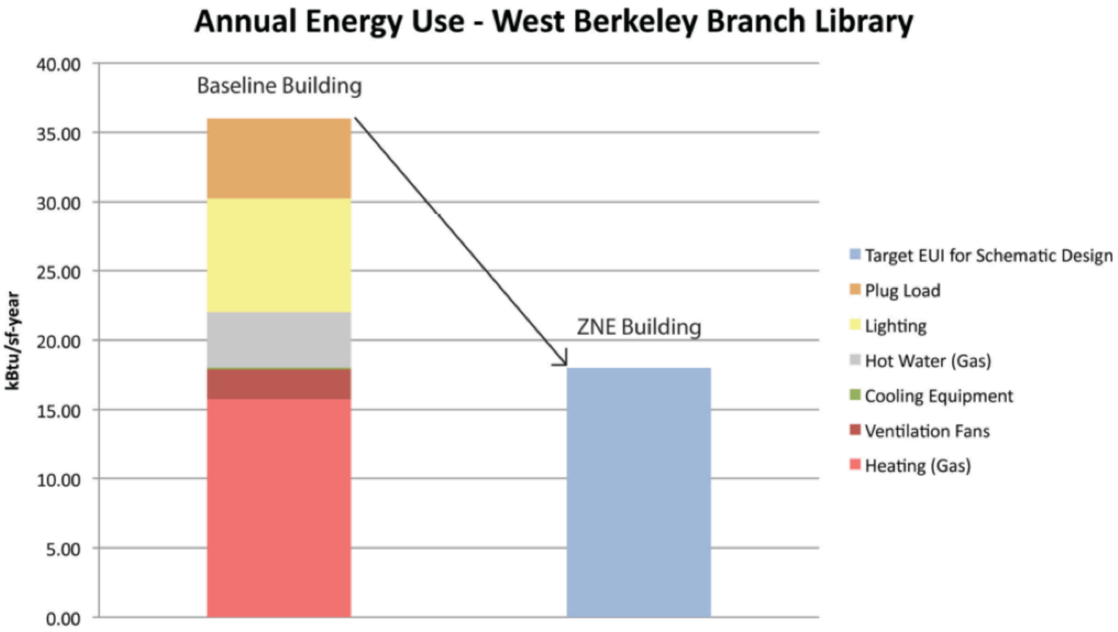


Figure 8.14 Target EUI in kBtu/ft2/year compared with a baseline building (Harley Ellis Devereaux 2013).

In order to reduce plug loads, the design team reduced the number of outlets in the new facility. This is meant to minimize the number of people who plug in their energy-gobbling laptops, smart phones, and tablets. The library will offer free computer and Internet access for visitors, but in lieu of desktops that are plugged in all day, users will be able to check out fully charged laptops. A charging station will allow the staff to track and control the amount of energy being consumed by the computers.

Mr. Lee and Mr. Bulander were fully confident that the library staff and patrons would embrace the resource conservation efforts (Change in behavior). A building performance dashboard will greet all visitors at the main entrance, providing a real-time snapshot of the building's energy production and energy/water consumption (Barista 2013).

According to Bulander, "We're taking advantage of the 'Prius effect'. When you see a display showing how much energy and water you're using, you feel more involved in trying to minimize it. It becomes a game" (Barista 2013).

The final load design load uses approximately half of the energy in service desk and public computers (Figure 8.15).

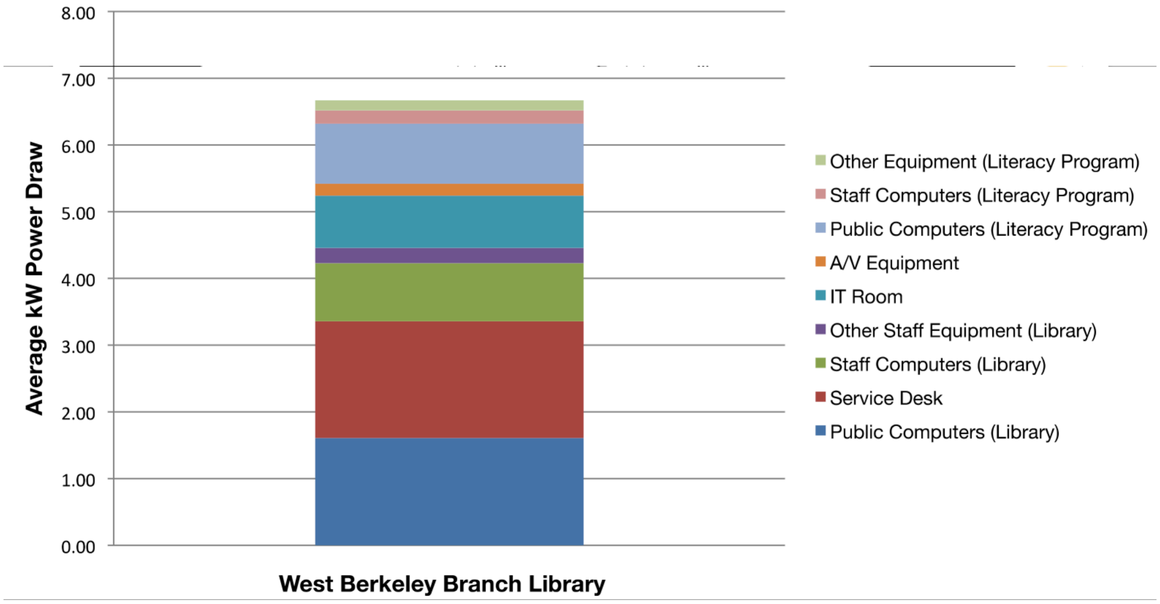


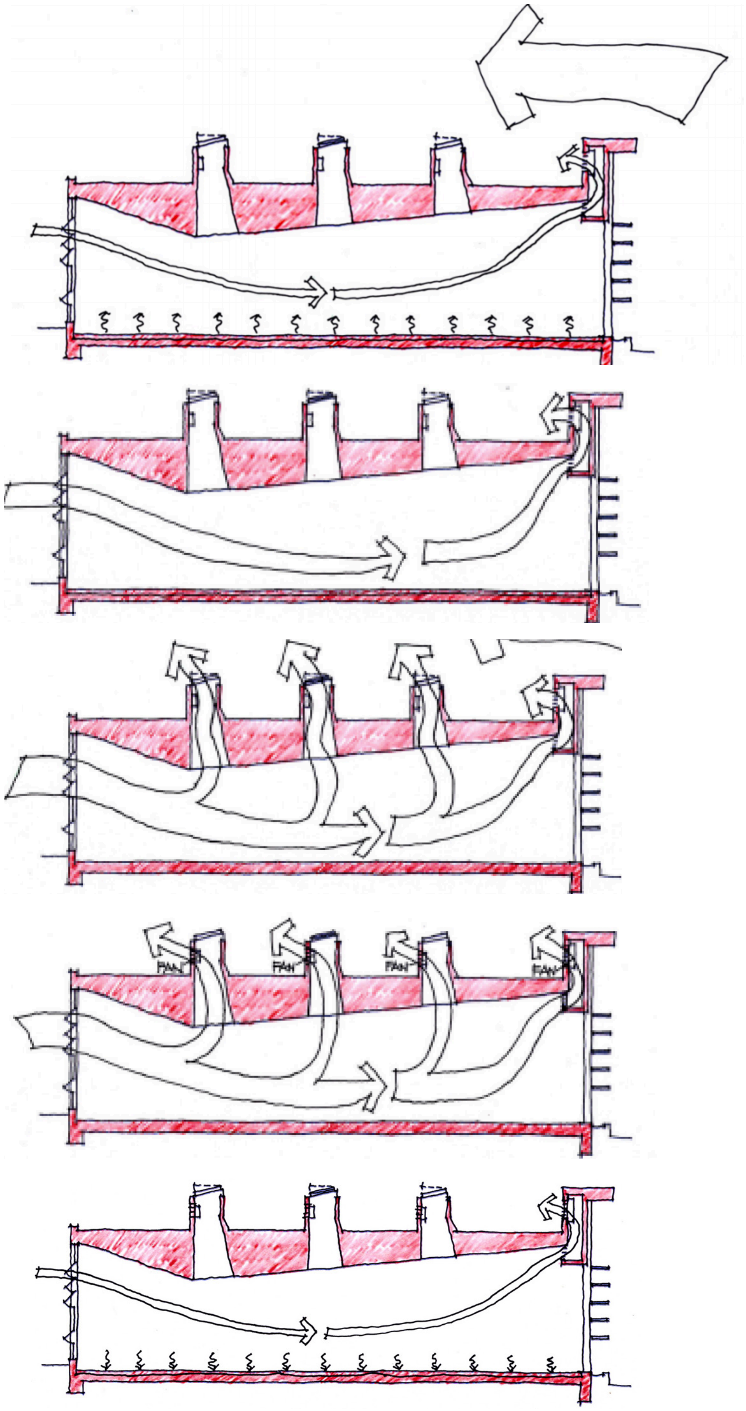
Figure 8.15 Final energy load design (Harley Ellis Devereaux 2013).

8.4.6. Ventilation Design

The design team with PG&E as a partner developed a Computational Fluid Dynamics (CFD) analysis of ventilation schemes (Barista 2013).

Prevailing winds off the bay made natural ventilation a logical approach, but the site was problematic because the building is located in a high-traffic area next to a stoplight. This made it unfeasible to place operable windows in the main facade, which would have posed air quality problems. “Trucks often wait at the red light in front of the building,” says Bulander. “We needed to block that out.” (Barista 2013).

“We’re essentially using the steady wind that is blowing over the top of the front façade to create a negative pressure that pulls the air through the building,” says Lee (Barista 2013). The final design includes natural ventilation, which pulls in outdoor air from the rear of the building and circulates it throughout the interior spaces. Figure 8.16 presents the different modes of operation of the ventilation system. The big arrow on the top represents the prevailing breeze direction (from the south and southwest), which generated the negative pressure.



Mode 1: Heating Season. Minimum outside air admitted

Mode 2: Swing Season. Varying amounts of outside air via wind chimney only

Mode 3. Early Cooling Season. Increased amounts of outside air for cooling via wind chimney and venting skylights.

Mode 4. Cooling Season. Maximum air movement via roof fans. (Skylights are closed.)

Mode 4a. (Same Diagram). Use of “night purging” using natural ventilation.

Mode 5. Peak Cooling Events. Minimum outside air. Cool space using chilled water in radiant slab from backup air source heat pump.

Figure 8.16 Final ventilation design (Adapted from PG&E 2013).

The openable windows on the north side of the building and air outlets at the upper part of the building will control the operation modes. The primary air outlet for the building is the ‘ventilation chimney’. At periods of higher cooling demand, designated skylights open to provide additional outlet area and air flow. A series of louvers and ventilation fans at the roof level will exhaust the warm air as needed, and radiant flooring will provide supplemental heating and cooling.

A Building Automation System (BAS) will monitor and control the entire process, ensuring that the interior climate remains comfortable for the staff and users. “We’re trying to make the facility as automated and foolproof as possible,” says Mr. Lee. He says the BAS will allow staff to override certain settings—such as closing an operable window on an unusually windy day—but it will automatically revert to its programmed settings at the end of the day. “For the most part, it’s a very intelligent building that needs very little interference from the librarians and staffers.” (Barista 2013).

The windows will automatically open in response to CO_2 sensors. According to PG&E (2013), “Building users control only a limited number of openable windows at floor level, which is intended for the psychological effect of a sense of control over comfort, thus providing motivation to allow a wider range of temperature swing.”

According to PG&E (2013), the BAS “also measures ongoing weather conditions and can predict expected temperature conditions. This allows the system in the case of anticipated high temperature days to call for the operation of the natural ventilation system at night, thus precooling the building in advance. The local microclimate is characterized by cool nights even during periods of hot days, allowing this ‘night purge’ operation to shave peak cooling demand and reduce peak electric demand. ”

8.4.7. Chimney Design

The shape and design of the tall front of the building creates a ‘ventilation chimney’ on the south side of the building. The design team considered different chimney options using CFD analysis, in order to improve the ventilation design, and to understand what the areas of accelerated airflow were under airfoil (Figure 8.17). According to PG&E (2013), a negative pressure area on the backside of this chimney is almost always present giving the prevailing winds. When the air outlets are located on this side of the chimney, a natural flow is created across the interior building spaces.

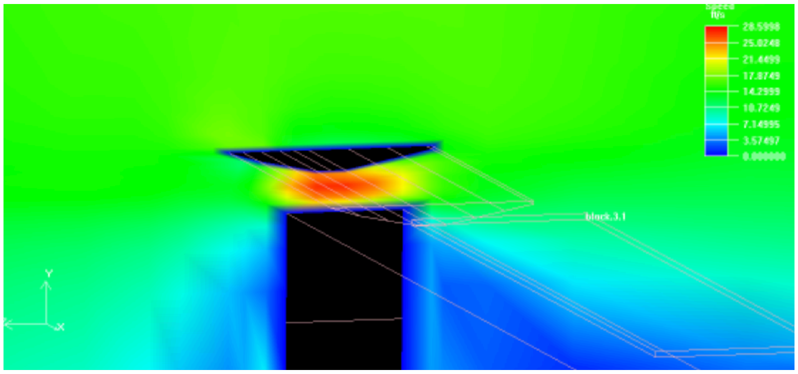


Figure 8.17 CFD analysis of chimney design (Harley Ellis Devereaux 2013).

The design team analyzed the gap between the chimney and the cap. The alternatives considered were no gap, 1 foot, 2 feet, and 3 feet gap.

8.4.8. Ceiling Shape

The design team considered different ceiling options. Ceiling shape studies and general airflow were conducted using Fluent from ANSYS Airpak. Figure 8.18 shows sloped vs. flat ceiling alternatives airflow analysis.

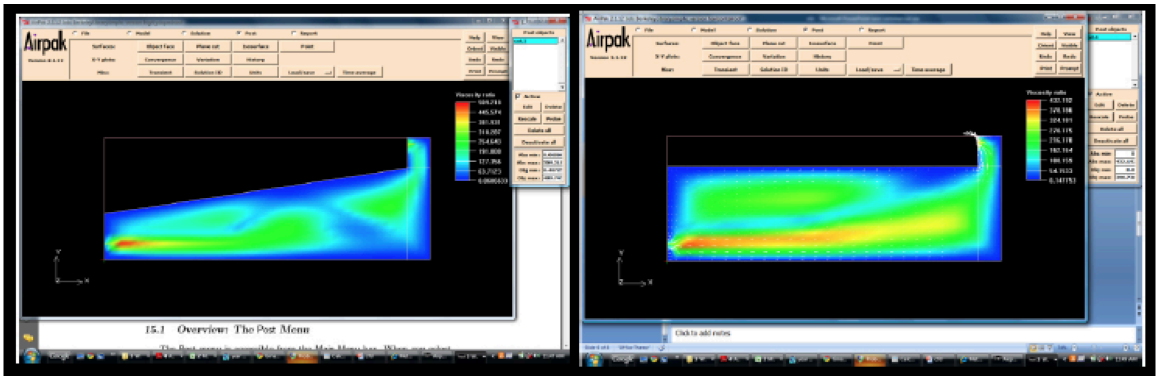


Figure 8.18 Sloped vs. flat ceiling alternatives (Harley Ellis Devereaux 2013).

According to PG&E (2013), the airflow was found to follow the desired path no matter what ceiling configuration is in place.

8.5. Step-by-Step CBA Application to Choose Building Layout Design

The following sections present how the analysis for choosing an alternative would look if the design team were applying Choosing by Advantages to this problem.

8.5.1. Step 1: Identify Alternatives

This is based on the real layout alternatives the design team was studying for this project (Figure 8.5, Figure 8.6, and Figure 8.7).

8.5.2. Step 2: Define Factors

Analyzing the alternative designs, one could expect that they are different in the following four factors: (1) incident solar radiation, (2) aesthetics, (3) interior light quality and (4) roof area. Other factors came to mind during the analysis, but they did not differentiate between alternatives. Therefore, those factors, such as view access, sound privacy and thermal resistance, were taken out of the decision.

8.5.3. Step 3: Define the ‘Must’ and ‘Want to Have’ Criteria for Each Factor

Four factors and criteria were considered in this decision.

(1) Incident solar radiation: This refers to how much solar radiation is incoming as a result of the building layout. The disposition of the openings (e.g., windows, skylights) makes a difference in the design. The ideal is to match the solar radiation with the desired comfort temperature, and to have an even distribution. The criterion is the more even and close to the thermal comfort, the better.

(2) Aesthetics: This refers to how inviting the design layout would be. The building layout will affect how appealing the building appears. The criterion is the more inviting, the better.

(3) Interior light quality: This refers to the solar light that can be obtained given the layout. The ideal is to obtain indirect light in order to avoid glare created by direct lighting. The criterion is the more indirect natural light the better.

(4) Roof area: This refers to the area that will be available for solar PV panels and solar thermal panels. The criterion is the more available roof area for solar panels, the better.

8.5.4. Step 4: Summarize the Attributes of Each Alternative

Table 8.2 sumarizes the attributes of the three layout alternatives. This information is based on the designers' input.

Table 8.2 CBA steps 1 to 6.

Factor (Criterion)	**Alternative A: Long high windows**		**Alternative B: Skylights**		**Alternative C: Long window and atrium**	
1. Incident solar radiation	Att.: Zone with low T in the middle		Att.: Even distribution except for southeast.		Att.: Even distribution, except for central east	
(Closer to comfort temperature is better)	Adv.:	Imp.:	Adv.: *Considerably better solar distribution than alt. A*	Imp.: 100	Adv.: Somewhat better solar distribution than alt. A	Imp.: 70
2. Aesthetics	Att.: Inviting		Att.: Inviting		Att.: Very Inviting	
(Nicer is better)	Adv.:	Imp.:	Adv.:	Imp.:	Adv.: *Nicer than alt. A and B*	Imp.:10
3. Light quality	Att.: Half of the area achieves 500 lux		Att.: Most of the area achieves 500l lux		Att.: two thirds of the area achieves 500 lux	
(More natural light is better)	Adv.:	Imp.:	*Adv.: Considerably more natural light than alt. A*	Imp.: 90	Adv.: Slightly more natural light than alt. A	Imp.: 60
4. Roof area	Att.: 9,500 ft^2 of roof		Att.: 8,000 ft^2 of roof		Att.: 9,000 ft^2 of roof	
(More area is better)	Adv.: *1,500 ft^2 more than alt B*	Imp.: 60	Adv.:	Imp.:	Adv.: 1,000 ft^2 more than alt B	Imp.: 40
Total IofAs		60		190		180

8.5.5. Step 5: Decide the Advantages of Each Alternative

Table 8.2 presents the advantages of the alternatives.

8.5.6. Step 6: Decide the Importance of Each Advantage

In this case the design team must decide what the paramount advantage is and then decide the importance of other advantages compared to the paramount advantage. Figure 8.19 shows the advantages color-coded by alternative. The question in this part of the process is how important is one advantage over another.

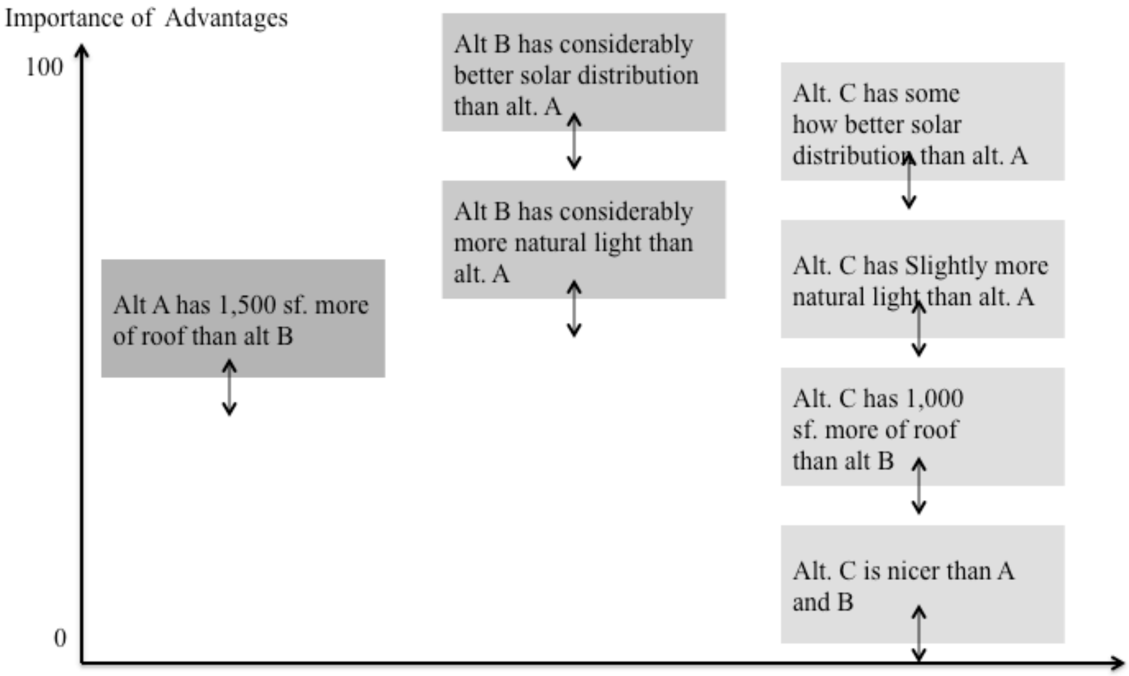


Figure 8.19 Comparison of importance of advantages.

Finally, stakeholders need to agree and decide on the Importance of Advantages (IofAs) Table 8.2 shows an hypothetical result of the importance of the advantages. In this example alternative B has a higher IofA than A and C.

8.5.7. Step 7: Evaluate Cost Data

Finally, once stakeholders have decided the IofA, cost comes into consideration. Figure 8.20 shows the IofA of each alternative vs. first cost. Here, we are considering only the first cost, but the lifecycle cost should also be analyzed.

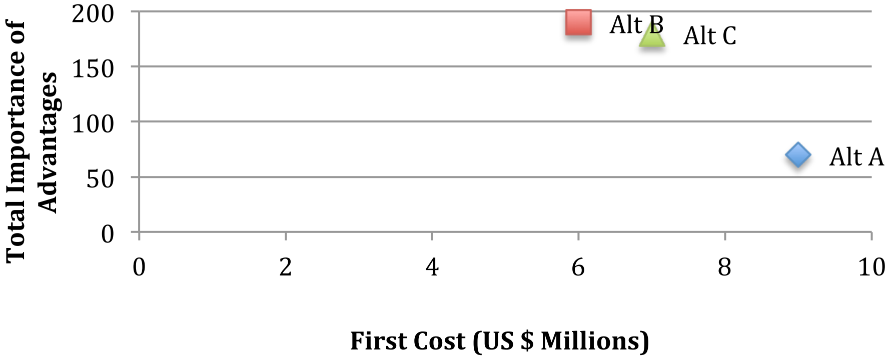


Figure 8.20 IofA vs. first cost.

In this case Alternative A is more expensive and provides a lower IofA; therefore, it should not be preferred over B or C. Alternative B provides more IofA and it costs less than alternative C. Therefore, the design team should choose alternative B, if there is no more information to compare the alternatives.

8.5.8. Step 8: Reconsideration Phase

During this phase stakeholders need to consider the following types of questions:

- Did we consider all the advantages?
- Can we create a new alternative by mixing attributes that provide advantages from non-selected alternatives?
- Do we have more time to optimize the design?
- Is there new information about assumptions that were made?
- How does this decision affect the rest of the decisions?

8.6. Discussion

Building consensus

Building consensus on what is the best alternative for each system and negotiating trade-offs between for example, light accesses for the skylights and avoiding casting shades on the PV panels may require a clear differentiation between alternatives. Consensus is important in order to move forward with the design and avoid negative iteration.

Incorporating objective and subjective attributes

CBA can help the design team in incorporating the objective and subjective attributes of the alternatives. As in the case of choosing a building layout, the design team needs to account for incident solar radiation, light quality, and roof area, which can be measured objectively. However, they also need to incorporate subjective attributes of the alternatives such as aesthetics.

As described in this case study, the design team performed various computational analyses to understand and predict the behavior of the alternatives they were studying in terms of light quality, energy usage, and airflow movement. This practice avoids decisions based on past experiences and clarifies how a particular design behaves in these specific project conditions. This is in alignment with CBA in which the attributes of the alternatives are described using units of measurement that represent the characteristic or consequences of the alternatives.

Documenting decisions

Documenting the decisions made by the design team can be valuable for several reasons. For example, as people come and go from the project, past decisions may need to be revisited. A documented history of decisions will expeditiously explain to project newcomers how and why the design team arrived at specific decisions. Maintaining documentation of this kind may also be useful for future projects as well. CBA provides a systematic and transparent way of making decision, which can be part of the design process. Decision need to be made with or without CBA, however the researcher thinks that by standardizing the way in which decisions are documented will be valuable for the design team for allowing continuous learning.

Incorporating advantages of discarded alternatives into the final design.

When using CBA the design team can analyze the advantages of the discarded alternatives. For example, when choosing the building layout, Table 8.2 shows that the alternative with higher IofA is B. Therefore alternative A and C will be discarded, but these two alternatives are better than alternative B in providing more roof area for installing PVs, then the design team should evaluate if there is any way of increasing the roof area without modifying the other advantages of alternative B.

Evaluating multiple decisions

An important issue is the interrelation of one decision with other decisions. In this case study it is clear that decisions are interrelated with one another. CBA could help in organizing this information in a way that facilitates optimization of the whole project and not just its parts. For example, the design team could create combinations of alternatives (Table 8.3).

Table 8.3 Combination of design alternatives.

Alternatives / Combinations	**1**	**2**	**3**	**4**	**5**	**6**	**n**
Scheme A							
Scheme B			x	x	x		
Scheme C	x	x					
Scheme D						x	x
Roof Height 12’				x			
Roof Height 18’	x		x				
Roof Height 24’		x			x	x	x
Loading Design 35 Btu/ft^2/year		x					
Loading Design 17 Btu/ft^2/year	x		x		x	x	x
Skylight Design A		x			x	x	
Skylight Design B	x		x				x
Ventilation System A		x			x		
Ventilation System B	x		x			x	
Ventilation System C				x			x
Chimney Design A	x				x		x
Chimney Design B		x	x			x	
PV Spacing A		x				x	x
PV Spacing B	x		x		x		
PV Spacing C				x			
PV on flat roof						x	x
PV tilted 30 degrees	x	x			x		
Sloped roof PV tilted 30 degrees				x			
Ceiling Flat	x		x	x		x	x
Ceiling Sloped		x			x		

In this way the design team would need to evaluate each combination of alternatives and decide which one has the higher IofA. Figure 8.21 demonstrates this hypothetical idea.

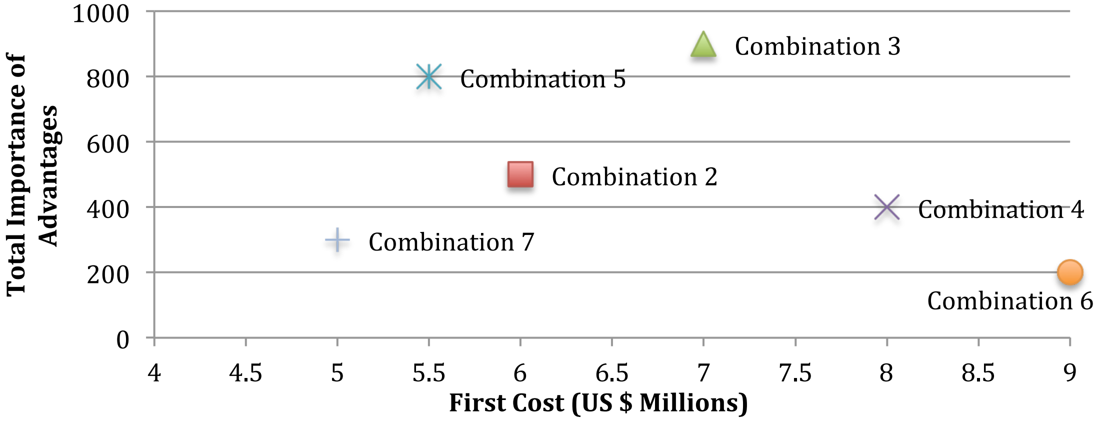


Figure 8.21 IofA vs. first cost for combination of alternatives.

As stated, the design team could also analyze the life cycle cost (Table 8.4) and compare this to decide which combination of alternatives to use. With this in mind, the design team could decide in a more transparent manner how to use their resources and what combination of alternatives to use.

Table 8.4 Life cycle cost analysis including operation and first cost.

Combination	**1**	**2**	**3**	**4**	**5**	**6**	**7**
IofA.	500	500	900	400	800	200	300
First Cost (US$)	7.7	6	6.7	7	5.5	7.5	5
Operation Cost (US$/year)	0.6	0.5	0.3	0.5	0.3	0.4	0.7
Total cost 50 years	37.7	31	21.7	32	20.5	27.5	40

Finally, this decision will lead to the final combination of alternatives to use. In this case the final design is shown in Figure 8.22.

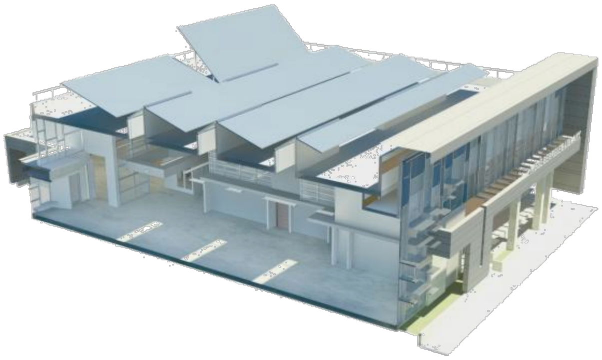


Figure 8.22 Final design (Harley Ellis Devereaux 2013).

In addition, the timing of the decisions needs also to be managed by the design team.

8.7. Conclusions

Apart from the conclusions in previous case studies showing that CBA can help in making transparent trade-offs, integrating multiple perspectives, and separating 'value' from the cost, this case study explores how CBA may help in:

- Evaluating multiple decisions (e.g., multiple building systems) in a more holistic way. The team can combine and create new design alternatives that provide a higher IofA, which allows evaluating interrelated decisions among different systems.
- Documenting multiple decisions using a similar language. This may help in continuous learning in the project especially when designers leave or enter the project, which was the case in this project.
- Incorporating advantages of discarded alternatives into the final design. If the design team documented all decisions, they could review what the advantages of discarded alternatives were and how those can be incorporated to the final design.
- Managing the timing of the interrelated decisions. In this case it was not clear the order in which the design team made the design decisions. However, applying CBA with Set-Based Design (SBD), in which decisions are explored until the 'last responsible moment' may help the design team in avoiding unnecessary iterations.
- Allocating cost for different decisions. CBA shows the 'value' of combinations of alternatives, which are associated with their costs. This may help in allocating cost to different building systems. This is aligned with the use of Target Value Design (TVD) in which the design team is able to re-evaluate allocated costs and move money across building systems in order to provide the best whole building design outcome.

By using CBA any member of the design team should be able to answer key questions. For example, what method was used for selecting this system? How do you document your decision? What were the alternatives considered for this system? What were the factors and criteria used for comparing the alternatives? Why did the design team not select the other alternatives? What advantages in the rejected alternatives might be worth integrating into the final design? What was the 'value' vs. cost analysis that supports the design team decision? The researcher found that many of these questions were not answered during exploratory interviews, which could affect awareness of the decision-making process. Therefore, using CBA can help to make better decisions than may be made otherwise.

9. CROSS-CASE ANALYSIS

This chapter presents a summary of the lessons learned through the case studies. Section 9.1 presents the comparison of Analytical Hierarchy Process (AHP), Weighting Rating and Calculating (WRC) and Choosing By Advantages (CBA) by summarizing comparative case studies 1, 2, and 3. Section 9.2 presents lessons learned from the test cases 1, 2, and 3 for applying CBA.

9.1. Cross-Case Analysis of Comparative Case Studies 1, 2 and 3

This section presents the differences between AHP, WRC, and CBA. These differences help to support the claim that CBA is superior to AHP and WRC for creating transparency, building consensus, and continuous learning.

9.1.1. Comparison of AHP, WRC and CBA

In light of the reasons and examples given in case studies 1 and 2, the researcher derived 10 factors and criteria that are reasonable to expect from a MCDM method when choosing a sustainable alternative in commercial building design. Table 9.1 presents a summary of the 10 factors and the attributes of AHP, WRC and CBA.

The following section explains the relevance of these 10 factors.

(1) Transparency of trade-offs within a factor. Attributes should not be weighted or normalized.

- In AHP, attributes are normalized. Therefore, it is assumed that increments in performance of attributes are equally preferred, which is not necessarily always correct, and is highly dependent on the scale used (Table 4.12 shows an example).
- In WRC, attributes are weighted and may be assigned a linear scale, which assumes that it is possible to assign 'value' directly to the attributes without considering the differences between alternatives.
- In CBA, the increments in performance are not assumed to be linear. Decision makers 'value' advantages depending on the relative increment of performance and the 'value' of other advantages when viewed in context.

(2) Transparency of trade-offs between factors: The assumption that trade-offs between sustainability factors are linear functions is not correct.

- In AHP and WRC, trade-offs between sustainability factors are presumably linear functions, which are not necessarily always correct.
- In CBA, designers make clear what the trade-offs between advantages are, and there is no assumed trade-off function. Advantages do not need to be weighted linearly or use any given function; they are weighted based on the importance that an advantage provides compared with the other advantages.

Table 9.1 Case-study findings on comparing AHP, WRC, and CBA.

Factor (Criterion) for MCDM methods	AHP	WRC	CBA
1. Transparency in trade-offs inside a factor (Must not assume that attributes can be weighted or normalized)	AHP assumes that sustainability factors have zero as a natural scale by normalizing them and attributing 'value' to those numbers.	WRC assumes that attributes can be weighted.	CBA does not assume that attribute scales have an inherent 'value'. 'Value' is assigned only to the differences between alternatives.
2. Transparency in trade-offs between factors (Must not assume linear trade-offs between factors)	AHP assumes that trade-offs between sustainability factors are linear functions.	WRC may assume that trade-offs between sustainability factors are linear functions.	CBA makes clear what the trade-offs between advantages are, and there is no assumed trade-off function.
3. Focus on differentiating between alternatives (Must help differentiate between alternatives)	AHP may not help in differentiating between alternatives due to the weighting of factors is not based on differences between attributes of alternatives.	Same as AHP.	CBA bases judgments on differences of alternatives (advantages).
4. Analyzing Cost (Must be treated separated from 'value')	Cost can be a factor and be mixed with the intrinsic 'value' of the alternative.	Cost can be a factor and be mixed with the intrinsic 'value' of the alternative.	Cost cannot be a factor and is treated separate from 'value'.
5. Consistency (The result must not change if irrelevant factors are eliminated from the decision)	AHP changes the result of the decision, or at least the intensity of the preference when irrelevant factors are eliminated from the analysis.	WRC changes the intensity of the preference when irrelevant factors are eliminated from the analysis.	CBA does not change the result when irrelevant factors, which have the same attributes for all alternatives, are eliminated from the analysis.
6. Collaboration (Must avoid weighting factors)	AHP requires weighting factors, which are a high order of abstraction concept. This exercise may be conflicting.	Same as AHP.	CBA postpones 'value' judgment until there is agreement on objective differences between alternatives (advantages), which may minimize conflict among stakeholders.
7. Context specific (Must consider a specific context for all judgments)	AHP lacks context specific judgments when assigning weights to sustainability factors.	WRC also requires weighting factors, allowing for a disconnection with the context.	CBA asks stakeholders to make judgments about the importance of the advantages, which do not exist without a context.

8. Subjectivity (Must do objective part first and then subjective part)	AHP asks stakeholders to make explicit which factors are more important (subjective task first), without considering the relevant differences between alternatives (objective task).	WRC asks stakeholders to make explicit which factors are more important (subjective task first), without considering the relevant differences between alternatives (objective task).	CBA Highlights the difference between alternatives first (which is an objective tasks) and then decides which advantages (positive differences) are more important (which is a subjective task).
9. Flexibility (Must facilitate the incorporation of new alternatives)	If a new alternative is added, the score of old alternatives needs to be recalculated.	If a new alternative is added, the score of old alternatives may not need to be recalculated.	If a new alternative is added, the advantages regarding that alternative need to be assessed.
10. Flexibility (Must facilitate the incorporation of new perspectives or factors)	If a new factor is added, the weight of all factors needs to be recalculated.	If a new factor is added, the weights of all factors do not need to be recalculated.	If a new factor is added, the advantages regarding that factor need to be assessed.

(3) Focus on differentiating between alternatives: The main purpose for choosing an alternative is to select the one that provides more valuable differences. Therefore, the MCDM method should guide stakeholders on how to differentiate between alternatives.

- AHP and WRC may not help the design team in differentiating between alternatives; this is the case when high weights are given to factors in which the alternatives have the same or very similar attributes. Section 4.2.8 presents more discussion on this.
- CBA focuses on differentiating between alternatives based on advantages. When all alternatives have the same attribute for a factor, that factor should not even be considered in the decision because it does not differentiate between alternatives.

(4) Analyzing Cost. The separation of 'value' and cost is important in order to be able to decide where to assign resources, especially if resources can move across building systems boundaries.

- In AHP and WRC cost can be a factor. However, it is not mandatory. In fact, the method does not specifically mention how to treat cost.
- In CBA, cost is neither a factor nor a criterion and it is treated separately as a constraint.

(5) Consistency: It is reasonable to expect that the decision should not change if factors that do not differentiate between alternatives are eliminated from consideration.

- In AHP, the result of the decision may change if irrelevant factors are taken out of the decision, as shown in Section 4.2.8 (first example).
- In WRC, the result of the decision will not change if irrelevant factors are taken out of the decision. However, the intensity of the preferences may change because other differences between alternatives will have greater impact on the decision.

- In CBA, the result of the decision will not change if irrelevant factors are taken out of the decision.

(6) Collaboration: It is important to incorporate different perspectives in sustainable building design decision, and avoiding unnecessary conflict is one requirement for collaboration.

- In AHP and WRC, designers assess which factors are more important. This may lead to conflicts since factors are high-level abstractions.
- In CBA, stakeholders postpone 'value' judgments until they agree on objective differences between alternatives (advantages), which may lessen conflict among stakeholders. There is no need to discuss whether one factor is more important than others, when the alternatives do not provide important differences according to that factor.

(7) Context specific: In order to account for the context when judging what is more sustainable, the design team should understand what the differences between alternatives are and how valuable those differences are according to project context.

- In AHP, factors may be weighted without considering the differences between attributes of alternatives. Factors are a general category such as 'sound privacy'. The importance of a factor will depend on the context of the decision. Without a context, it would be difficult for people to agree on the importance of a factor. Even when the weighing of factors is agreed among stakeholders, there is a risk of missing important differences between alternatives.
- In WRC, factors are weighted directly and may not consider differences between attributes of alternatives. In fact, in several applications of AHP and WRC, designers are given the weights of factors beforehand and those are used to evaluate different decisions regardless of the decision context (e.g., Bhatt and Macwan 2012, and Gloria et al. 2007).
- In CBA, designers must first understand the differences between alternatives (advantages), so that they can account for the context when making judgments about what is more sustainable. Advantages do not exist without a context. Defining an advantage involves knowing the alternatives being compared, the sustainability factors being evaluated, the attributes of the alternatives, and a criterion for judgment.

(8) Subjectivity. Decision makers may benefit from keeping decisions objective as long as possible in the decision-making process. This may reduce decision-maker biases and helps in differentiating between facts and judgments. Section 10.1.4 presents more discussion on decision biases.

- In AHP and WRC, designers need to make explicit which factors are more important (subjective task first), without necessarily considering the relevant differences between alternatives (objective task).

- In CBA, designers have to first identify the advantages of alternatives (objective task) using the criteria they articulated and only then evaluate (subjective task) how important those advantages are.

(9) Flexibility in adding alternatives. Decision makers may need to compare new alternatives into the decision when new possibilities are discovered or created (e.g., reconsideration phase); therefore, the number of steps or recalculations required to add a new alternative will be relevant to avoid wasting time.

- In AHP, every time a new alternative is added, the attributes of older alternatives need to be reevaluated since AHP normalizes the values of the attributes. If the new alternative has an attribute that is greater or smaller than the ones in the previous alternatives, the normalized values of older alternatives will change as well.
- In WRC, attributes of older alternatives do not need to be recalculated if new alternatives are added. If the new alternative has an attribute that is greater than the previous alternative had for one factor, the scale of the attributes can be expanded. If an attribute is lower than the previous alternative had for one factor, the weight of the attributes may need to be recalculated, especially if the new attribute has a negative weight in the original scale.
- In CBA, if a new alternative is added, the advantages of that alternative need to be assessed. If the new alternative has an advantage more important than the paramount advantage, the scale of IofAs can be expanded. If the new alternative has a new least preferred attribute for one factor, the advantages and IofAs of that factor need to be recalculated. In addition, if the new alternative has an advantage regarding a new factor that was not previously considered, that factor should be added to the decision.

(10) Flexibility in adding factors. Decision makers may need to incorporate new perspectives into the decision, as more information becomes available in the course of design; therefore, the number of steps or recalculations required to add a new factor will be relevant to avoid wasting time.

- In AHP, designers need to recalculate the weight of all factors any time a new factor is added to the decision. Therefore, a number of recalculations will be required depending on the number of factors used.
- In WRC, designers can add a relative weight to the new factor without recalculating the weight of old factors. This is true if the method used does not require that the sum of the factors weights is 100% or 1, such in the case of AHP.
- In CBA, designers have the flexibility to add more factors with no impact on the previous assessment of alternatives. In CBA the new factor can generate a new paramount advantage, and decision makers can expand the previous IofA scale without needing to weigh again previous advantages.

9.1.2. Conclusions

In conclusion, CBA is superior to AHP and superior or at least equivalent to WRC in every one of the 10 factors and criteria derived from the case studies. This is mainly due to the fact that AHP and WRC assigns weights separately for factors and attributes – these weights represent 'value' to the decision maker. In contrast, CBA assign weights to advantages, which considers the difference between attributes of two alternatives regarding one factor, therefore factors and attributes are not weighted separately. Advantages incorporate information about the factors, criteria, and attributes. These advantages are then weighed and their weights represent the 'value' to the decision maker. In CBA 'values' are assigned only to the advantages of the alternatives given the context. This presents a significant research finding considering the prevalence of AHP. Based on the evidence, the researcher advises AEC practitioners to select CBA over AHP or WRC when making material, component, or assembly selection decisions. The problem of choosing sustainable materials, components and assemblies is also found outside of the AEC industry, where the findings of this research may be applied.

9.2. Cross-Case Analysis of Test Cases 1, 2 and 3.

Through CBA testing cases the researcher demonstrated the feasibility and effectiveness of the CBA method for choosing among alternatives, where multiple factors are involved. CBA applies for choosing between materials (Chapter 4), components (Chapter 6), building systems (Chapters 5 and 7), and also for providing a comparison of the 'value' of multiple decisions, as demonstrated in Chapter 8.

In every one of these applications CBA was supporting:

- Design team understanding of the 'value' of each alternative in contrast with each other, according to the particular decision context
- The incorporation of multiple perspectives in the decision
- Initial design team analysis of the differences between alternatives and then evaluating their subjective importance. This is well aligned with SBD in which decision makers need to wait until the last responsible moment to make decisions. CBA can complement SBD, by documenting the decisions and preparing the team for understanding the alternatives before the decision needs to be made.
- The alignment of interests within the design team, demonstrating that the relevant factors are the ones that presented important differences between alternatives, not the ones that want to be achieved individually.

In testing cases 2 and 3, CBA was also presented as a tool to evaluate and compare multiple decisions, which may help the design team to evaluate interactions between building systems. This is aligned with Target Value Design (TVD), where the design team needs to evaluate cost vs. 'value' for multiple building design decisions.

9.2.1. Lessons Learned in CBA Implementations

Lessons learned through the testing cases that may increase effectiveness in applying CBA are:

- *The description of attributes and advantages* must be done in a way that is easy to understand for everyone. These descriptions should be clear enough so a person who was not present when the decision was made could clearly understand it. This is especially helpful for documentation and continuous learning purposes.
    - Avoiding the use of acronyms in describing attributes or advantages facilitates the understanding of the alternatives, especially after the decision is made.
    - Describing the advantage using actual units and avoiding percentages when possible is helpful in understanding the relevance of the advantages. For example, the advantage that one insulation material is 100% lighter than another may or may not be important depending on the scale of the difference. If the difference is 1 pound vs. 2 pounds per ft^2 the person installing it may not feel the difference. In contrast, if the difference is 10 pound vs. 20 pounds per ft^2 the difference may be important.
- *Perception of 'value' from a holistic perspective*. It is important that decision makers ask question such as: What is the 'value' of this particular advantage? Is the advantage going to be perceived by the users of the building? Does the design team understand the relevance of an advantage? Have the opinions of experts been considered in explaining the relevance of the advantages? How does a particular decision affect other building systems?
- *The display of the information in the application of CBA matters*. The application of CBA should not be limited to filling in a spreadsheet in a computer screen or projector. The use of 'post it' notes was really helpful for describing the attributes, describing the advantages and especially for providing flexibility when assigning weights to IofAs.
- *Training is important*, but also needs to be simple. Suhr (1999) recommends that CBA cannot be used for the first time in a very important decision. It is better to try it in less important decisions first, so the practitioners can get use to the vocabulary and understand the method, rather than being concern about the outcome of the decision.

9.2.2. Conclusions

In conclusion, CBA is applicable to a large range of applications, when alternatives can be described with enough detail to understand and assess the 'value' of the differences between alternatives.

CBA is well aligned with lean principles and can help to make more transparent decisions in a way that is easy to document and use for continuous improvement. A3 reports can also help in documenting CBA applications. CBA can complement Set-Based Design (SBD) and Target Value Design (TVD) by helping to differentiate between 'value' and cost and postponing 'value' judgments until the last responsible moment.

10. CONCLUSIONS

This chapter presents the dissertation's conclusions. Section 10.1 summarizes research findings, Section 10.2 presents contributions to knowledge, Section 10.3 offers insights for future work, and Section 10. 4 offers some final remarks.

10.1. Research Findings

Through theoretical comparison of (1) Goal-programming and multi-objective optimization methods, (2) Value-based methods (including Analytical Hierarchy Process (AHP) and Weighting Rating and Calculating (WRC)), (3) Outranking methods, and (4) Choosing By Advantages (CBA), the researcher demonstrated relevant differences between these methods, amplifying the fact that different methods can lead to different outcomes. This fact is all too often forgotten in real-life decisions. The researcher also demonstrated that the assumption that factors can be weighted or ranked forces trade-offs, which may not represent reality. Decision makers may not be aware of the assumptions they are making, thereby resulting in an inaccurate decision.

Through the application of comparative case studies, the researcher found that CBA is superior to AHP and WRC for choosing a sustainable alternative when the alternatives are known and finite in number. The researcher derived 10 factors that differentiate AHP, WRC, and CBA from one another (Table 9.1), providing a contribution to knowledge in decision-making theory.

Through the different applications of CBA, the researcher demonstrated the feasibility of using CBA to choose a sustainable alternative in commercial building design and provided insights for its future application and research.

10.1.1. Opportunities to apply CBA in the AEC Industry and Other Industries

The research findings, specifically the superiority of CBA over the other Multiple-Criteria Decision-Making (MCDM) methods studied, can also be expanded to include other types of decisions, both inside and outside the AEC industry. CBA is useful whenever decision makers need to compare alternatives using multiple criteria and when they have detailed descriptions (i.e., attributes) of the alternatives. The CBA method helps decision makers to provide an understanding of the differences between the alternatives. In fact, according to Suhr (1999), the CBA tabular method is applicable for any type of decision in which alternatives are mutually exclusive.

10.1.2. CBA Limitations

Some of the limitations of CBA identified in this research are:

- CBA does not provide insights into considering uncertainty in attributes of alternatives.
- CBA does not provide guideline to understand possible interrelations between factors or criteria.
- CBA may be impractical in evaluating an infinite number of alternatives.

- CBA does not provide explicit guidelines to avoid cognitive biases in decision-making.

10.1.3. Rating Systems Impacts on Decisions

Several case studies in this research were of projects pursuing LEED certification (Chapter 4's comparative case 2, Chapters 6, and 7). From these applications the researcher realized that focusing on obtaining LEED points may lead to underestimating or ignoring important differences between alternatives especially in regards to their sustainability.

For example, in comparative case study 2, LEED incentives for selecting an insulation material considered only the following factors: (1) recyclability, (2) recycle content, (3) use of regional materials, and (4) rapidly renewable materials.

Cotton insulation provides more Materials and Resources (MRs) points than fiberglass. In particular, it contributes significantly in achieving recycled content (cotton has 85% recycled content), recyclability, and it can be helpful in earning rapidly renewable materials points. By contrast fiberglass insulation can provide LEED points only for buying regional materials.

Following LEED-credit incentives, cotton insulation undoubtedly would be the better option. However, by just following LEED points decision makers ignore the important advantages that fiberglass has over cotton, such as installation speed. When using CBA, decision makers can account for all relevant factors in the decision, avoiding the use of predefined factors and assumed weights or points among them.

10.1.4. Cognitive Biases in Decision Making

From the reviewed literature the researcher studied different cognitive biases that decision makers may have when making decisions.

The researcher found some practical advice in the literature to reduce cognitive biases that may be applicable to the CBA application. Kahneman's (2011) advice for deciding individually first and then discussing differences within the group to prevent one decision-maker from prevailing over the others, can be applied for CBA. This will require decision makers to decide the Importance of Advantages (IofAs) individually and then compare and discuss the deviations among themselves. In addition, Lehrer (2012) provides advice for stimulating richness in the argumentation process in group thinking. For example, dissent stimulates new ideas because it encourages people to engage more fully with the work of others and to reassess their previous points of views (Nemeth 2003). Moreover, exposure to unfamiliar perspectives can also foster creativity (Palermo and Jenkins 1964). The researcher thinks that this advice may also help in overcoming cognitive biases when the design team is choosing which alternative is more sustainable in commercial building design. This is especially relevant because many stakeholders have predefined interests according to what his or her role is in the design process.

Also, since CBA does not allow pre-assigning weights to factors or even defining what factors will be relevant in the decision without understanding the differences between alternatives, the CBA method is less likely to allow for cognitive biases. For example, it is less likely to allow for the ‘focusing illusion’ (Section 2.13.1) that may cause decision makers to heavily weigh factors that do not differentiate between alternatives, or to ignore important differences between alternatives.

The literature on cognitive biases and decision making is extensive, but the researcher consulted only a limited portion of the complete body of literature. The researcher believes that more opportunities for supporting decision making in groups are available in the literature.

10.2. Contributions to Knowledge

This research contributes to knowledge by providing:

(1) A theoretical evaluation of four types of MCDM methods. Chapter 3 demonstrated the different methods, their assumptions, and how those assumptions affect decision outcomes.

(2) A practical and a theoretical evaluation of CBA vs. AHP and CBA vs. WRC (Chapters 4 and 5). The cross-case analysis in section 9.1 summarizes factors and criteria for evaluating the ability of the AHP, WRC and CBA methods to assist practitioners in deciding what alternative is more sustainable in commercial building design. These factors and criteria are specific for the comparison of CBA, WRC and CBA, and cannot be used for comparing all MCDM in different contexts.

(3) A rationale for recommending MCDM methods in the research context. This research provides evidence and explanations of why CBA is better than the other MDCM methods studied for choosing a sustainable alternative in commercial building design, when finite alternatives with known attributes are being considered.

(4) An analysis of the application of CBA for different types of decisions. This research provides evidence of the applicability of CBA in a wide range of decision alternatives, from choosing building materials, components, and building systems to building layouts. It demonstrates how CBA may be applied consistently in every design decision and used for analyzing combinations of alternatives (Chapter 8).

In addition to the study of MCDM methods, the researcher found the three following contributions in related topics in which this research provided insights and ideas for future research.

(5) An analysis of how different sustainable rating systems affect decisions. Section 2.8 presented the literature reviewed and Section 10.1.3 presented final discussions.

(6) A literature synthesis on cognitive biases that can affect group decision making in building design decisions. Section 2.13.1 presented the literature reviewed and Section 10.1.4 presented final discussions. More research is needed to understand how CBA helps (or not) to avoid cognitive biases.

(7) An analysis of how rhetorical tools can be applied together with CBA in order to provide a better decision-making process. Section 2.13.2 presents the literature synthesis on rhetorical tools, and Section 6.7 presents an example, discussion, and conclusions.

Through these seven areas of contribution, the researcher provides a basis for discussing MCDM method selection in commercial building design that may be expanded to other applications, and for advancing our understanding of the relationship between decision-making methods and building outcomes.

10.3. Future Work

After the development of the case studies the researcher was able to identify areas that require further research:

- Measure the impact of decision-making methods on the outcomes.
    - How can the impact of a decision-making method vs. another one be measured?
- Understanding further applications as well as limitations of CBA and proposing ways to overcome them.
    - Can CBA help in choosing one among an infinite number of alternatives?
    - What other problems besides the choosing problem does CBA apply to?
    - Does CBA apply to settings that are not necessarily collaborative? For example choosing problems may occur in situations where the attributes of the alternatives are not known a priori (as may be the case when selecting an alternative in a bidding process). Can the decision makers come up a priori with a suitable scale for IofAs before seeing the alternatives?
    - How can CBA help practitioners in considering the interdependence among decision factors?
    - What are other appropriate uses of CBA?
- Understanding social aspects to support the CBA application, how argumentation is done.
    - How may rhetoric be used in CBA to avoid cognitive biases or to build consensus among decision-makers?
    - How can you teach CBA and have a team fully embrace its use in decision making?
- Testing how CBA may or may not help in building consensus compared with other MCDM methods. It would be interesting to study the consensuses obtained using different MCDM methods by first obtaining individual preferences and then comparing them with the group preferences.
    - Does CBA increase the possibility of reaching consensus in decision making when compared to value-based methods?
- Incorporating sustainability.
    - Are more-sustainable alternatives necessarily more expensive?
    - How can the interrelation of different building systems be incorporated in the decision-making process? The example in Section 8.6 broached this topic, but it did not get into issues such as optimizing sequencing decisions to reduce negative iteration.

    - How can we set appropriate environmental targets for building systems?
- Creating new alternatives.
    - How can CBA help (or not) the design team to discover new alternatives or combinations of existing ones?

10.4. Final Remarks

This research explains what CBA is and how it works. It expands previous knowledge about the method, and provides a comparison with other MCDM methods, including AHP and WRC.

Through the different case studies the researcher demonstrated a range of applications for CBA, from selecting a single material, component, or system to multiple systems.

CBA is the best available MCDM method for choosing a sustainable alternative in commercial building design, considering a relatively small number of alternatives with known attributes.

In conclusion, CBA is recommended as a MCDM for choosing a sustainable alternative, because CBA is helpful in providing a structure and a transparent way of making decisions. CBA helps the design team to build consensus by encouraging team members to understand the differences between the alternatives in the particular decision context. If they evaluate the same alternatives in different contexts, they may end up with different decision results. CBA provides the design team with an uniform language, helping team members to provide a rationale for decision making that allows for continuous learning. CBA may help the design team to better articulate and understand customer 'values' and also may provide ideas to generate new alternatives.

Finally, CBA can be further studied in order to fully understand the benefits of the method, and utilize synergies with other lean tools such as SBD, TVD, and A3 reports that can positively influence the decision-making process of choosing a sustainable alternative. By using a synergistic set of tools, instead of a disparate set or no tools at all, it is more likely that the design team will make better decisions considering social-, environmental-, and economic aspects of whole building design.

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