INTEGRATED PERFORMANCE FRAMEWORK TO GUIDE FAÇADE RETROFIT

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INTEGRATED PERFORMANCE FRAMEWORK
TO GUIDE FAÇADE RETROFIT

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SUMMARY

The façade retrofit market faces some key barriers in the selection of performance criteria and the reliability of the performance data. On the demand side, the problem is approached from an investment perspective which creates "split incentives" between the stakeholders who pay for the investment and those who benefit from it. On the supply side, there is an inherent complexity in modeling these options because of the incomplete knowledge of the physical and cost parameters involved in the performance evaluation. The thermal comfort of the building occupant is an important component of the retrofit performance assessment. The challenge is that the investment in a façade retrofit requires a degree of confidence that the predicted energy benefit will occur and deliver a reasonable return.

This research augments and improves current approaches to façade retrofit decision by 1) quantifying uncertainties in these three dimensions of performance, 2) incorporating new financing models available in the retrofit market, 3) considering the target and risk attitude of the decision maker. The methodology proposed in this research integrates key indicators for delivery process, environmental performance, and investment performance. The purpose is to provide a methodological framework for performance evaluation. The main contribution is the validation of the framework through the application to a specific retrofit type, the building façade. A residential case study is conducted to test the proposed framework. Three retrofit scenarios including the financing structure are examined. Each façade retrofit scenario is then evaluated based on the level of confidence to meet or exceed a specific target improvement for the Net Present Value and the risk to fall below a minimum improvement threshold. The case study results confirm that risk must be considered for more reliable façade retrofit

decision-making. Research findings point to further research needed to expand the understanding of the interdependencies among uncertain parameters.

CHAPTER 1
INTRODUCTION

1.1. Motivation

The goal for a sustainable built environment remains a challenge. The growing awareness that buildings are the largest energy consumers, contributing to natural resource depletion, has compelled efforts across disciplines and scales to improve the building lifecycle. At the global scale, policy initiatives first started with the Rio Earth Summit (UN 1997) and the Kyoto Protocol (unfccc.int) aimed for a more comprehensive approach integrating environmental impact with socio-economic risk assessments. At the national scale, the US congress first mandated performance standards in the Energy Conservation Act of 1976, followed by the Department of Energy publishing Energy Performance Standards in 1978 (Joskow 2003). More recently, the impact of the energy crisis has led to federal initiatives included in the American Recovery and Reinvestment Act (energy.gov) to invest in research for alternative energy sources and develop strategies to retrofit the existing building stock (Figure 1).

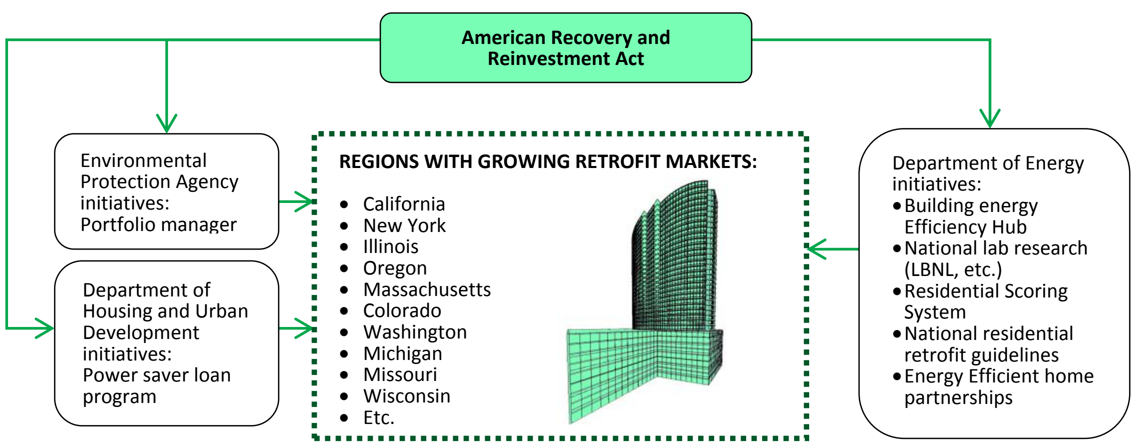


Figure 1: Developing infrastructure in the U.S. Energy Efficiency Retrofit Market (based on energy.gov and recovery.gov)

The scope of activities and initiatives from the Department of Energy, DOE, the Environmental Protection Agency, EPA, and the Department of Housing and Urban Development, HUD, range from advising to providing technical and funded assistance to implementers and investors of local and regional retrofit programs (Onyeagoro et al. 2011). A list of policies and incentives at the state level can be found in (dsireusa.org). It is expected that in the next 30 years 150 billion square feet of the building stock will be retrofitted or renovated (arch2030.org).

In the Architecture Engineering and Construction (AEC) industry, various performance standards and rating systems have been created to evaluate sustainable or "green" buildings. In the United States, the AEC industry has adopted the Leadership in Energy and Environmental Design, LEED standards, created by the United States Green Building Council, USGBC. The Green Building Challenge has promoted environmental performance assessments using selected buildings as exemplars of good practice. Integrated project delivery methods have started to be implemented to improve building procurement and renovation. Architects are becoming more active in the retrofit market, expanding their scope of services to have a continuous presence throughout the building lifecycle (aia.org).

Within this context, the concept of building performance has been widely utilized to support buildings assessments and meet sustainability goals. However, the lack of a consistent definition of building performance or agreement on how performance assessments should be structured permeates throughout the AEC industry (Gross 1996; Clevenger et al. 2009). Researchers in the field of building technology have proposed multiple tools and interfaces have been proposed for the evaluation of energy performance. Notably, De Wilde has proposed a tool to facilitate the selection of energy saving measures(De Wilde 2004). The "DAI prototype" uses a process model to manage the dialogue between design and analysis, identify the analysis scenario, and link performance assessment tasks with analysis applications (Augenbroe et al. 2003; De Wilde et al. 2003). A "Computer Supported Design Environment" has also been implemented to integrate a database with building product information, a simulation engine, and a result analysis module (Clarke 2001; Hobbs et al. 2003; Morbitzer 2003). In addition, other studies show that there is a knowledge gap between building scientist and architects and the type of feedback they require to make decisions. (Warren 2002; Hobbs et al. 2003; Mahdavi et al. 2003). A recent survey finds that architects prefer tools with an integrated knowledge base to support quick analysis and facilitate decision making (Attia et al. 2009). Although many research efforts have made improvements in the building procurement process, the diverse objectives and perspectives toward building performance have yet to be integrated.

1.2. **Research Background**

An energy retrofit constitutes a series of changes to a building for better environmental performance. Three basic types of building retrofit have been identified: partial, full, and renovation (Rosenfeld et al. 1999; Rey 2004). Retrofit alternatives have been classified as strategies associated to the building envelope or the building services (Wulfinghoff 2000; Slaughter 2001; Kolokotsa et al. 2009). Recently the approach to building retrofits have changed from upgrades to the mechanical system or lighting system to a comprehensive approach, known as "deep" retrofit, which investigates other areas of improvement, including the building envelope and its direct link to energy efficiency (Bloom 2010; Fluhrer et al. 2010). A recent report estimates that these deep retrofits approximately double the building energy savings, compared to a lighting system retrofit (Thorne Amann et al. 2005). This new approach to energy retrofits provides great opportunities to reduce energy consumption in existing buildings with facades designed and built when the cost of energy was not an issue. Although sources of consumption vary between residential and commercial buildings (Figure 2), the need for heating and lighting could potentially be reduced with an improvement in the building façade. The next sections provide context into the complexity of a façade retrofit assessment, based on the physical separation of the façade components, the market classifications for the sources of energy consumption, and the diversity of retrofit strategies.

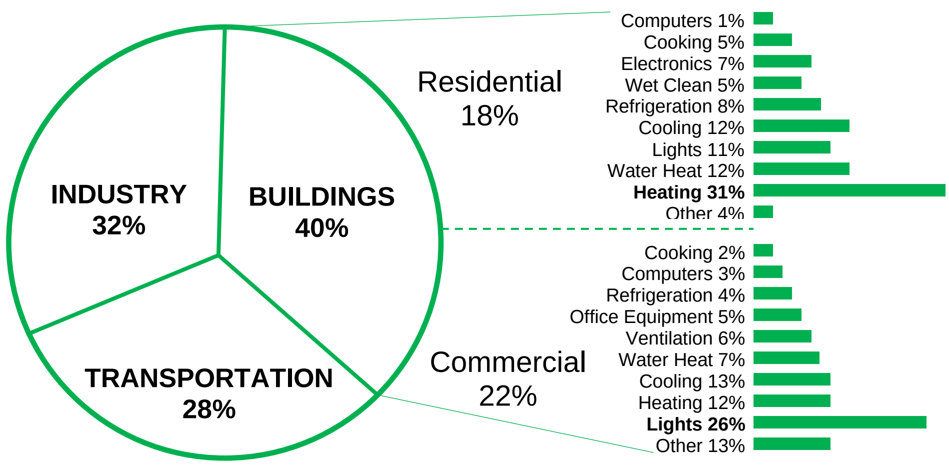


Figure 2: Energy consumption by sector constructed from 2006 Buildings Energy Data Book, http://buildingsdatabook.ere.doe.gov (Lee 2010)

1.2.1. Evolving complexity of façade technologies

The evolution of the design and construction of the building façade is tied with the development of high-rise construction in the 1890's (Condit 1964). The development of a wrought iron structural framework marks the beginning of the separation of the physical elements of building enclosure, separating a load bearing frame from non-bearing infill. High-rise buildings brought about technological innovations such as the elevator and the curtain wall, followed by the standardization of mechanically heated and ventilated buildings in the 1940's (Straube et al. 2005). These innovations in the era of standardization and mass production, led to the contemporary concept of the building envelope, as a complex system, including the building façade, with 3 layered subsystems: structure, frame, and infill panels (Knaak et al. 2007). The load-bearing structure for the building is connected to the framing systems for the façade lightweight infill panels. This separation of the layers of the building facade facilitated the design of large areas of glass, partly to express modern aesthetic desire for transparency (Ascher Barnstone 2005; Elkadi 2006). The result is a building façade which is more susceptible to environmental changes. Designers have responded to this problem with more complex facade systems to mitigate environmental impact, by adding components or layers such as shading devices, double skin facades, and intelligent skin systems (Wigginton et al. 2002).

1.2.2. Market classification for buildings and façade construction

The evolution of complex façade systems as part of AEC technological innovation must also be considered from a market perspective. Retrofit decisions driven by the need to mitigate the rising cost of energy use, are intractably connected to the dialogue between supply and demand (Figure 3). The U.S. Energy Administration Information provides statistical data on energy use patterns according to four market sectors: transportation, residential, commercial, and industrial (eia.gov). Table 1 shows how these sectors can be classified into five separate segments of the economic market, based on stakeholder profile, regulatory environments, building and façade types (Onyeagoro et al. 2011). The selection of the façade system, construction types, and retrofit options is also tied to market classifications. The residential sector has two basic building types: single or two-family detached houses and multi-family low-rise and high-rise residential buildings. The commercial and industrial sectors are organized into two segments, with buildings organized into small and large. Institutional buildings, such as educational or healthcare facilities are in a separate segment. These five market segments have different economic constraints which limit the scope of retrofit options.

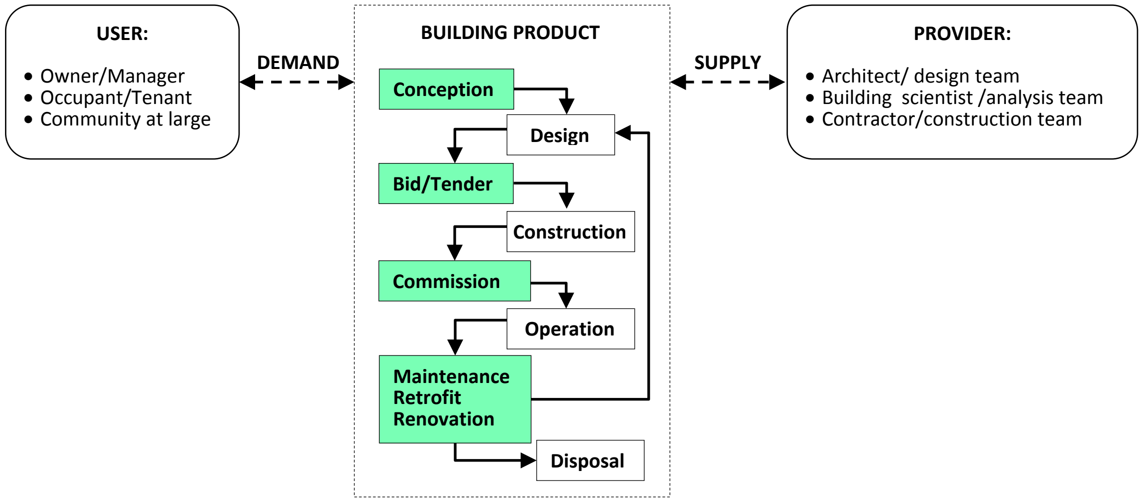


Figure 3: Building product lifecycle phases and decision stages including retrofit decision (constructed based on (Straube et al. 2005)

Table 1: Market classification, associated building and façade construction types (Created based on Onyeagoro et al, 2011)

Market sector	Building type	Typical façade construction
RESIDENTIAL	Single or two-family detached houses	Timber platform-frame structure; plywood sheathing; various claddings, wood shingle, vinyl siding, brick veneer, etc.; wood framed windows
RESIDENTIAL	Multi-family low-rise & high-rise buildings	Low-rise: Timber platform-frame structure; plywood sheathing; various claddings, wood shingle, vinyl siding, brick veneer, etc.; wood framed windows High-rise: Steel or concrete structure; brick veneer, aluminum framed windows
COMMERCIAL/ INDUSTRIAL	Small (under 75,000 sq.	Steel or concrete structure; various claddings, metal siding, brick veneer, etc.; various glazing types, aluminum framed windows, metal
COMMERCIAL/ INDUSTRIAL	Large (over 75,000 sq. ft.)	Steel or concrete structure; various claddings, metal siding, brick veneer, etc.; various glazing types, aluminum framed windows, metal
COMMERCIAL/ INDUSTRIAL	Institutional buildings	Custom construction types

1.2.3. Diversity in façade retrofit strategies

In terms of overall building performance, when building retrofits are considered comprehensively, changes to the building envelope become an important part of the retrofit options. It is generally understood that improving the efficiency of lighting and mechanical systems combined with an insulated airtight building envelope is a major step toward reducing the use of energy during building operation (Woods 2007). However, building façade retrofits involve additional solutions, ranging from the upgrade of the existing windows to the use of operable components to control of natural light and natural ventilation in a multi-layered façade.

Facade retrofit strategies have been classified according to the construction type, the spacing between the façade layers, and the system ventilation parameters (Kaluarachchi et al. 2005). An overview of retrofit strategies for commercial office buildings has been categorized in a historical time period (Ebbert 2010). Façade retrofits can be generalized for all building types into four strategies: replace façade components, add new components to the façade, add a new layer to the façade, or replace the entire façade.

- **Replacing façade components**

This type of retrofit usually focuses on replacing the façade infill system, either the opaque or the transparent surfaces, and providing new seals to avoid leakage. New insulating glazing unit products (IGUs) have appeared in the market to provide thermal resistance and provide better control of solar heat gains (energystar.gov). This new generation of improved IGUs, also called high performance windows, combine improvement to the glazing and the framing, such as the use of tinted or laminated glass, low-emittance and spectrally selective coatings, or added glazing layers, low conductance airtight frames, using vinyl or fiberglass.

- **Adding new components to the façade**

This type of retrofit consists of adding shading devices. Shading devices have been categorized as external, internal, or integrated within the IGU. In addition new photovoltaic panels have been incorporated to façade systems to act both as solar energy collectors and provide shading.

- **Adding new layers to the façade**

This type of retrofit is also very popular ranging from adding new layer of insulation to the opaque surface such as new structural insulated panes, new storm window units to the existing windows, or creating a double skin façade system.

- **Replacing the entire building façade**

This type or retrofit is a drastic approach to retrofit. Façade replacement occurs typically where the façade has suffered damage to various subsystems, such as the infill and framing as when exposed to fire or water. Otherwise façade replacements become part of a large renovation project where the building function and internal layout has changed.

1.3. **Research Problem**

The retrofit market faces some key barriers in the selection of performance criteria and the reliability of the performance data. Stakeholders approach the retrofit project with different performance expectations (Figure 4). On the demand side, some of the building owners and users' motivations include increased property value, reduced Greenhouse Gas emissions, and energy savings. One of the barriers to retrofit investments is the issue of "split incentives" between the stakeholders who front for the investment and those who benefit from it. On the supply side, the process to find an optimum solution between project cost and energy benefit is not transparent.

In a given retrofit scenario, the façade design options can range from window upgrades to more complex changes. There is an inherent complexity in modeling these options because of the incomplete knowledge of the physical and cost parameters involved in the performance evaluation. From an engineering perspective, the retrofit goal is for an optimum solution between project cost and energy benefit. From an architectural perspective, "firmness, commodity, and delight" must be equally considered (Vitruvius 2001). When retrofitting a building façade, the architect's intent is for a solution that is aesthetically pleasing and structurally sound, which provides occupant comfort, guarantees a productive lighting and acoustic environment, and decreases energy consumption by reducing the use of mechanical and electrical systems for lighting, ventilation, etc. (Wigginton et al. 2002). This enlarges the facade retrofit problem to include qualitative as well as quantitative aspects such as aesthetics and thermal comfort. Ultimately, the challenge is that the investment in a façade retrofit requires a degree of confidence that the predicted or anticipated energy benefit will occur and deliver a reasonable return.

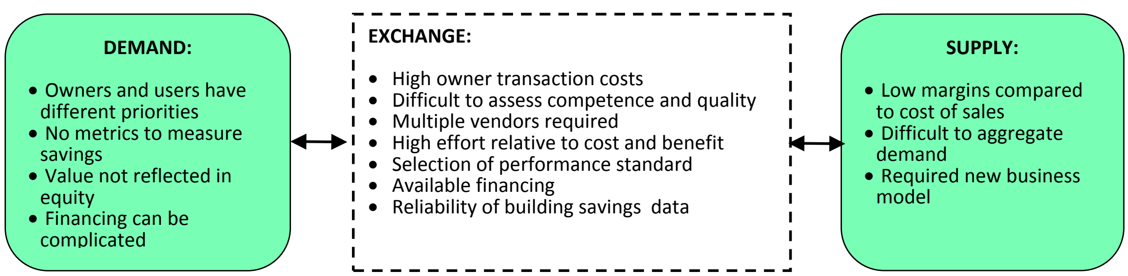


Figure 4: Retrofit market barriers between stakeholders

1.4. Purpose

This study in performance assessments for façade retrofit decisions confronts a major challenge that has not been resolved in prior research: the role of model uncertainty on the confidence level of retrofit decision making. The methodology proposed in this dissertation research integrates key indicators for delivery process, environmental performance, and investment performance. The purpose is to provide a methodological framework for to guide façade retrofit decisions with more confidence, insight and risk-awareness.

1.5. Hypotheses

Hypothesis 1: Façade retrofit decisions are made with false confidence.

Hypothesis 2: Uncertainty quantification in multiple performance aspects is essential to make risk-aware retrofit investments.

This raises the following research questions:

- **How to best support performance evaluation for façade retrofit?**
- **How reliable are energy performance predictions for façade retrofits?**
- **How to quantify risks to support façade retrofit decision-making?**

1.6. Contribution and significance

This dissertation builds on research efforts to support façade retrofit decision-making. The main contribution is a framework to support decision making for a specific retrofit type, the building façade. Three dimensions of performance are integrated, retrofit delivery process, environmental, and financial performance. This research attempts to fill a gap in the approach to façade retrofit decision by 1) quantifying uncertainties in these three dimensions of performance, 2) incorporating new financing models available in the retrofit market, 3) considering the decision maker's target confidence and risk threshold.

1.7. **Outline of the thesis**

- Chapter 1 presents the motivations for the thesis.
- Chapter 2 reviews the literature on performance-based evaluations and decision-making relevant to retrofit analysis.
- Chapter 3 presents a theoretical framework and describes the research approach and procedures for collecting and analyzing the research data.
- Chapter 4 describes the case study and organizes the results.
- Chapter 5 discusses the findings in detail, provides a conclusion and proposes directions for further study.
- Appendix A provides a description of the modeling process.
- Appendix B includes two diagrams describing the NPV calculation.
- The last section lists all references sited.

CHAPTER 2
PERFORMANCE-BASED DECISION-MAKING FOR ENERGY EFFICIENCY MEASURES

2.1. Introduction

A building is a unique product by a multi-domain team, perhaps working together for the first time. Throughout the phases of the building lifecycle, making a decision to improve building performance is a complex process involving stakeholders with different perspectives and objectives. Research in the design and construction phases has focused on supporting decision-making in multiple ways, including a new approach for integrated practice and project delivery (Owen et al. 2010); a methodology to quantify uncertainties and assess risk to extend the building operation (Garvey 2009); and a framework to support preliminary design evaluations (Sanguinetti et al. 2012). Research focused on the building operation phase also aims to support the dialog between stakeholders with diverse perspectives. Specific to the façade lifecycle, the American Society for Testing and Materials (ASTM), provides guidelines and recommendations to owners deciding on maintenance and repair (Erdly et al. 2004). Within this context, risk is the key consideration in decision-making and investment planning (Garvey 2009).

In addition to system maintenance, sources of risk increase when performance requirements change due to revised facility objectives or other environmental conditions altering the building use. Strategies have been proposed to accommodate this type of building changes: isolation of systems, prefabrication of components, and design for overcapacity (Slaughter 1998; Slaughter 2001). However, recent research in building energy management shows that the focus on specific strategies often lacks a holistic approach to the problem of decision-making (Kohler et al. 2003; Kolokotsa et al. 2009). As described in chapter 1, the incentives and pressures to meet sustainability goals for a façade retrofit project create additional tension between what is expected and what is feasible, in terms of performance, cost, and time. It is often difficult for the stakeholders to weigh the benefits against the cost of the investment, without a clarification of the risks.

Within the literature on building façade retrofit, researchers study the selection of a solution as either an optimization of design components or cost. For example research focuses on reducing energy consumption through the selection of the best combination of window and shading device (Lee et al. 2009) or the addition of external insulation to the façade's opaque surface (Lattke 2010). Other researchers study the use of double-skin façades in commercial retrofits to mitigate the energy used by the mechanical system (Brunoro et al. 2011). Recent research has focused on the cost of energy and turned to financial evaluation of the building retrofit. For example, research seeks to optimize the selection of retrofit measures based on the equivalent annual cost which results from subtracting the expected retrofit cost from the expected annual energy use (Polly et al. 2011). In contrast, this dissertation is focused on integrating various performance dimensions for the evaluation and selection of façade retrofit measure. In this line of research, other studies have used multi criteria decision making methods to analyze the solution. This chapter reviews two areas of knowledge relevant to making decisions toward a façade retrofit. The first section examines the decision process and what are the risks and uncertainties impacting the performance assessment. The second section reviews the approach to the retrofit decision as an investment and identifies who are the stakeholders and their criteria for decision-making.

2.2. **Multi-criteria decision-making under uncertainty**

2.2.1. Risk analysis

Early research studies in the perception of risk recognized the need to incorporate qualitative and quantitate characteristics when examining risk in new products and technologies. Slovic (1987) identifies two risk dimensions, founded upon knowledge and control, which influence stakeholders in a decision-making process (Figure 5). He finds that a comprehensive measure of risk is needed to improve communication between experts and non-experts. Current studies in risk analysis address these two dimensions, focusing on risk assessment, as the identification and quantification of risk, and risk management, as the decision-making process where appropriate strategies are selected considering qualitative and quantitate criteria (Tesfamarian et al. 2010).

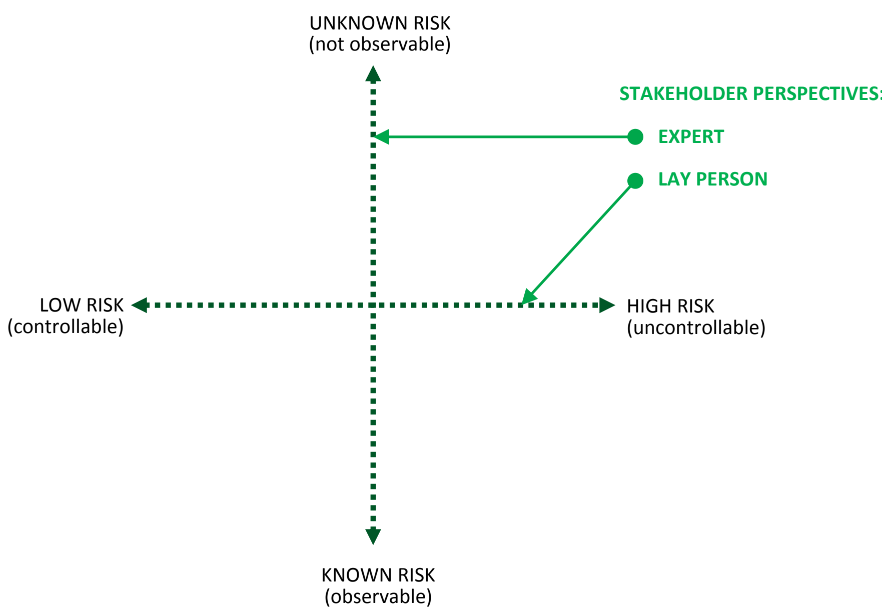


Figure 5: Factor space of risk perception (Slovic, 1987)

The concept of risk has been expressed in the following ways:

- **Risk is a function of possible consequences and its associated uncertainties.**

Risk = f (Probability, Impact)

- **Risk is a probabilistic event y given a root cause x.**

$0 < P(y \mid x) < 1$

- **Risk is considered part of decision-making, in terms of outcome uncertainty and utility.**

$\int u(d, \theta)\, p(\theta)\, p(x \mid \theta)\, d\theta$ (Lindley 2000)

Where, d = a list of decisions; θ is an uncertain parameter or quantity; u (d, θ) is termed the utility of the consequence. The optimum decision maximizes expected utility given data x.

Risk analysis is an integral part of the decision-making process in many fields, such as systems engineering, social science, economics, business, and statistics (Lindley 2000; Aven et al. 2005; Garvey 2009). In the AEC field, the quantification of uncertainties has been used extensively in analysis of the risks involved in seismic retrofits, power plants, and civil infrastructure (Corotis 2009; Tesfamarian et al. 2010). In these areas of high risk, studies distinguish between lack of knowledge and randomness as two types of uncertainties, epistemic and aleatory (Ellingwood 2001). Garvey (2009) proposes a “Technical Performance Risk Index Measure” to monitor performance in complex systems over an extended period of time. This risk indicator is derived by normalizing and weighing the set of performance indicators for the system, and measuring the “distance” between the system performance and a performance threshold. Zavadskas et al. (2010) identify three areas of risks impacting the construction process: 1) project risks such as cost, construction time, technological resources, work quality and safety; 2) external risks brought about by changes in the socio-political context, the economy, and the weather; and 3) internal risks such as lack of cooperation among project stakeholders, and the unavailability of materials or equipment. Specific to the area of sustainability, risk indicators have been proposed to support occupant decision-making for a zero-energy house, by combining and ranking the uncertainties in power reliability, building specification, and climate (Hu 2009) to support risk-conscious stakeholders when selecting among building retrofit options. The research shows that risk must be quantified as part of the decision making process. Although researcher offers various measures of risk specific to the discipline, these approaches can be generalized as the estimation of probability based on uncertainties in the quantification of performance.

2.2.2. Decision Analysis

Howard (1966) defines decision analysis as a logical procedure involving three phases: 1) the deterministic phase where the decision problem and alternative solutions are identified; 2) the probabilistic phase which includes uncertainty analysis, risk preferences and alternative selection using a decision-making method; and 3) the post-mortem phase, which requires research and information-gathering to verify the decision (Figure 6). The goal of this approach is to enable rational communication among stakeholders facing uncertainty.

Figueira et al (2004) provide a comprehensive review of the various methods and models for decision analysis. Chen et al. (1992) classify methods utilizing deterministic, stochastic, or fuzzy data for the decision analysis. Triantaphyllou (2000) distinguishes between real-life decisions by a single decision-maker vs. a group. A review of group decisions can be found in Csaki et al (1995), Bose et al (1997), and Belton et al (1997). Methods for multi-criteria decision analysis have been used in various domains where multiple performance criteria and conflicting objectives render decision-making difficult.

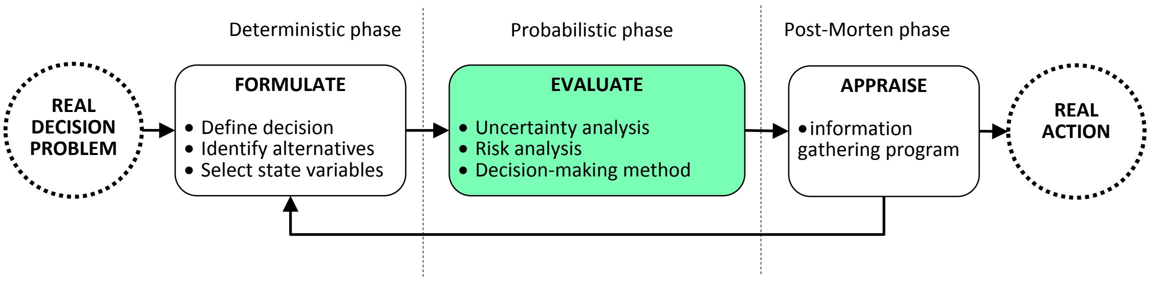


Figure 6: Decision analysis framework (Howard 1988)

- **The multi-criteria decision-making problem has been expressed as a decision matrix, A [m, n]:**

	C_1	C_2	…	C_n
	w_1	w_2	…	w_n
A_1	X_{11}	X_{11}	…	X_{11}
A_2	X_{21}	X_{22}	…	X_{2n}
⋮	⋮	⋮	⋮	⋮
A_m	X_{m1}	X_{m2}		X_{mn}

Where X_{ii} is the performance rating, for an option Ai, based on criterion Ci, with a determined weight of importance *wi*.

- **The MCDM decision-criteria can be decomposed into attributes or dimensions, which may have conflicting goals or different units.**
- **The MCDM decision-criteria can be organized hierarchically or is assigned normalized weights of importance.**

Zimmermann (1996) categorizes two types of multi-criteria decision-making (MCDM) methods: multi-objective, where optimization is used to find a solution among a large set of options in a continuous solution space; and multi attribute, where comparison of quantified attributes is used to find the alternative solution within a small set of discrete options. Other reviews and comparisons of multi-objective decision making (MODM) and multi-attribute decision making (MADM) can be found in Starr and Zeleny (1977), and Hwang and Yoon (1981). Belton and Stewart (2002) classify MCDM methods in three categories: outranking models with aggregated preference criteria; value measurement models, with numerical scores for each criterion; and reference level models with criterion divided into levels or goals, where the optimum option is the closest desired goals. Table 2 provides a selection of the MCDM methods found in the literature.

Table 2: Classification of multi criteria decision making (MCDM) methods

MCDM METHODS	acronym	references
Outranking methods		(Roy 1976)
Elimination and Choice Translating Reality	ELECTRE	(Benayoun et al. 1966); (Roy 1968)
Preference Ranking Organization Method for Enrichment Evaluations	PROMETHEE	(Brans et al. 1985); (Brans et al. 1986)
Technique for Order Preference by Similarity to Ideal solution	TOPSIS	Huang and Yoon, 1981
Multi-attribute utility theory	MAUT	(Keeney et al. 1976)
& Multi-attribute value theory	MAVT	
Weighted sum method	WSM	
Weighted product method	WPM	
Simple multi-attribute rating technique	SMART	(Edwards 1977); (Edwards et al. 1994)
Analytical hierarchy process	AHP	(Saaty 1980)
revised AHP		(Belton et al. 1983)
Analytical Network Process	ANP	(Saaty 2004)
Multi-objective decision-making	MODM	(Starr et al. 1977)
Compromise programming		(Yu 1973); (Zeleny 1973)
Goal programming		(Lee 1973)
Discrete representation		(Armann 1989)
Pareto-based ranking methods		(Fonseca et al. 1993)
Vector Evaluated Genetic Algorithm	VEGA	(Schaffer 1985)

Specific to the area of sustainability, Pohekar et al. (2004) review multi-criteria decision-making (MCDM) methods for energy planning. The authors find that these methods are increasingly used because they support group decisions where compromise is needed to reach consensus. Dorini et al (2011) apply compromise programing, MODM method, to quantify uncertainties and help decision-makers (DMs) rank among options that require estimation of cost, environmental impact, and technical performance. Figure 7 shows two types of uncertainties in decision-making: 1) data uncertainties propagated in the models used to calculate the decision criteria; 2) DMs preference uncertainty, or weight of importance, used in the MCDM method. Table 3 shows a selection the MCDM literature focused on energy management decisions in the building lifecyle.

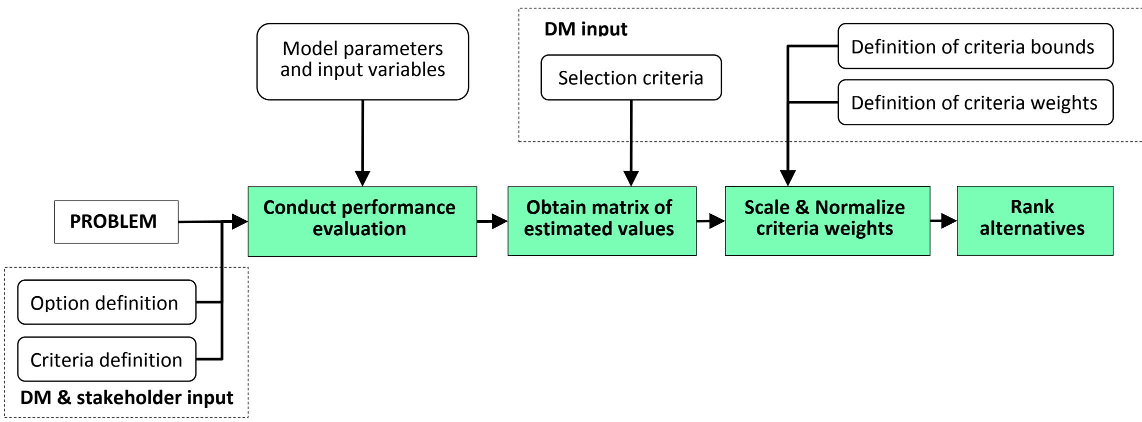


Figure 7: MCDM method applied to sustainability assessment under two levels of uncertainty (Dorini et al. 2011)

Previous research in the decision process provides various methodologies to support multi-stakeholders decisions through the use of weight factors to quantify the value assigned to performance criteria. In addition the research has shown that parameter uncertainty must be quantified to understand the risks in a performance assessment. The next section reviews research on the building retrofit as an investment decision and the approach to uncertainty quantification.

Table 3: Classification of MCDM methods applied to building energy-related decisions

Decision stage in the building lifecycle	MCDM METHOD	name or acronym	references
Design and construction decisions			
Building shape design	Multi-objective	CAMOS	(Marks 1997)
	Multi-objective	Pareto dynamic programing	(D'Cruz et al. 2003)
Technical system design	Outranking	PROMETHEE	(Le Teno et al. 1998)
	Multi-objective		(Jedrzejuk et al. 2002)
	Multi-attribute	Extended AHP	(Hopfe 2009)
Operation and maintenance decisions			
Environmental system control strategy	Outranking	ELECTRE	(Blondeau et al. 2002)
	Multi-objective	MOGA	(Wright et al. 2002)
Facility management investment	Multi-attribute	COPRAS	(Banaitiene et al. 2008)
Retrofit option selection	Outranking	ELECTRE	(Roulet et al. 2002)
	Multi-objective	TOBUS	(Flourentzou et al. 2002)
	Multi-attribute	COPRAS	(Zavadskas et al. 2008)

2.3. Retrofit decision under financial uncertainly

2.3.1. Retrofit as investment

Growth in the financial sector of the sustainable building market reveals that the approach to the retrofit decision has changed from a lifecycle cost to an investment opportunity (Bernstein et al. 2008; Managan et al. 2012). A joint study by the Building and Construction Authority and the Department of Real Estate in National University of Singapore finds that building retrofits can increase capital value by 2% and save operating costs by 10% (Yu et al. 2011). In the commercial sector, Ciochetti et al (2009) report that building owners seek to invest in energy retrofits to enter the market with "green" amenities such as a retrofitted building façade; meet investor and occupant demands; and compete with new constructed facilities. For example, recent retrofits of the Empire State building in the New York and the Willis Tower (formerly the Sears Tower) in Chicago involved façade retrofit to improve the overall energy performance of the building, attract a different renter profile, and raise the building occupancy. Although other case studies have reported economic gains in the commercial sectors in term of energy savings due to the capital invested in retrofit improvements (Binkley 2007), there is a lack of consistent data and clear methodology to assess the impact of retrofit investments (Bloom et al. 2011). In the residential sector, Amann (2006) finds that homeowners will retrofit their property because they value non-energy benefits such as indoor air quality and aesthetic enhancements. These studies reveal that stakeholders' social and psychological preferences should also be considered when valuing the cost-effectiveness of a retrofit as an amenity (Rosen 1974),(Heerwagen 2006).

In addition to owners and developers, a third group of related stakeholders who share in the financial risks is beginning to play a key role in the investment decision. For example, the Property Assessed Clean Energy (PACE) financing model involves three key stakeholders in the energy retrofit investment decision: the owner, the finance provider and the municipality (Figure 8). With the Managed Energy Service Agreement, (MESA), a lender finances the retrofit and manages payments of the utilities for up to ten years. The lender revenue is based on the difference between the cost of energy before and after the retrofit (Figure 9). A report by the World Economic Forum (Dyer 2011) provides a summary of the benefits, barriers, and stakeholders involved in current financing models for energy retrofits (Figure 8 to Figure 14). These financing models aim to incentivize the retrofit market and reduce the strain of first costs on the building owner. In some of these financing models lenders become partners in the retrofit investment. From this investment perspective, the expected revenue must be evaluated against a quantification of the risks.

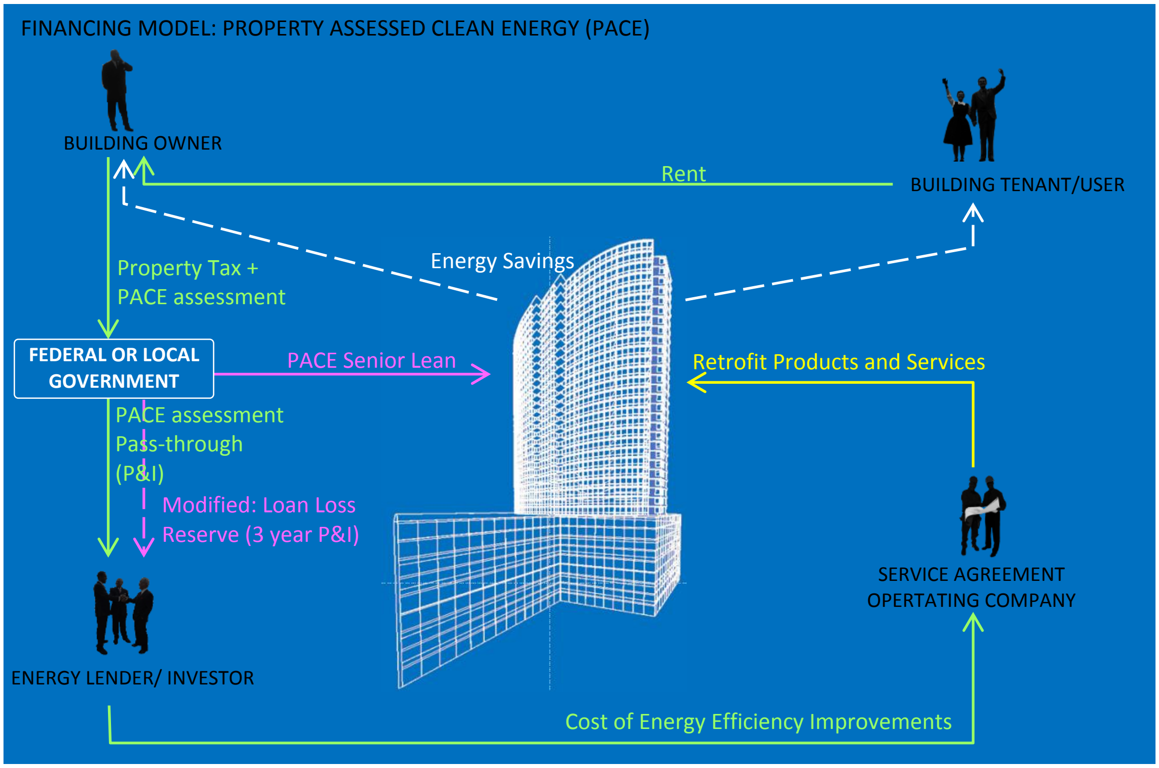


Figure 8: Property Assessed Clean Energy (constructed based on Dyer 2011)

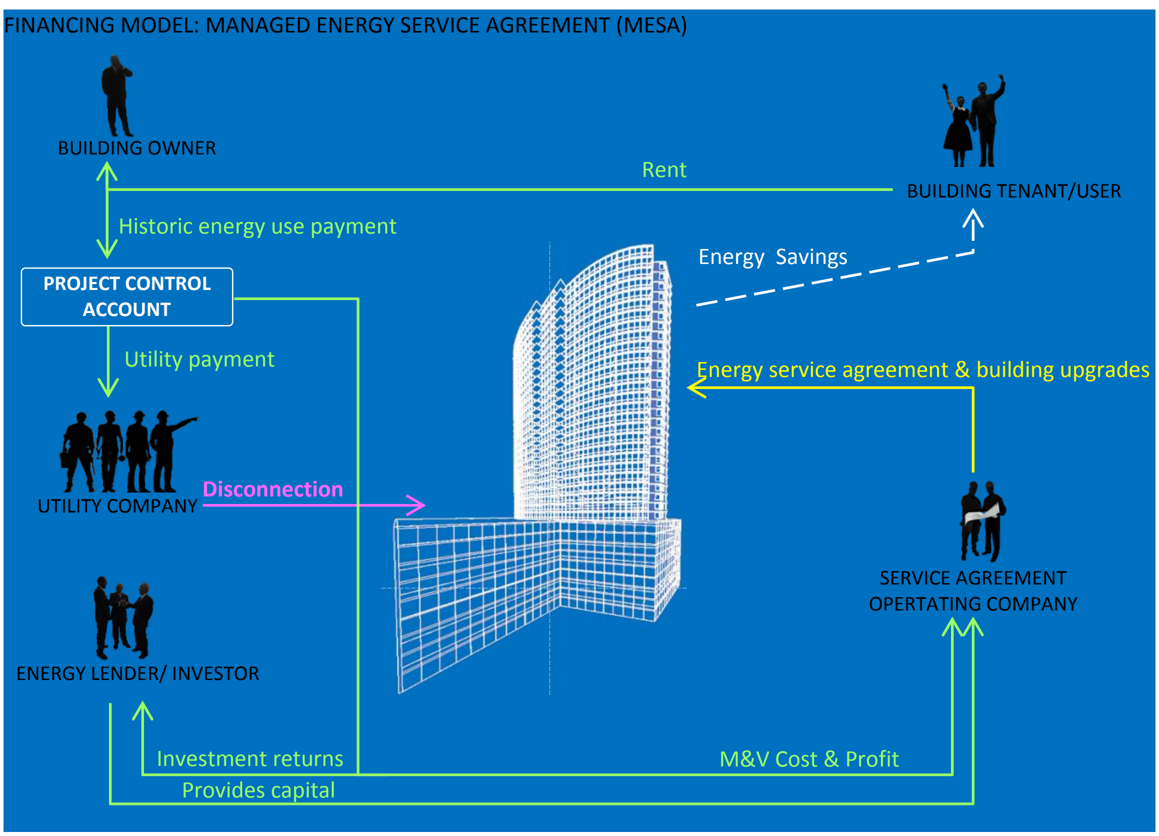


Figure 9: Managed Energy Services Agreement (constructed based on Dyer 2011)

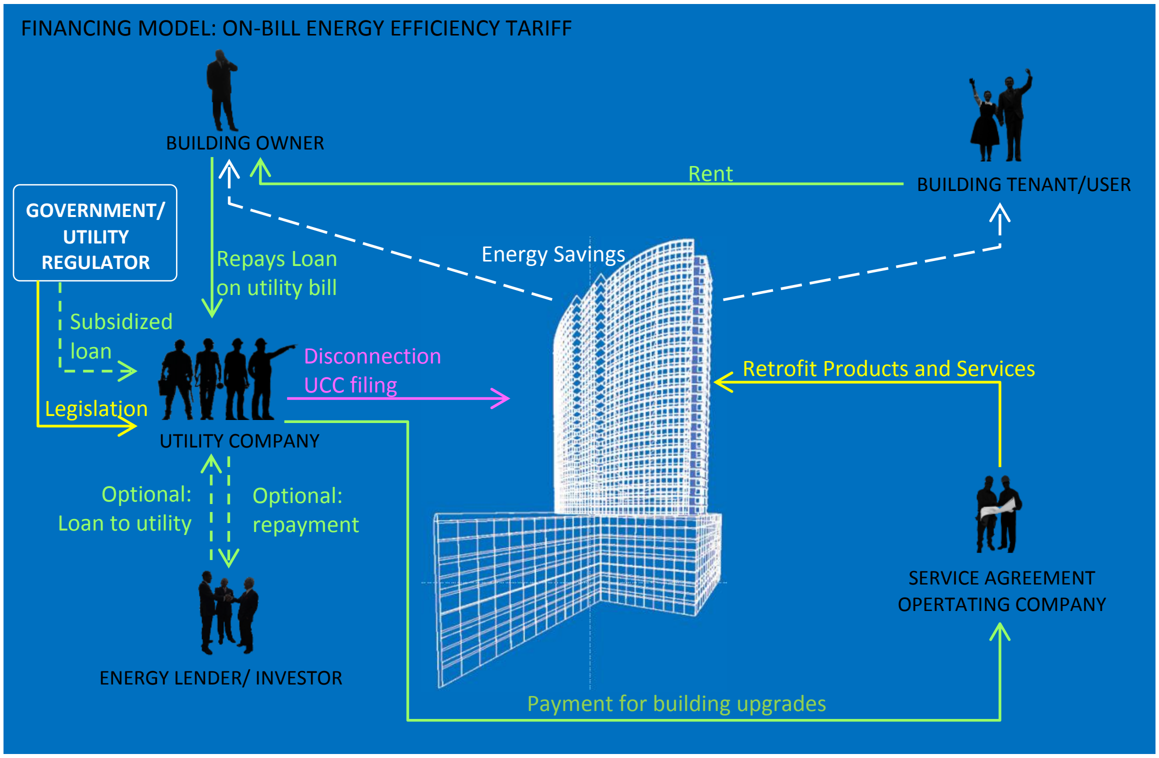


Figure 10: On-Bill Energy Efficiency Tariff (constructed based on Dyer 2011)

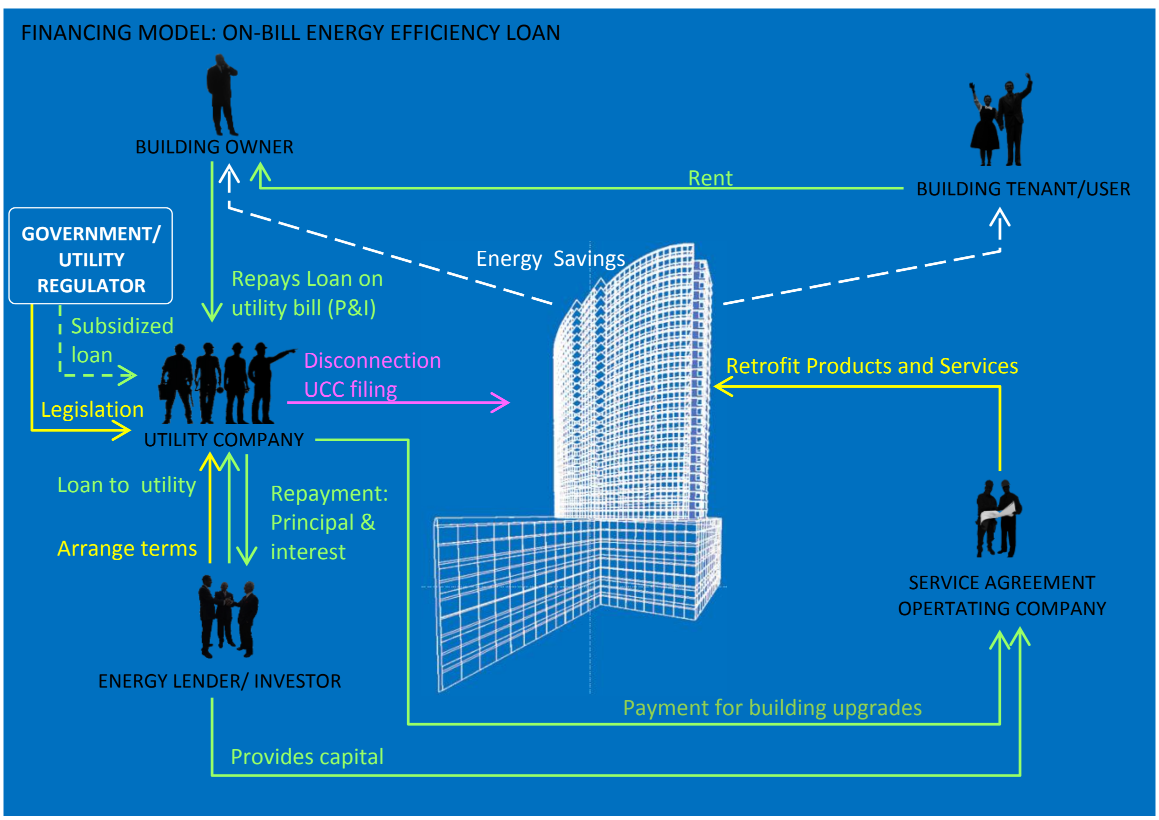


Figure 11: On-Bill Energy Efficiency Loan (constructed based on Dyer 2011)

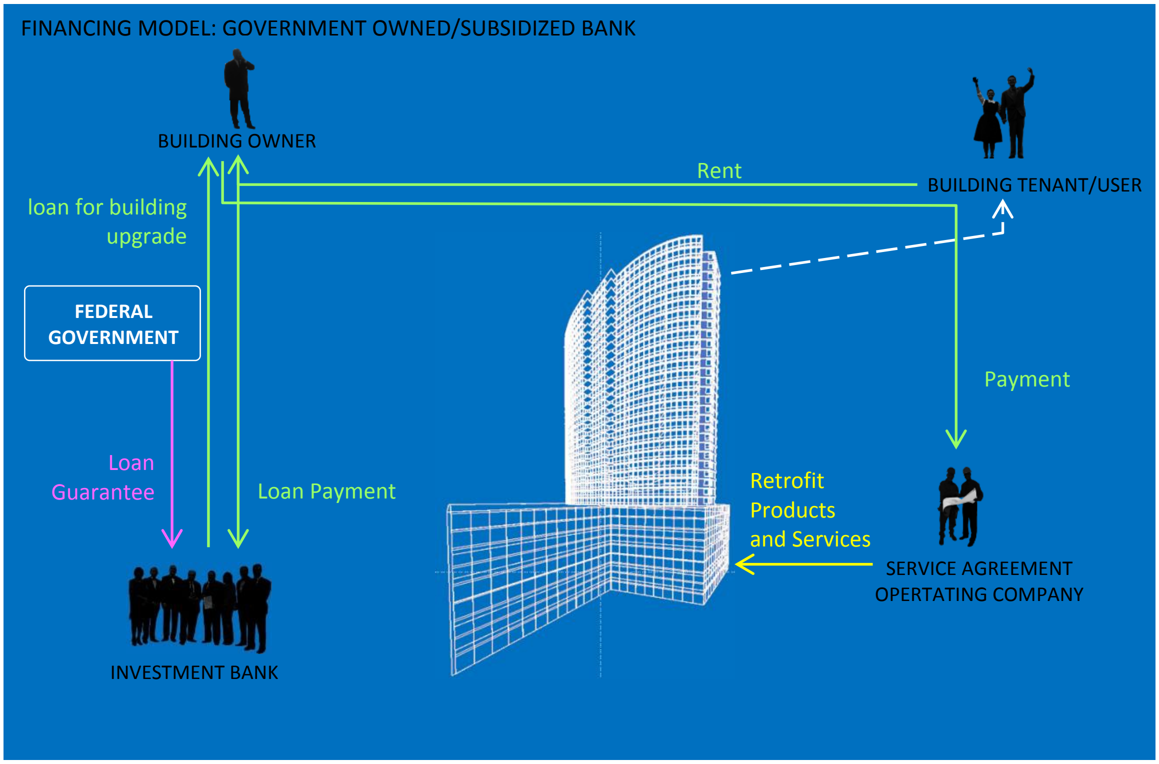


Figure 12: Government-Owned or subsidized development Bank financing model

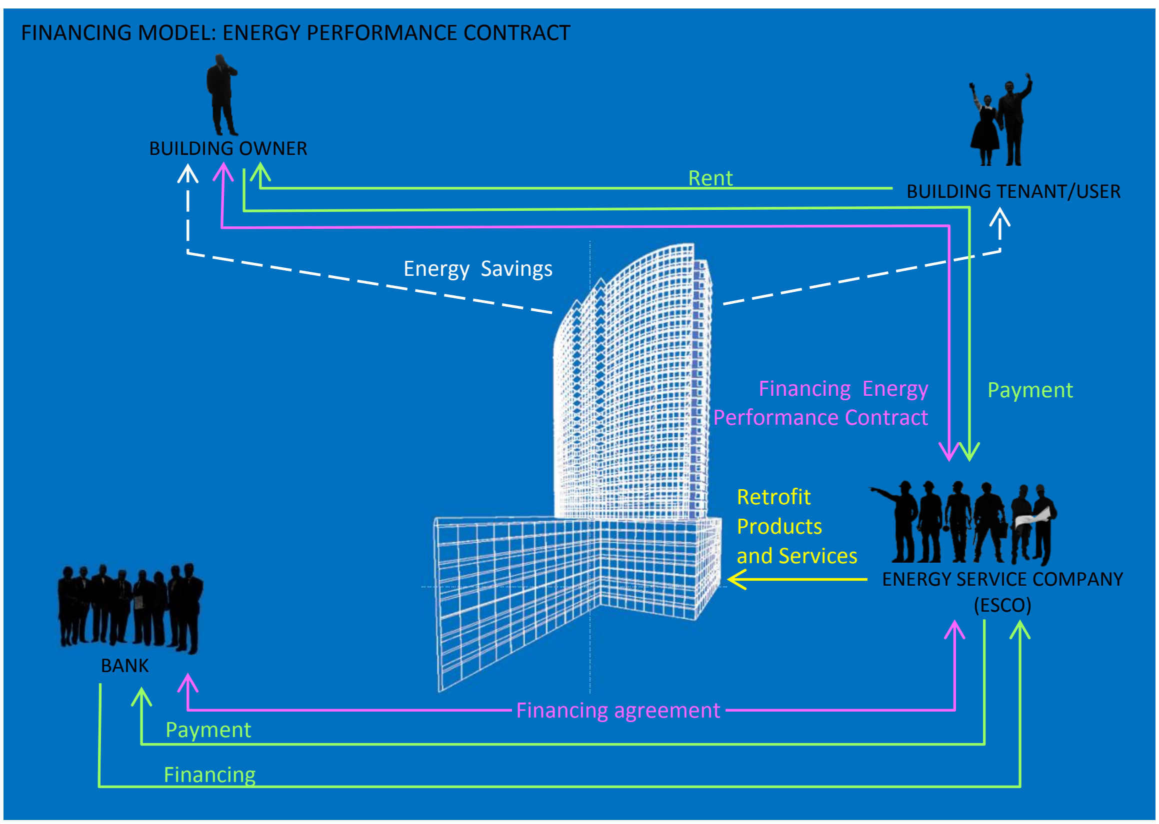


Figure 13: Energy Performance Contract, EPC

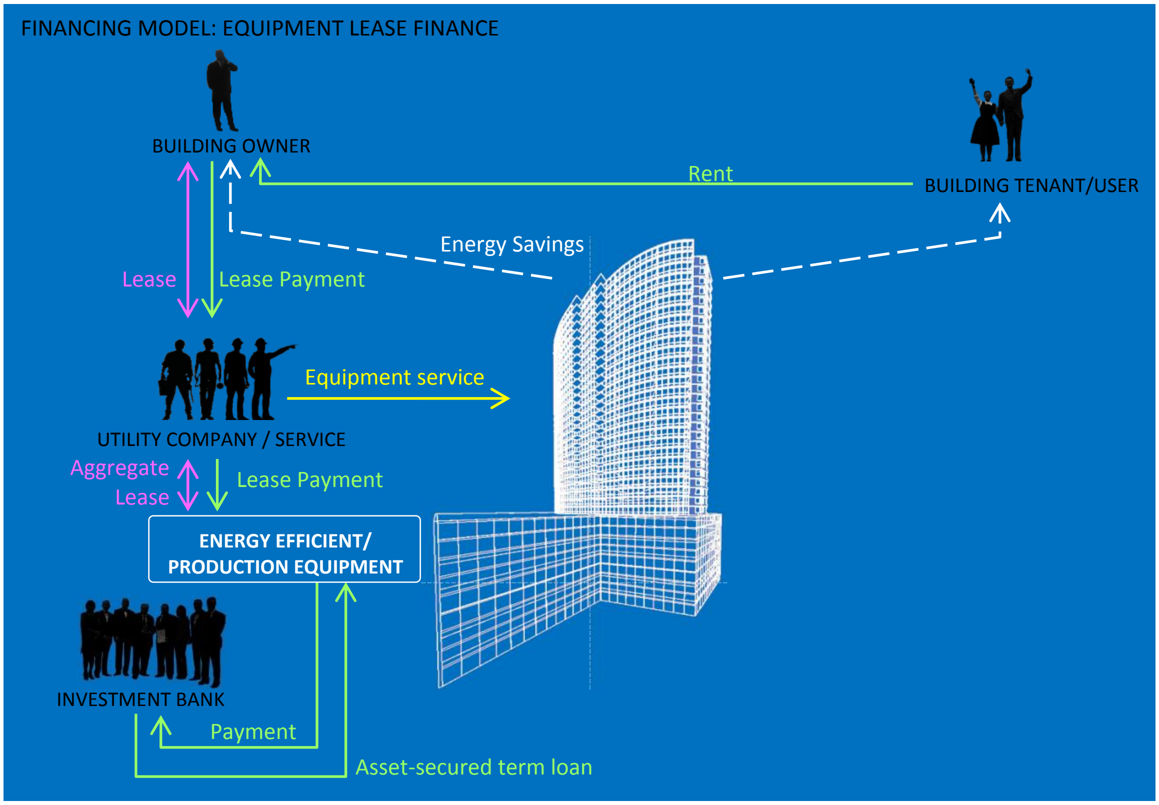


Figure 14: Equipment Lease (constructed based on Dyer 2011)

2.3.2. Uncertainty quantification and financial risk

Research in energy efficiency investment can be organized into two approaches to the problem: a broad view of sustainability focused on the definition and selection of performance indicators and another view focused on the calculation of investment benefit and concerned with the cost of energy. For example, Muldavin (2009) proposes a real estate framework to incorporate quantitative and qualitative measures of sustainability and financial performance. Menassa (2011) presents a framework to analyze retrofit investments in relationship to the building lifecycle. She identifies four uncertain measures: value of the building, demand for green space, energy savings, and operation costs. Mills et al (2006) points to the wide discrepancy between prediction and real energy consumption in buildings due to three intrinsic project volatilities: Energy volume risk (change in energy use), asset performance risk; and energy baseline uncertainty risk. Blyth et al (2007) identify three types of risks affecting investments in the energy sector: economic, legal, and political risk involving regulatory policies. These researchers consider the changes in energy costs in Net Present Value (NPV) calculations using Real Options Analysis (ROA) to address investment uncertainties (Figure 15). Other studies have also proposed the use of Real Options to measure the impact of waiting or deferring the retrofit investment decision due to energy cost uncertainty (Kumbaroglu et al, 2011, Heydari, 2010). The use of ROA for retrofit investments is driven by the fact that the timing of an investment is crucial to maximizing profits, because investment risk changes over time. Traditional calculation methods such as pay-back analysis, internal rate of return, return on investment, are geared to reduce investment risk by favoring short term-savings and provide a minimum acceptable rate (EBAR). These measures can eliminate profitable retrofit investment options. In addition, the combination of cash-flow calculation with ROA for retrofit investments provides an expanded set of options in managing the risks stemming from the cost fluctuations in various sources of energy. This approach includes the decision-maker risk tolerance in the decision-making process (Jackson 2008).

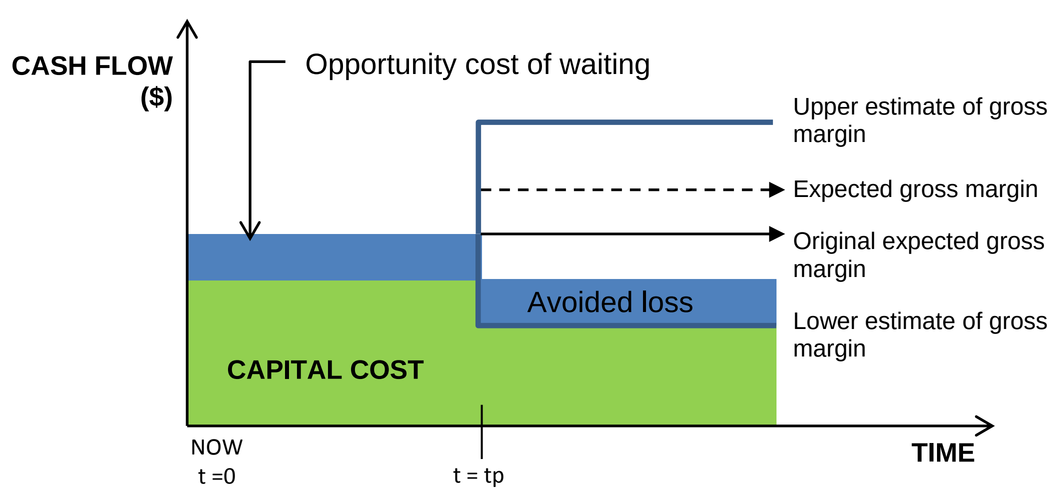


Figure 15: Understanding the value of waiting and its effect on investment (constructed based on Blyth et al 2007)

2.4. **Need for a comprehensive approach to decisions for façade retrofits**

Previous research has shown that calculation and verification of energy savings in retrofit projects is a source of risk. A review of the literature shows that researchers concerned with decision-making for energy efficiency do not consider the impact of the current financing models on a) the relationships between the various stakeholders involved and b) the calculation of investment costs. In addition, research on façade retrofit decisions has focused mainly on the physical behavior of the system. A framework has been proposed to prioritize among three basic façade cladding systems, based on climate zone and hydrothermal behavior, to facilitate maintenance and reduce the risk of incurring in costly repairs (Kyle et al. 2008). Other researchers have studied detailed aspects of façade hygrothermal behavior. Mukhopadhyaya et al (2003) develops a tool to evaluate the moisture and energy performance of masonry façade retrofit. At this scale, the decision problem examines localized uncertainties in the retrofit technologies coming from physical parameters.

Researchers have also found challenges in using rating systems such as LEED to evaluate the performance of retrofit investments in the commercial sector (refs.) Although LEED ratings are highly regarded as demonstrations of sustainability and energy efficiency in the U.S., only a fraction of the points needed for platinum, gold, or silver LEED ratings is directly related to energy improvements of existing buildings (LEED-EB). Other researchers have been challenged by lack of performance metrics for certain retrofit technologies, and have evaluated strategies based on how they impact major sources of energy consumption such as artificial lighting *Osborn et al (2002) Lam (2008), or heating and cooling (*Emmerich et al 2005). When making decisions on energy retrofit investments, there is conflict between decisions at the local building levels vs. overall portfolios. Engblom (2006) makes a case for façade retrofit as a viable approach to reduce energy consumption. However the economic analysis has shown that payback periods for retrofit packages that included the façade were at least 10 years for buildings constructed after 1969.

In the current energy market a more comprehensive approach is needed to address the range of retrofit financing options. The state of the art in retrofit investments points out that while energy management decisions still rely on traditional investment performance indicators; other areas have developed more sophisticated measures. Researchers have focused on finding answers to several problem involved in an investment decision, including the uncertainty in predictions rooted on the changing cost of energy. This research approach seeks to answer the question of when is the right time to invest in an energy retrofit.

We find that risk-conscious selection of façade retrofit measures should include quantification of both physical and financial uncertainties against various lifecycle scenarios. The next chapter presents a framework to consider the various sources of uncertainty in energy efficiency retrofits. The goal is to provide a road map to façade retrofit decision-making.

CHAPTER 3
INTEGRATED RISK-ANALYSIS FRAMEWORK FOR A FACADE RETROFIT

3.1. Introduction

Retrofitting a building is a complex decision problem. Muldavin (2009) identifies five levels of performance for a sustainable property investment: process, feature, building, market, and financial performance. In the case of a façade retrofit, the interrelationship between these performance dimensions needs to be examined. For example, various measures of financial investment performance are impacted by mutually dependent types of building performance: thermal performance, HVAC performance, and daylight performance, and acoustic performance (Ruck 1989). In addition, many uncertainties affect the façade retrofit decision. At the level of building technology evaluation, physical uncertainties need to be quantified. In terms of an investment evaluation, financial uncertainties also need to be quantified to support different stakeholders' approach to risk. The problem being researched is rooted in the fact that a façade retrofit decision must integrate multiple stakeholder perspectives towards uncertainty and associated risks. This raises the following research questions:

- **How to best support performance evaluation for façade retrofit?**
- **How reliable are energy performance predictions for façade retrofits?**
- **How to quantify risks to support façade retrofit decision-making?**

This chapter details a methodology where the sources of uncertainties play a role in the decision making process. Three approaches are discussed in the context of a retrofit decision, followed by a proposal for an integrated analytical framework, and an outline of the decision process.

3.2. Theoretical models relevant to AEC industry decision-making

The central question is how to support better decision for façade retrofits. There are two market perspectives that need to be considered in this process: demand and supply. Three relevant models are reviewed, based on their approach to the building product: the performance-based building framework, the cash-flow model, and the living building concept.

3.2.1. Performance based building framework

- **Overview**

The Performance Based Building framework (PBB) brings together business and engineering concepts. The framework is introduced to support innovative solutions throughout the building lifecycle, placing emphasis on the building's output performance (Gibson 1982; Foliente 2000). In the PBB framework a building is a complex system, in a market environment with multiple stakeholders (Becker et al. 2005). The main characteristic is a validation mechanism for the building stakeholders which quantifies and evaluates the building's performance-in-use against a target performance.

The performance-based building concept has been described using models to represent the dialogue between supply and demand and the verification of the project outcomes (NKB 1978; Gielingh 1988; Gielingh et al. 1993; Ang et al. 2005; Spekkink 2005). A "Total Performance Systems Models" shows the parallels between a regulatory approach that integrates prescriptive and performance-based codes and a non-regulatory approach (Meacham et al. 2002). All models indicate the importance of performance verification and validation where supply and demand are compared. An "aspect system model" has been proposed to represent the one-to-many relationship between a performance requirement and various indicators, and the one-to-one relationship between a performance indicator and its quantification and verification method (Augenbroe 2009).

Two basic steps bracket design activities in a performance-based building framework: development of a performance criteria and performance verification. In current practice building simulation is the tool of choice to represent the complex behavior of building systems and evaluate their performance (Clarke 2001; Malkawi et al. 2003; Augenbroe et al. 2004). This approach to performance verification requires a certain level of detail which is usually not available in the early design stages (MacDonald 2002; Eastman 2009). The evaluation and verification process requires for the performance evaluation criteria to be made explicit. Performance evaluation is a validation procedure which entails quantification to support rational decision-making. However, this quantification is also a source of uncertainty (Saltelli et al. 2008).

The development of performance criteria is the process of translation from qualitative statements to quantifiable conditions. First, user needs are identified and expressed as a series of qualitative statements of functional requirements (Blyth et al. 2001). These statements are decomposed and expressed as a set of quantitative requirements of performance, with a set of specifications, including numerical values, tolerance, and units. Performance requirements are compiled into performance specifications including acceptable testing methods, indicators, and target values (Preiser et al. 2005). Design solutions are tested using verification calculations established in the specifications, such as normative calculations, simulations, or measurements collected in the building operation phase. In performance-based design, performance verifications calculations are considered experiments conducted in a scenario of use where functions can be observed and data collected (CIB 1975). Calculation results are then aggregated. A performance indicator is the quantified normalized result obtained through the aggregation of the data collected for analysis. Performance indicators are validated by comparing them against established performance targets (Szigeti et al. 2005).

- **Deterministic vs. probabilistic models**

The performance-based approach has been adopted in the early phases of the building lifecycle to provide meaningful feedback to the architect or other decision-makers. More recently research has focused on improving process exchanges between design and analysis domains including interoperability of tools and data types. Most energy simulation tools available in the market today provide a deterministic output. Input data into a simulation is a series of data models dealing with weather, internals occupancy loads, building technical systems, and the HVAC system operation. All these data sources have embedded uncertainties which need to be made explicit to the stakeholders who use the simulation output to support their decision-making process. Researchers have proposed that performance evaluations resting on simulation output data need to include uncertainty and sensitivity analysis (MacDonald et al. 1999; De Wit 2001; De Wit et al. 2002; MacDonald 2002; Struck et al. 2007). The underlying argument is that it is more appropriate for decision-making to communicate "performance values against the probability of their occurrence" rather than to compare a set of a simulation results to a benchmark value (De Wit 2004).

Four types of uncertainties have been identified in the use of simulation for energy performance evaluations and decision-making in the early phases of the building lifecycle. (MacDonald et al. 1999; De Wit 2001):

- Scenario uncertainties from statistical data for weather conditions and occupancy patterns
- Physical uncertainties from incomplete specification in building properties
- Modeling uncertainties from assumptions made in the simulation model due to the simplification of physical phenomena.
- Numerical uncertainties from inappropriate time-step or the approximation scheme of the differential equation

A review of uncertainty quantification methods using probability can be found in Lomas and Eppel (1992), Helton (1993), Macdonald (2002), and Saltelli (2008). Various statistical approaches to uncertainty and the identification of parameters sensitivity have been utilized to analyze building simulation output (Morris 1991; Saltelli et al. 2008). Morris (1991) first proposed a method to evaluate uncertainty by isolating a single uncertain parameter at a time. Lomas and Eppel (1992) compare three approaches to sensitivity analysis to evaluate the error in simulation output in the design stage, associated to the lack of knowledge of the geometric definition and the thermal properties of the building elements. An uncertainty analysis interface is implemented as part of a building performance evaluation tool (MacDonald et al. 1999). De Wit (2001) conducts uncertainty analysis as cycle, beginning with a coarse model that is subsequently refined using sensitivity analysis to identify the parameters with greater uncertainty. In his study, two meta-parameters are identified: wind pressure coefficient, and air temperature distribution. Through the refinement of uncertainty analyses, lower levels of uncertainty can be identified and quantified in order to modify the simulation. His study uses probabilistic inversion which combines expert knowledge and simulation output as two probability distributions used to refine the input parameter uncertainty (Cooke 1994; Kraan et al. 2000).

Uncertainty analysis followed by sensitivity analysis has been used as tools to study the input parameters that influence the simulation model output. Researchers developed probabilistic sensitivity analysis to study the variability in the model output, as well as the interaction between them (Sobol 1993; Saltelli et al. 2008). In particular, variance-based sensitivity analysis is able to deal with parameter groups. Recently, Standardized Regression Coefficient and Adaptive Component Selection and Smoothing Operation have been used as sensitivity measures for climatic factors affecting the output results of energy models (Tian et al. 2011).

In contrast to deterministic evaluation resting on a single model output, posterior probability distributions from uncertainty analysis can be used to consider risk in energy performance assessments (Hu 2009). Figure 16 shows a graphic comparison to evaluate a baseline to a model output for a performance indicator, PI. Risk of underperformance is understood in two ways. The area where the two probability density function curves overlap indicates the probability of the model output to simply match the performance baseline. The green shaded area indicates the probability for the model to perform below the minimum requirement.

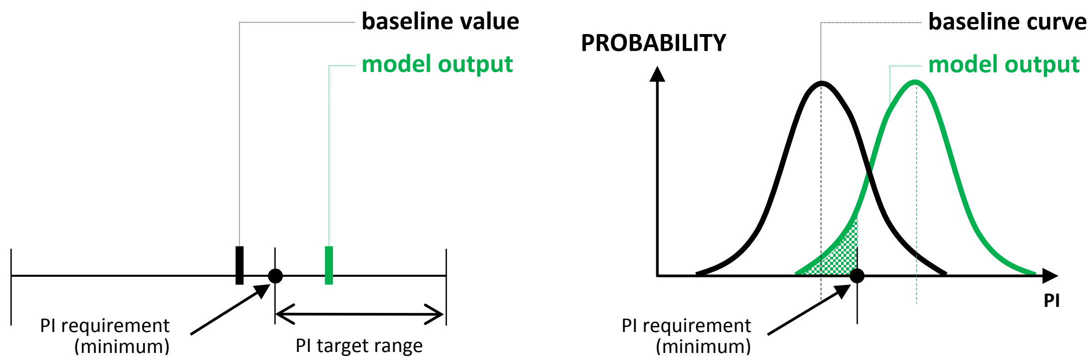


Figure 16: a) Deterministic approach; b) Risk-based approach to a performance indicator, PI

3.2.2. Product process performance

The AEC industry has identified performance measures for the construction and delivery of a building product (CURT 2005). Cost, quality, timing, and safety are some of the aspects to be included in the evaluation of the construction management process. The industry has also adopted new methods for team collaboration and verification in the early phases of the building lifecycle to respond to client demand for transparency, efficiency, and sustainability (CURT 2005). Integrated Project Delivery (IDP) has been widely adopted to improve the communication of the project team and reduce error and waste in the design and construction process. New service contracts define these new working relationships, including Design-Build, CM-at-Risk, and other forms of multi-party contracts. In addition, commissioning is used at various stages of construction to verify performance targets. These activities are also important to in a retrofit process. For example, job order contracting has been implemented to improve the scheduling or renovation and repairs during building operation. Retro-commissioning is used to improve the performance of existing buildings (Mills 2003). Pati et al. (2009) identify ten performance indicators to support maintenance decisions by stakeholders with different expectations. Paslawski (2008) studies the modularity of façade installation to a) achieve flexibility in project planning, and b) incorporate uncertainties that arise with changes in the construction schedule.

Augenbroe et al. (1998) propose a paradigm shift in building construction from traditional performance measures such as cost, time, and quality, to a broader set of sustainability indicators for human satisfaction, minimal environmental impact, and minimal consumption of resources. The authors identify key limitations in quantifying environmental impact, using building lifecycle analysis to assess construction performance. De Ridder et al. (2005) introduce the Living Building framework to interconnect value, cost, and price, using dynamic contracting to manage changes and responsibilities throughout the building lifecycle. van Nederveen et al. (2009) build upon this framework to manage the life of the building. A building product model is used to monitor performance of building modules and components. The management strategy identifies three decision stages: maintenance, disassembly and up-cycling, and destruction and recycling.

3.2.3. Investment performance models

Mathematical models used to evaluate financial performance have been classified as classical or neo-classical, based on the input parameters used to calculate the value of an investment (Torrez et al. 2006). Laudon et al. (2004) identify six classical methods used to make decisions on capital projects: the payback method, the rate of return on investment (ROI), the cost-benefit ratio, the profitability index, and the rate of return (IRR), and the net present value (NPV), based on the Discounted Cash Flow (DCF) model. Among these classical methods, the use of the DCF is a powerful method for sustainable capital investments decisions (Blyth et al. 2007; Fuss et al. 2010). Reviews of financial valuation with the DCF method can be found in Reilly et al. (2000) and (Koller et al. 2005). The DCF can be represented as the sum of expected future earnings:

$$\text{DCF} = \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \cdots + \frac{CF_n}{(1+r)^n}$$

Where, *CF* is a projection of future cash flow; and *r* is the discount rate such as capital cost, calculated for a set of time intervals, *n*. In this traditional approach, *CF* values are usually considered as certain, i.e. not stochastic variables.

In the financial realm, it is generally understood that investment finances have many uncertainties. For example, investment costs may be different from mean expected values due to uncertainties associated to technical or operational costs. The evaluation of portfolio efficiency and diversification uses variance of expected returns to measure the overall risk of an investment portfolio (Markowitz 1952). The Capital Pricing Asset Model (CAPM) extends the diversified portfolio theory, and incorporates the uncertainties inherent in cash flow elements (Sharpe 1964; Lintner 1965; Black 1972). The CAPM can be represented as the relationship between capital investment cost and market returns:

$$E(R_i) = R_f + \beta_i(E(R_M) - R_f)$$

Where, *E* is the expectation operator; *Ri* is the return on portfolio *i* for the investment project; *Rf* is the risk-free rate; R_M is the return on the market portfolio; the factor *(E(*R_M*)- Rf)* is the overall market risk premium; and the *βi* coefficient is the covariance between the investment project return and the market return. *βi* is a measure of systematic risk on portfolio *i* which arise from uncertainty in the return due to fluctuations in the market as a whole. In this model, risk is resolved as a continuous constant rate.

This approach to risk results in a distribution of the projected investment value that does not reflect “real” future uncertainties needed to make strategic investment decisions for retrofit investments (Ashuri et al. 2011; Kumbaroğlu et al. 2011; Menassa 2011). The real options valuation framework makes a parallel between capital investments and financial options, in which the exercise of an option can be deferred (Dixit et al. 1994; Trigeorgis 1996; Amram et al. 1999). The financial options calculation method was originally derived to price financial call options and bet on financial assets such as stock or bonds (Black et al. 1973; Merton 1973). As an alternative to traditional deterministic calculation, Myers (1984) first proposed the use of the options calculation, to address the risks in “real options” such as capital investments and incorporate the uncertainties in profitability.

Other researchers have expanded on the use of the real options analysis. Margrabe (1978) provides a variation to the Black-Scholes original calculation to support the exchange of options. Dos Santos (1994) calculates the value of exchanging investment options considering uncertainties in both the cost and the benefits. Cox et al. (1979) propose a decision tree as a graphic representation for real option analysis (Figure 17). The investment decision is seen as a sequential process where a binomial tree is used to calculate the option value at discrete times. This methodology utilizes the full uncertainty, or volatility in the cash flow calculation of the Net Present Value (NPV) of an investment. The NPV provides information on the value of the project in relationship to a time horizon and a discount factor, to compare the value in the future to the current value. In this approach, flexibility is incorporated in the decision to invest, based on an NPV margin greater than the value of waiting.

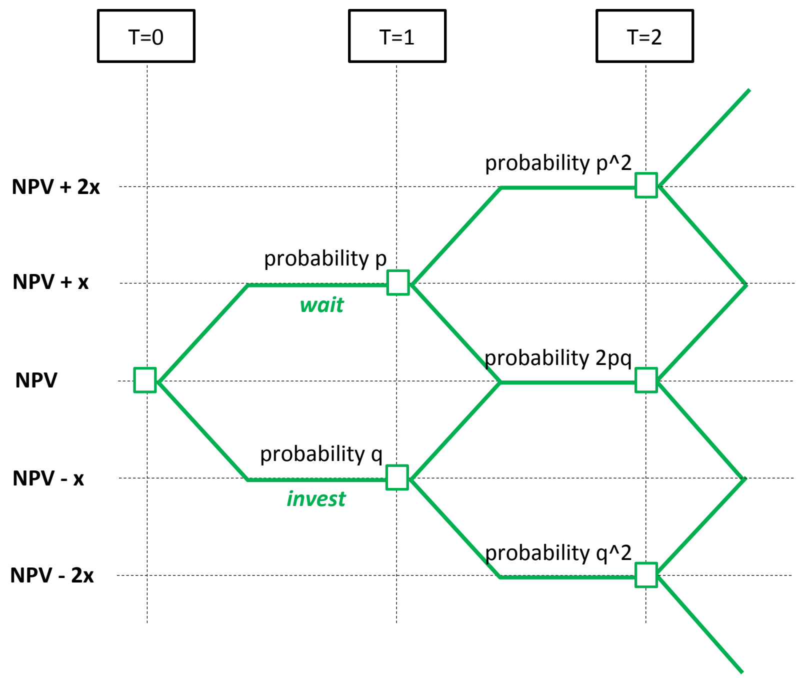


Figure 17: Sequential decision for real option investment based on Dixit & Pindyck (1994)

3.3. Insights and limitations

The utilization of any of the three current models would inform the decision by privileging a perspective over another. A decision considering the façade configuration and delivery process alone, could lead to the selection of a retrofit option with least interruptions on the building operation, regardless of its cost. A lifecycle assessment would facilitate the decision by using a cost benefit analysis, which privileges cost over other measures. Although the Living Building Concept proposes the definition of value as a good measure for decision-making, the question is left open on how to really quantify the project value. A real options approach to the sustainable investment monetizes value. It is in essence an optimization method in which the uncertainties affecting financial performance are made explicit. However this approach has the added difficulty of defining risk profiles. It has also been argued that real options may not reflect all the characteristics of real investments (Kogut 1991; Bowman et al. 2001). An environmental approach to the retrofit problems seeks to identify sensitive parameters that affect the physical behavior of the retrofit system. This approach privileges solutions that have the most impact on the energy model, which usually focus on HVAC system improvements. This approach may reduce the decision to a system optimization problem with energy consumption as objective function.

Facades solutions require a more holistic approach. Approaches that incorporate expanded performance indicators such as productivity and human comfort still utilize simple models for the financial performance quantification. In the field of real estate management and other domains that view the building retrofit as an investment, the physical parameter that affect performance are over-simplified. The physical performance dimension is crucial in any analysis of façade retrofit. Therefore, our research focuses on integrating these three dimensions to avoid the limitations of a single perspective. The methodology proposed in this dissertation combines existing models into a larger framework. The main contribution is the application to a specific retrofit type, the building façade. This type of retrofit is a complex problem which could potentially make a significant impact on the overall valuation of the building. In contrast to other studies discussed in Chapter 2, this research attempts to fill a gap in the approach to façade retrofit decision by a) incorporating multiple stakeholders' objectives in the selection process; and b) quantifying uncertainties in three dimension of performance, to make façade retrofit decision with more confidence, insight and risk-awareness.

3.4. **Integrated performance dimensions for the evaluation of a façade retrofit**

A façade retrofit decision necessitates the evaluation of three dimensions that impact the costs and benefits. Figure 18 shows the integrated framework that describes the relationship between delivery process, environmental performance, and investment performance for a façade retrofit technology. The retrofit delivery performance involves a) demolition and installation, as part of the modification of the existing façade or the construction process of a new system; and b) the surrounding tasks of staging and temporarily altering the building operation. Environmental performance refers to the quality and functioning of the retrofit system. Financial performance measures the predicted gain resulting from environmental performance and the cost of the retrofit delivery process. These three dimensions are interrelated. The retrofit delivery process influences both the environmental and financial performance measures. Environmental performance directly affects financial performance. Financial performance impact the choices made for the retrofit delivery process.

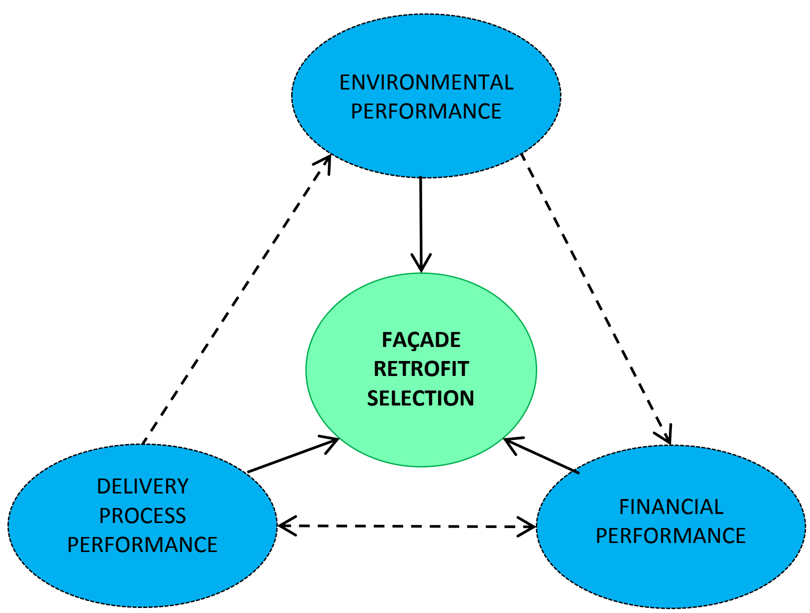


Figure 18: Dimensions of a facade retrofit decision (dashed lines: influence direction; solid lines: information direction)

Indicators have been identified for major aspects of building performance. Ruck emphasized the link between building performance and human performance, where human responses to a building environment are categorized based on four aspects: thermal comfort, indoor air quality, acoustical comfort, and visual comfort. A referenced list of performance indicators for energy use, costs, global environment, and occupant comfort is found in Kolokotsa et al. (2009) and Guan (2006). Indicators for facility management have been categorized as “hard” founded on environmental science, and “soft” related to environmental psychology (Pati et al. 2009). Another well-known indicator for the building envelope is the Overall Thermal Transfer Value (OTTV) which is part of AHSRAE’s 90-75 Standard (Guan 2006). Indicators of building intelligence have also been proposed, identifying the following criteria to evaluate the building façade: environmental performance, user comfort, work efficiency, technological performance, and cost effectiveness (Wong et al. 2008). The concept of building intelligence has also been discussed in the context of building stock and retrofit actions, to include indicators of value for the cultural and social impact of buildings (Kua et al. 2002; Kohler et al. 2003). Quantification of value has also been discussed as part of contract negotiations, as the aggregation of “measurable performance aspects such as form (aesthetics), function (e.g. capacities) and technical quality (e.g. energy consumption) (de Ridder et al. 2005). The following sections describe performance criteria and indicators relevant to a façade retrofit.

3.4.1. Environmental performance criteria

The environmental performance of a building is dependent of the activities of the building users. Therefore, when dealing with the quantification or energy savings, human comfort must be considered. The calculation of energy saving is the difference between energy consumed before and after the retrofit. The calculation of energy consumption is anchored on the assumption of thermal equilibrium, where thermal energy lost or gained is equalized by the energy produced from a mechanical system to maintain a desired internal temperature range.

Human comfort is contextual, linked to people's experience and expectations in a specific environment (Ruck 1989). For example, visual comfort and discomfort are linked to light levels, flicker, glare, shadow generated by the light source, and veiling reflections created by the properties of the lit surfaces. The quantification of Daylight Autonomy is an indicator defined as the percentage of time where artificial lighting is not required. Visual Comfort Probability, VCP, is used in the United States to calculate the percentage of occupant experiencing visual comfort and compare luminaires (IESNA 2000). Research on thermal comfort uses various statistical methods to quantify comfort considering the occupant behavior within an environment. There are two widely used-approaches to quantifying thermal comfort. The skin heat balanced approach calculates the range of comfort for occupants of a climatic chamber, founded on the steady state heat transfer theory (Fanger 1967; Gagge et al. 1976; de Dear et al. 1989). Two indexes serve as scales to evaluate thermal comfort: the Predicted Mean Vote (PMV), described in the ISO 7730 standard, and the Predicted Percentage Dissatisfied (PPD). Researchers have shown that comfort levels not just depend on the local indoor environment but vary based on climate, building type, and occupant gender and age, and location in the building (Choi et al. 2011). The adaptive approach thus uses statistical information from field surveys to quantify how human response changes and adapts to the indoor context (Brager et al. 1998). Schweiker et al. (2012) study the behavioral, physiological, and psychological aspects of the adaptive process to quantify Thermal Acceptance. Another line of research aims to integrate the two approaches to quantify thermal comfort and support variability in acceptable comfort ranges (Nicol et al. 2002; Stoops 2004).

Thermal comfort parameters include air temperature, relative humidity, air velocity, clothing insulation, and the activity level of the occupants. The ASHRAE standard 55-2004 defines draft as a key source of thermal discomfort. The performance indicator DR or draft rate is used to quantify the percentage of people dissatisfied due to draft. Park et al. (2008) propose three performance indicators based on the quantification of the draft rate caused specifically by a hot or cold glazing surface, using Heisenberg's equation (1994):

$$\mathrm{PD} = 13800\left[\left(\frac{\bar{\mathrm{v}}-0.04}{\mathrm{t_a}}\right)^2 + 0.0293\right](\%)$$

Where, PD is the percentage of people who are dissatisfied due to draft from nearby glazed surfaces, t_a is the air temperature, and $\bar{v}$ is the mean air velocity. The authors use these indicators to quantify the acceptability of comfort for this condition: the percentage dissatisfied due to draft (PD), the average PD, and the percentage of hours within comfort range. The ASHRAE 55-2010 standard specifies a PD value of less than 20% to be within human comfort levels. This quantification of thermal comfort performance will be used in this dissertation, to study the changes in comfort levels associated to a façade retrofit. Of specific importance will be the changes in peak winter and summer months where the temperature difference between the exterior and interior environments tend to increase which often results in an increase in levels of discomfort.

3.4.2. Delivery process criteria

It is generally understood that the building lifecycle involves phases dealing with the design, construction and operation of the building facility, where the design and construction phases are also understood at the building delivery process. During the building operation, a retrofit improvement will involve a three-step delivery process: procurement, process, and result. Mbugua et al. (1999) provide an overview of performance indicators for these stages, where time and cost are used to measure various aspects such as profitability and productivity. Love et al. (2000) propose building lifecycle indicators considering stakeholder perspectives, but focused on different end-results, such as productivity and quality. Pillai et al. (2002) proposes an integrated performance index build around evolving concerns for the selection, execution, and implementation a building project. Takim et al. (2002) classify performance aspect for three building construction stages based on six project stakeholders: client, consultant, contractor, supplier, end-user, and community. These researches adopt a model by Cooke-Davis (2002) for construction performance, in terms of the effectiveness of the end result which is related to the efficiency of the delivery process. In their model, efficiency measures include safety, profitability, scheduling and budget requirements. Safety has been characterized as a measure of the number of accidents in the construction site (Teizer et al. 2008). Profitability is directly related to scheduling and budgeting. The quantification of scheduling performance can be expressed as the variance between the expected vs. the actual (or current) construction completion. Budget performance is based on the cash flow calculation. During construction, one of the main sources of uncertainty is the number of change orders and its impact on the project cost and the profit margin. Roper et al. (2005) suggest that the base contract cost should be separate from the cost associated to change orders. de Ridder et al. (2006) use a “dynamic model” with probability distributions for the quantification of benefit, as the difference between value and cost; and profitability, as the difference between price and cost.

3.4.3. Financial performance criteria

The Net Present Value of the retrofit investment aggregates and monetizes performance. Within this investment perspective, mean-risk models are typically used for performance assessments. These models traditionally use the variance σ^2, to measure the spread around the expected value μ, or mean (Markowitz 1952; De Wilde 2004). More recently researchers have looked at the importance that investors place on the frequency of exceptionally high or low returns which affect the "shape" of the distribution. For example, researchers have proposed risk measures to differentiate between the negative deviations and positive deviations from the mean (Fishburn 1977; Konno et al. 1991; Ogryczak et al. 1998; Ogryczak et al. 1999; Rockafeller et al. 2003). This area of research in investment risks considers the asymmetry of the output distributions, where the downside risk may be more important.

A review of the research in decision-making based on financial performance of building retrofit and the calculation of capital budget are presented in sections 2.3 and 3.2.3, respectively. To properly account for risks due to the energy costs, the quantification of the NPV using Real Options Analysis has been used for the evaluation of retrofit investments. The spread and asymmetry from the expected value can be considered by calculating the kurtosis (k) and skewness (s) of a distribution with *n* output samples.

$$k = \frac{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \mu)^4}{\sigma^4} - 3$$

$$s = \frac{n}{(n-1)(n-2)}\sum_{i=1}^{n}\left(\frac{x_i - \mu}{\sigma}\right)^3$$

The time horizon for the investment will be a 20-year period. The NPV will be calculated for an initial investment in the façade retrofit construction in an investment scenario where the externally financed capital and annual operation costs, and rental revenue are discounted to the present value.

3.5. **Analytic framework**

With the integration of three aspects of performance and the quantification of uncertainty, the purpose is to provide a methodological framework to guide façade retrofit decisions with more confidence, insight and risk-awareness. Figure 19 presents an integrated analytical framework for façade retrofit decision-making. The proposed framework does not intend to provide a complete account of all the drivers for a retrofit investment, but rather to support communication and collaboration. The framework involves three mains tasks: identification of a decision case, the quantification of performance, and risk-aware decision analysis.

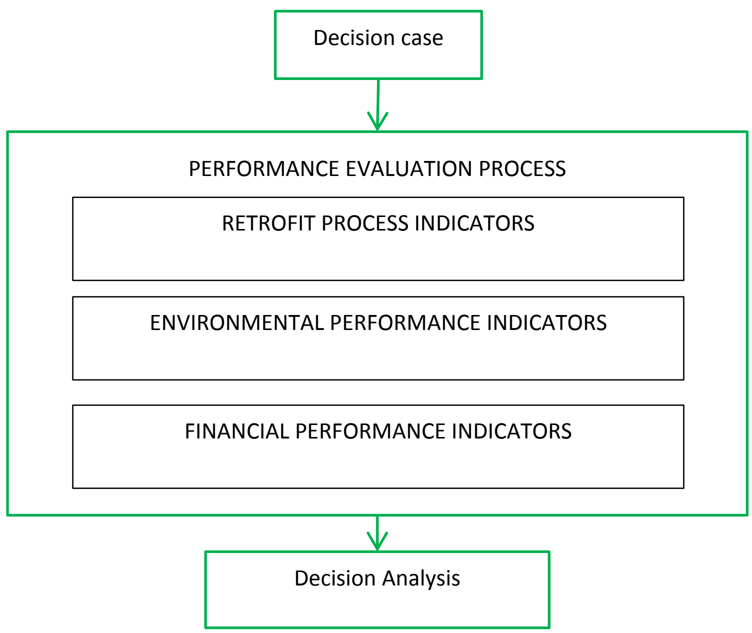


Figure 19: Framework for a façade retrofit decision

3.5.1. Decision case scenarios considering investment models

The proposed framework involves the identification of a discrete decision to retrofit a non-structural façade system. The current financing models create complex relationship between various stakeholders impacted by the retrofit investment decision.

For example, the Managed Energy Service Agreement reduces the impact of first cost to the building owner but paces the cost to the tenant. Therefore overall calculation of cost and benefits needs to be adjusted according to the impact of the retrofit financing model on the perception of value. Table 4 shows the decision stakeholders involved in the retrofit decision based on the financial models discussed in section 2.3.1. The building owner and/or the tenant are typically the recipients of the energy savings, except in the case of the Managed Service financial models, where the bank or lender is the recipient. Although the retrofit measure may bring considerable savings, research has shown that building owners are reluctant to commit to a retrofit because of lack of information and incentives (Beheiry et al. 2006; Bloom 2010; Dyer 2011). For other stakeholders involved in the retrofit investment decision, such as lending institutions, taking calculated risks in an uncertain financial market is a necessary part of the process (McCaffree 2010; Supple et al. 2010). For these large portfolio owners, the return on an investment is considered in the larger context of portfolio diversification and the state of the market (Markowitz 1952; Sharpe 1964).

Table 4: Stakeholders in the retrofit decision, based on financing model

decision stakeholders	PACE	Managed services	On-Bill Tariff	On-bill Loan	Government Bank	EPC	Equipment lease
Building Owner	x	x	x	x	x	x	x
Building Tenant	x	x					x
Energy Contractor	x		x	x			
Government Agency	x			x	x		
Energy Lender/Investor	x	x	x	x			
Utility Company		x	x	x			x
Energy Service Company						x	
Bank/Lender					x	x	x

3.5.2. Performance evaluation under uncertainty

Two sources of uncertainty affect the façade retrofit evaluation: exogenic sources, such as the effect of the financing model on the cash flow calculation; and endogenic sources, such as the physical behavior of the façade retrofit components.

Figure 20 shows how these uncertainties can be classified by their impact on investment and building performance assessments. Financial uncertainties in the investment assessment are linked to four sources: government financial incentives, interest payment depending on the financing model, initial investment of retrofit construction, and the cost savings due to improved building performance. Cost savings from the façade retrofit are obtained using an energy model for the building performance assessment. Four other sources affect this calculation: uncertainty in the scenario assumptions, physical behavior of the building systems, simplifications, and errors inherent in the energy model abstraction.

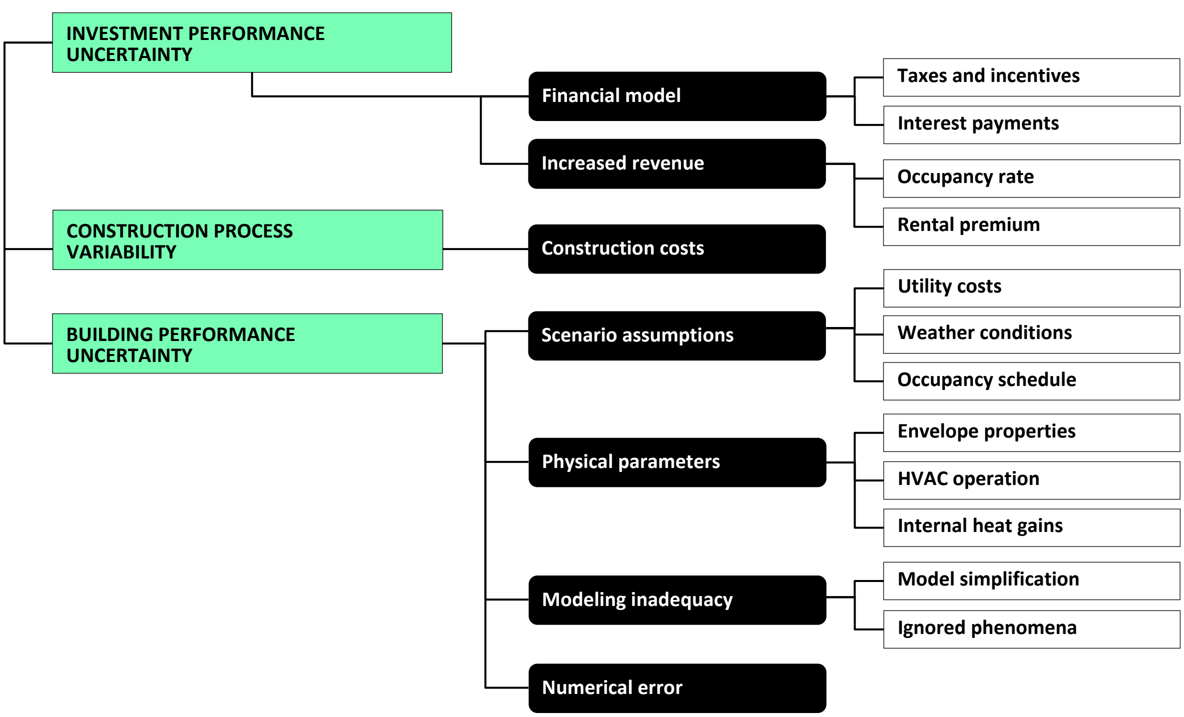


Figure 20: Sources of uncertainty in a facade retrofit evaluation

- **Envelope properties and energy consumption**

There are many physical causes affecting a building's environmental performance. The major source of energy consumption in residential and commercial buildings is attributed to loss during the generation, transmission, and distribution of electricity (source EIA). In residential buildings a façade retrofit to improve energy efficiency may focus mainly on improving the insulating properties of the façade to reduce heating and cooling demand. In commercial buildings façade retrofit emphasis is placed on controlling sunlight and solar heat gain. In the commercial sector, energy costs represent approximately 30% of the operations costs of which a third is attributed to the solar heat gain through the building façade (Murray 2006). In addition, recent research has found that air infiltration through the building envelope is directly responsible for the energy consumed and lost in heating and cooling a building (Emmerich et al. 2005). Uncontrolled air leakage through the envelope is due to air pressure differentials (Figure 21), holes in the envelope, or gaps where two subsystems meet, such as the façade and the roof, or a window in an exterior wall (Table 5). When air leaks, it carries vapor which results in moisture infiltration or exfiltration causing additional impacts to the building's indoor air quality and the occupants' thermal comfort. Air infiltration is also associated to the operation of windows and doors in the building.

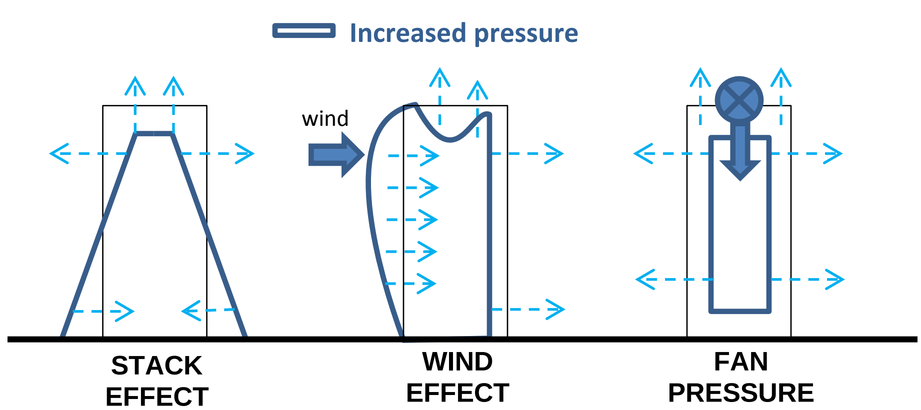


Figure 21: Classification of air pressure causing air leakage in the façade

Table 5: Classification envelope retrofits to reduce air leakage (adapted from Woods (2007)

Importance	Building area	Examples
1	Top of building	Façade/roof intersections; and other roof penetrations.
2	Bottom of building	Vents and service penetrations; and underground parking entry points.
3	Vertical shaft	Egress doors; elevator shafts; plumbing and other service penetrations.
4	Openings in the exterior wall	Window or door framing and weather-stripping; and exhaust fans.
5	Compartmentalization	Vented mechanical rooms; airlocks; and other unique environments.

- **Thermal comfort and profitability**

The recent retrofit of the Empire State Building involved the retrofit of the façade and systems to improve the interior comfort levels and increase the marketability of the property (Lockwood 2009; ESBC 2012). This type of financial investment in commercial retrofits calls attention to the marketability of sustainable buildings and the relationship between occupant comfort and profitability. Table 6 shows the recent research in the valuation of sustainable buildings. Profitability in sustainable buildings is categorized into market value, occupancy rates, and general cash inflow. These studies have shown a premium for buildings with sustainability ratings, with profitability increases between 4.8% to 17% for office rental properties and 6% for residential apartments.

In the case of facade retrofits, resulting improvements in the thermal comfort of the building occupants could also increase profitability. Other research studies point to the relationship between thermal comfort and energy use. For example, Papadopoulos et al. (2002) monitor the comfort level in the Greek building stock in conjunction to energy use patterns. The authors propose energy efficiency measures to improve the thermal properties of the buildings' envelope and retrofit the heating systems to achieve an average 28% energy savings. Occupant behavior has also been identified as a key factor in improving energy consumption in buildings (Papakostas et al. 1997; Haas et al. 1998; Wood et al. 2003; Andersen et al. 2009; Gill et al. 2010). For example, Blight et al. (2011) conduct a sensitivity analysis to examine the relationship of occupant behavior and energy use in a Passivhaus rated apartment building. The authors find that the room set-point temperature to be the most significant contributor to energy use. Rijal et al. (2007) quantify the effect of operating windows using the adaptive approach to thermal comfort (Humphreys et al. 1998). A 7% reduction in heating demand is obtained when occupants operate windows to achieve comfort. Klein et al. (2012) develop and agent-based simulation to incorporate the input of occupant thermal comfort preferences in a building control strategy. They find the percentage energy savings can reach up to 12.17% with an optimized set point temperature to improve comfort levels 5% above the baseline.

Other studies have also looked at thermal comfort and work productivity. Wyon (1993) and Clements-Croome (2006) provide good reviews of the literature on the levels of productivity of office workers and the relationship to room temperature. For example, Tham et al. (2003) find a 5% increase in productivity in room where the temperature is lowered 2K below the level of thermal comfort. Toftum et al. (2005) also find reduced productivity in room where the temperature is raised 4K above the comfort level. Wargocki et al. (2006) study the productivity of children in school buildings. They find that reducing the temperature by 1°C improves performance in school work between 2 and 4%. Occupant health or wellbeing has also been identified as a key factor in improving productivity (Robinson 2005; Turner 2005). Kats (2003) reports on the increased productivity in LEED rated buildings in California. The author quantifies increased productivity between 36.89 and 55.33 $/ft2

The current body of research identifies energy efficiency and productivity as function occupant thermal comfort. Thus an increase in occupant thermal comfort associated with a facade retrofit will also increase profitability. For a rental apartment, profitability will probably be reflected in energy savings and rental income.

Three studies show evidence in the valuation of sustainable buildings due to rental income. Miller et al. (2008) report on higher occupancy rates and rental rates in buildings with a LEED or Energy Star rating. Fuerst et al. (2008) also quantify the rental premium associated to sustainability ratings. Eichholtz et al. (2009) provide a clear link between energy efficiency and rental income in office buildings. In their study of 8182 rental buildings, an average 6% rental premium was found in buildings with an energy star rating.

However one study has found that energy use is higher in rented vs. owner-occupied apartments when the cost of energy is included in the rent (Leth-Petersen et al. 2001). In addition, rental income in green or sustainable buildings has high volatility which can affect the expected revenue over time. Das et al. (2011) review the premium in LEED rated rental value between 2007 and 2010. Fluctuations in quarterly profitability occurred when the financial market was down, with sustainable buildings having higher rental rates of 2.4%. Jaffee et al. (2010) compared the effect of energy factors on the market price of 548 Energy Star-rated office rental properties, based on three types of leasing structures. These researchers find fluctuation in profitability, dependent on city hub, with an average net operating income 11.96$/ft2 with a standard deviation of 7.02$/ft2. They also find an average price of 183.66 $/ft2 with a standard deviation of 108.8 80 $/ft2, and a fluctuation in the capitalization rate between 2001 and 2010 ranging from 2.8% to 13.14%, with an average of 7.71%.

In addition, rental price volatility is also a result of the specific characteristics and attributes of the rental property such as the floor area construction type, and proximity to local amenities. A recent study finds that volatility increases on the return on real estate investment for apartment buildings in U.S. cities with larger concentration (Luo 2011). Deng et al. (2012) review 697 buildings with a Green Mark rating in Singapore. Their study shows that although attributes such as floor area and construction type increase volatility in the market price, the yield from condominiums with Green label is higher than other housing types.

Finally, improvements to occupant thermal comfort in a building undergoing energy efficiency measures will increase its value. Although the quantification of energy savings can be directly linked to thermal comfort, the estimation of rental revenue needs to consider for volatility over time. Therefore the rental premium used to calculate rental revenue will be treated as another uncertain parameter in the cash flow calculation of the façade retrofit investment.

Table 6: Current research in sustainability valuation, developed based on Newell et al. (2011) and Sayce et al. (2010)

Value category & Sustainable rating	Building type	Profitability	references
Selling market value			
Energy performance certificate (The Netherlands)	Residential	+2.8%	(Brounen et al. 2011)
MINERGIE rating (Switzerland)	Residential apts.	+3.5%	(Salvi et al. 2010)
Tokyo green labeling (Japan)	Residential apts.	+6.0 to 11.0%	(Yoshida et al. 2010)
Green Mark rating (Singapore)	Residential	+4%	(Deng et al. 2012)
LEED or Energy Star rating	Residential	+3.0% to 9.6%	(Griffin et al. 2009)
LEED rating Energy Star rating	Office	+11.1% +13.0%	(Eichholtz et al. 2009; Eichholtz et al. 2010)
LEED or Energy Star rating	Office	+31.0 to 35.0%	(Fuerst et al. 2008; Fuerst et al. 2011)
Rental market value			
MINERGIE rating (Switzerland)	Residential apts.	+6.0%	(Salvi et al. 2010)
NABERS rating (Australia)	Office	+9%	(Newell et al. 2011)
LEED rating Energy Star rating	Office	+5.9% +6.6%	(Eichholtz et al. 2009; Eichholtz et al. 2010)
LEED or Energy Star rating	Office	+6.0%	(Fuerst et al. 2008; Fuerst et al. 2011)
Energy Star rating + other amenities	Office	+4.8 to 5.2%	(Pivo et al. 2008; Pivo et al. 2010)
LEED or Energy Star rating	Office	+7.0 to 17.0%	(Wiley et al. 2010)
Occupancy rates			
LEED rating Energy Star rating	Office	+8.0% +3.0%	(Fuerst et al. 2008; Fuerst et al. 2011)
Energy Star rating +other amenities	Office	+0.2 to 1.3%	(Pivo et al. 2008; Pivo et al. 2010)
LEED or Energy Star rating	Office	+10.0 to 18.0%	(Wiley et al. 2010)
Cash inflow			
Energy Star rating +other amenities	Office	+2.7 to 8.2%	(Pivo et al. 2008; Pivo et al. 2010)

3.5.3. Risk-aware decision analysis

Research in behavioral finances has found that decision-makers' approach to risk is contextual (Cyert et al. 1963; Wolf 1977). To accommodate varying approaches to risk, Mukherji et al. (2008) propose to use of three reference values instead of a single performance benchmark, and to replace the value-related weight space by a two-dimensional space (risk/return) used for scoring investment decisions. Nunez Nickel et al. (2002) provide a review of the research in risk-return relationship, from two theoretical perspectives, economic and organizational. A risk-averse approach exemplifies a positive relationship between risk and return, where the decision stakeholder will accept a proportional increase between risk and return (Roy 1952; Fishburn 1977). In line with a risk-averse investment approach, the quantification of the NPV using Real Options Analysis has been used for the evaluation of retrofit investments, to properly support delaying risky investments. For example, Menassa (2011) examines the options available to decision-makers over an extended period of time, and the possibility to manage risks by staging the implementation of retrofit strategies. In contrast, a risk-seeking approach, involves a negative or curvilinear relationship between risk and return (Bowman 1980; Bowman 1982). In terms of decisions toward sustainable buildings, Verbruggen et al (2011) make a distinction between risks due to randomness and lack of knowledge. These authors argue that, although the implementation of energy efficiency measures may seem risky, the "irrevocability and preclusion" of energy efficiency investment should be considered more closely in the face of climate change.

The integrated framework proposed in this dissertation accommodates varying approaches to investment risk. For the selection of a façade retrofit alternative, the final evaluation for retrofit selection involves:

- **Determination of two reference values: minimum risk threshold, Tr, and a confidence target, Tc.**

- **Quantification of confidence and risk for each scenario as follows:**

$$P_{confidence} = \Pr\{y \geq Tc\}$$

$$P_{risk} = \Pr\{y < Tr\}$$

Where, y is the normalized improvement in the Net Present Value (NPV) of the façade, i.e. the NPV of the retrofit investment divided by the NPV of a base case or existing condition.

- **Selection of the retrofit alternative based on Pconfidence and Prisk.**

3.6. Conclusion

This chapter introduces the conceptual framework for evaluating a façade retrofit proposal base on product delivery, and environmental and financial performance. A key aspect of this approach is to incorporate uncertainties in the evaluation process to raise the confidence level in the decision made by the project stakeholders. It is also important to consider the threshold of confidence and risk of the stakeholders involved in the decision. Because of the many financing models available, the configuration of the decision makers varies. This framework will be tested and validated in the subsequent case study

CHAPTER 4
CASE STUDY: RISK-BASED PERFORMANCE ASSESSMENT FOR A RESIDENTIAL FAÇADE RETROFIT

4.1. **Introduction**

A façade retrofit decision is multidimensional and requires examination of several aspects. This chapter examines the application of this integrated performance method for a real case: the decision to retrofit a residential façade. The case study is organized in four sections: 1) description of the base case, retrofit scenarios, and performance criteria; 2) modeling and quantification of benefits, costs, and risks with each scenario; 3) retrofit decision analysis; and 4) conclusions.

The case study is based on a real building conditions and potential retrofit alternatives. This study demonstrates how the integrated risk-analysis framework and methodology can be implemented to support decision-making with more than one uncertain measure. The selected case examines competing stakeholder preferences and considerations of what is a valued benefit, including savings, comfort, and costs. The case study provides an example analysis where a large range of uncertainty is quantified, to address the complexity between alternatives and to support a transparent rational decision.

4.2. **Residential multi-family building retrofit**

In the residential market sector, the façade of a multi-family "high-end" residential building is to be retrofitted, to reduce the energy bills of the current tenants. Three energy retrofit scenarios involving changes in the window wall façade were examined.

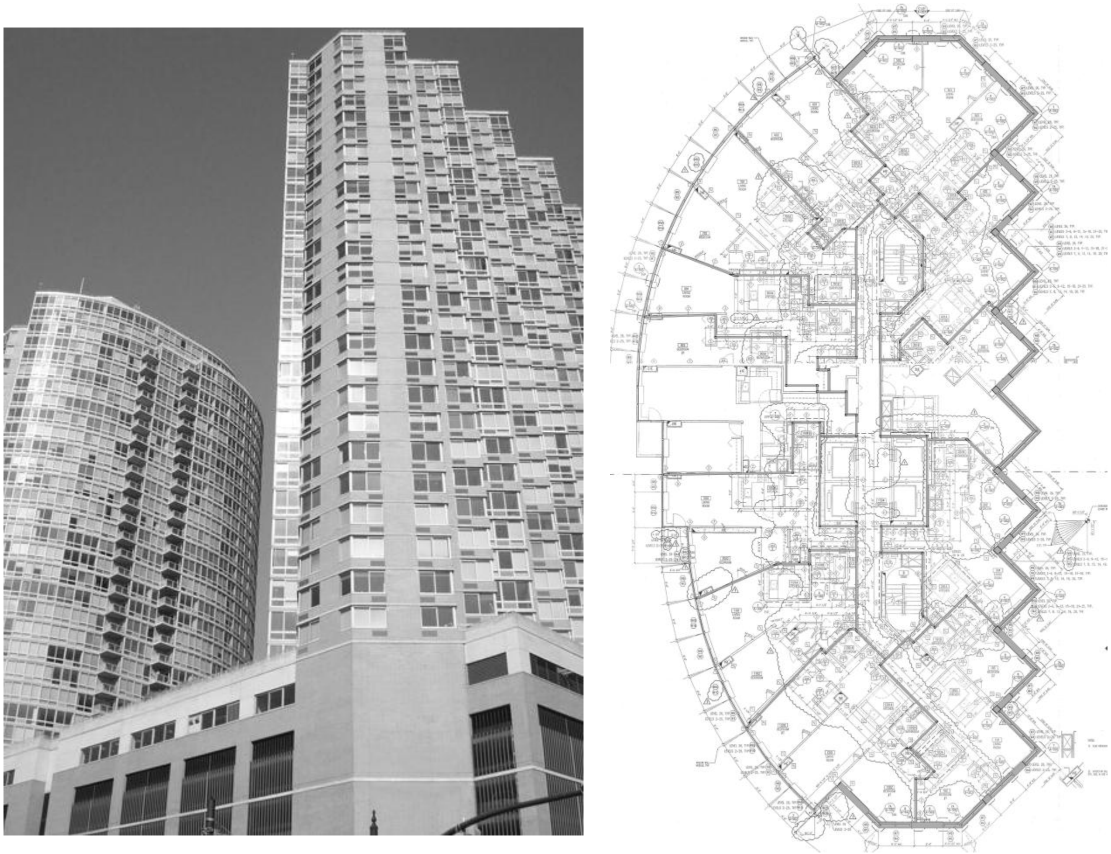


Figure 22: Residential building case, facade view and typical floor plan

- **Building name: Liberty View Towers**
- **Location: 33 Hudson Street, Jersey City, NJ 07302**
- **Year of construction: 2001**
- **East Façade: brick veneer wall with aluminum framed window and exposed concrete floor slabs**
- **West Façade: aluminum framed window wall with exposed concrete floor slabs**
- **Floor area: 2023 m2 per floor**
- **Number of apartments per floor: 12**
- **Number of floors: 37 stories with 28 levels for apartments**

The building is an example of multistory residential building constructed at the turn of the millennium (Figure 22). The building has 8 levels of parking and other residential amenities, 28 levels of apartments, a mechanical floor with access to the mechanical equipment at the roof level. This building was considered a prototypical residential building in an urban setting, the building façade consist of a window wall system with single pane glass and an exposed floor slab without a thermal break (Figure 23).

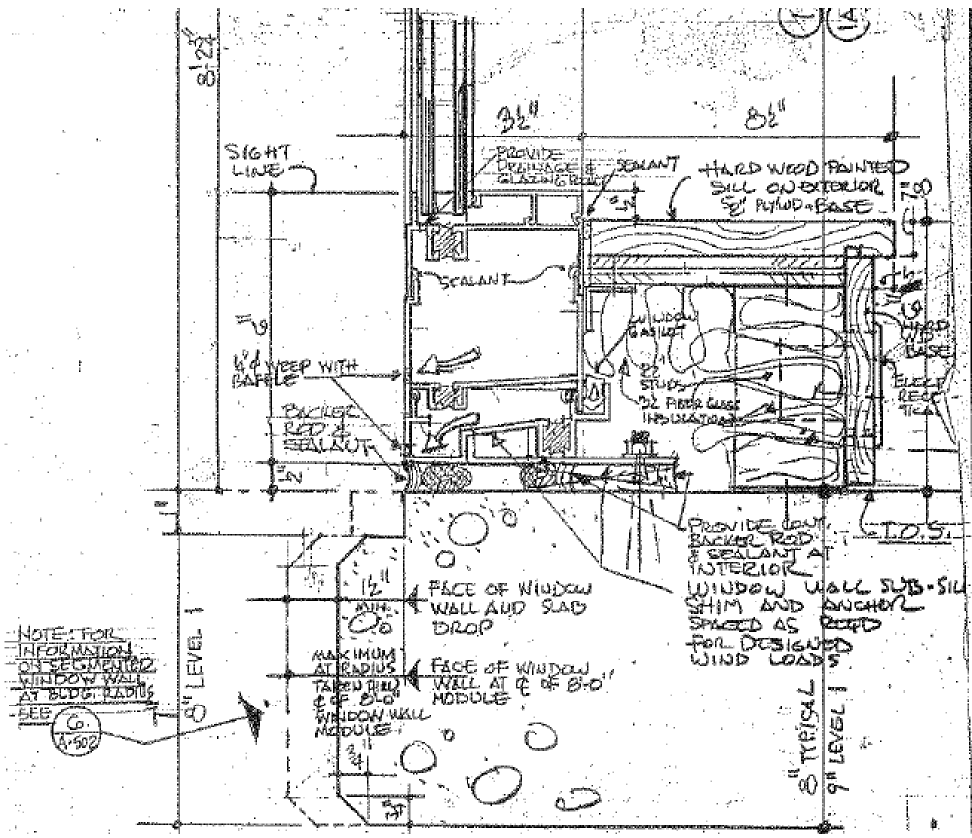


Figure 23: Facade detail of window frame and exposed floor slab

Façade retrofit improvements are geared to reduce heat transmission. Current inhabitants have complained of the very high utility bills. The façade is to be retrofitted to update the aesthetic appearance of the building and reduce the impact on energy consumption. Adding a new internal layer to the façade or replacing façade components are considered viable alternatives based on the potential to reduce energy use and the associated implementation costs. Table 7 provides list of the energy efficiency scenarios for the façade, including a description of the retrofit measures and financial models.

Table 7: Retrofit scenarios considered in the case study

Scenario	Retrofit measure	Retrofit delivery	Financing model
1	Low-e storm window through DOE bulk program (~25% reduced leakage)	Typical energy efficiency	PACE
2	Low-e storm window and air seal (~60% reduced leakage)	Deep retrofit	PACE
3	Window and packaged terminal heat pump (PTHP)	Deep retrofit	MESA

To provide an integrated performance evaluation, the performance criteria for the case study include the quantification of five performance indicators within the three categories of retrofit delivery and construction, environmental, and financial performance:

- Retrofit cost: it is expected that the retrofit delivery and implementation cost per floor area will not exceed 50 $/m2.
- Annual Energy Savings: it is expected that the estimated electricity use will be reduced by 20%.
- Thermal comfort: it is expected the level of comfort and number of hours the building occupants are comfortable will be increased by 10%.
- Cash flow: it is expected that the yearly energy use will be reduced by at least 10%.

4.3. **Modeling and quantification**

The analysis method for each retrofit scenario involves uncertainty analysis and comparison with a pre-retrofit base case. First, an uncertainty and sensitivity analysis are conducted to identify the most sensitive window parameters impacting of the façade. A base case model of the window assembly is created in Therm 5 (LBNL 2012). Appendix A provides a detailed description of the modeling process. This model output U-value and Solar Heat Gain Coefficient (SHGC) are included in the set of uncertain parameters consider in the energy model created in Energy Plus. Second, uncertainty analysis to quantify the uncertainties in the energy use prediction and the quantification of retrofit investment costs. Parameter variability is considered through Monte Carlo sampling using SimLab (SAMO 2004).

Table 8 through Table 11 show a list of the modeling assumptions, for the uncertain parameters in the base case and three retrofit scenarios. Parameters are classified into physical façade parameters, building system and operation parameters, and financial cost parameters. For the cost analysis parameters, the National Residential Efficiency Measures Database (NREL 2012) was consulted to determine the associated first costs for each scenario. COP values for the new PTHP units conform to the Federal Energy Conservation Standards for PTHPs in effect in 2012. The estimated utility variability was obtained from the Annual Energy Outlook projections to 2030.The National Institute of Standards and Technology (NIST) escalation rates for the cost of electricity were used for Net Present Value calculations (Rushing et al. 2011). Other financial parameters were fixed including the 5% discount rate stipulated for PACE financing.

Table 8: Uncertain parameters in the base case (pre-retrofit condition)

	Facade parameters	min	max	unit
X1	IGU SHGC	0.493	0.495	
X2	IGU thermal conductivity	2.186	2.213	W/m2-K
X3	air leakage @ 75 Pa	0.001	0.047	m3/s.m2
X4	brick cladding: conductivity	0.635	0.943	W/m-K
X5	brick cladding: density	1670.000	1770.000	kg/m3
X6	brick cladding: specific heat	657.000	1017.000	J/Kg-K
X7	concrete block: conductivity	257.950	258.050	W/m-K
X8	concrete block: density	671.000	719.000	kg/m3
X9	concrete block: specific heat	789.000	1173.000	J/Kg-K
X10	GWB: conductivity	0.346	0.514	W/m-K
X11	GWB: density	1452.000	1524.000	kg/m3
X12	GWB: specific heat	768.000	1148.000	J/Kg-K
	Operation parameters	min	max	unit
X13	cooling set point	22.500	25.500	C
X14	heating set point	19.500	22.500	C
X15	PTHP heating COP	2.220	2.700	
X16	PTHP cooling COP	2.442	3.082	
X16	occupant heat gain	81.000	207.000	W/person
	Cost parameters	min	max	unit
X17	electricity	0.080	0.12	$
X18	occupancy rate	0.90	0.99	
X19	escalation rate for eneergy cost	annual factors established by NIST		

Table 9: Scenario 1 parameter values

Uncertain parameters in Scenario 1		min	max	unit
X1	IGU SHGC due to added storm window	0.435	0.454	
X2	IGU thermal conductivity due to added storm	1.351	1.423	W/m2-K
X3-X19	Same as pre-retrofit condition			
X20	Air leakage reduction factor due to air seal	0.710	0.770	
X21	Storm window installation cost	10.00	15.00	$/ft2
X22	Air seal cost	0.23	0.60	$/ft2
X23	Rent premium	0.06	0.10	
Fixed financial parameters		Expected value		unit
	PACE Loan Period	20		years
	PACE Annual interest rate (%)	5		
	Analysis period	20		years
	Inflation Rate (%)	3		
	Real discount rate (%)	5		

Table 10: Scenario 2 parameter values

Uncertain parameters in Scenario 2		min	max	unit
X1	IGU SHGC due to added storm window	0.435	0.454	
X2	IGU thermal conductivity due to added	1.351	1.423	W/m2-K
X3-X19	Same as pre-retrofit condition			
X20	Air leakage reduction factor due to air seal	0.400	0.450	
X21	Storm window installation cost	10.00	15.00	$/ft2
X22	Air seal cost	1.1	4.7	$/ft2
X23	Rent premium	0.06	0.10	
Fixed financial parameters		Expected value		unit
	PACE Loan Period	20		years
	PACE Annual interest rate (%)	5		
	Analysis period	20		years
	Inflation Rate (%)	3		
	Real discount rate (%)	5		

Table 11: Scenario 3 parameter values

Uncertain parameters in Scenario 3		min	max	unit
X1	IGU SHGC due to replacement window	0.26	0.40	
X2	IGU thermal conductivity due to	1.476	1.703	W/m2-K
X3-14	Same as pre-retrofit condition			
X15	PTHP heating COP due to replacement unit	3.3	3.7	
X16	PTHP cooling COP due to replacement unit	3.3	3.7	
X17-19	Same as pre-retrofit condition			
Uncertain financial parameters		min	max	unit
X20	Window replacement and installation cost	21.00	41.00	$/ft2
X21	New PTHP replacement and installation cost	1322	1696	$/unit
Fixed financial parameters		Expected value		unit
	MESA Loan Period	10		years
	MESA Annual interest rate (%)	5		
	Analysis period	20		years
	Inflation Rate (%)	3		
	Real discount rate (%)	5		

4.3.1. Retrofit costs

Figure 24 shows the raw outcomes per sample (horizontal axis) the spread in results for the estimated costs for the retrofit delivery and construction in all three scenarios. Table 12 compares the expected value, tendency, and spread for each scenario. Figure 25 shows the frequency distribution and Figure 26 the cumulative frequency for each retrofit cost scenario.

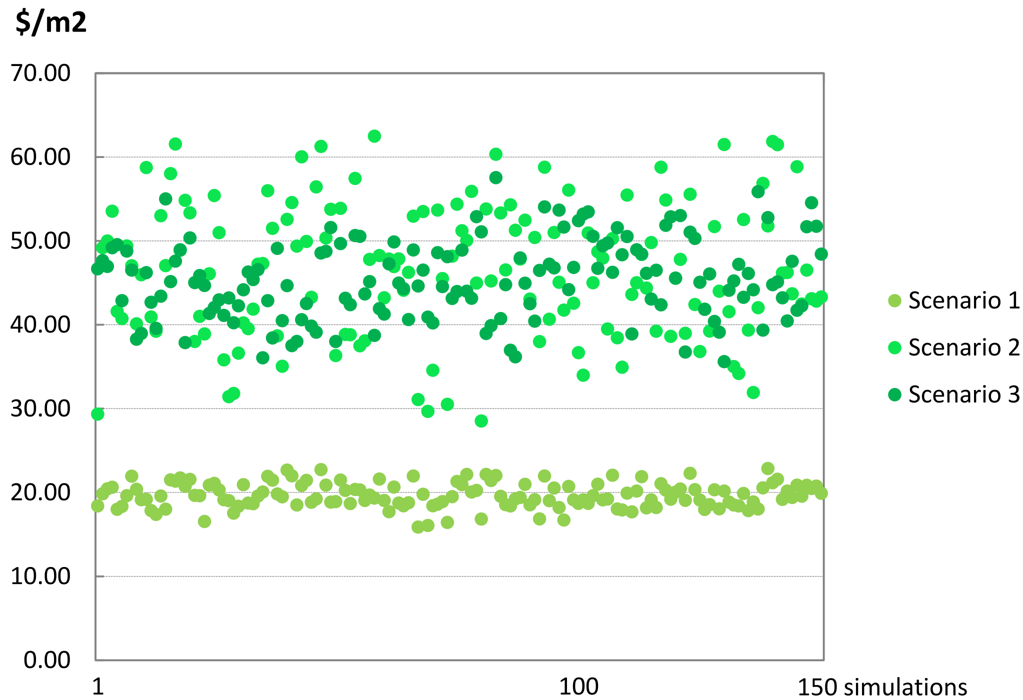


Figure 24: Estimated retrofit cost

Table 12: Mean (μ), standard deviation (σ), kurtosis (k), and skewness (s) for each retrofit delivery cost scenario

Retrofit cost	μ	σ	unit	k	s
Scenario 1	19.65	1.46	$/m2	-0.337	-0.050
Scenario 2	46.40	7.97	$/m2	-0.0640	-0.064
Scenario 3	45.39	4.71	$/m2	-0.0582	0.125

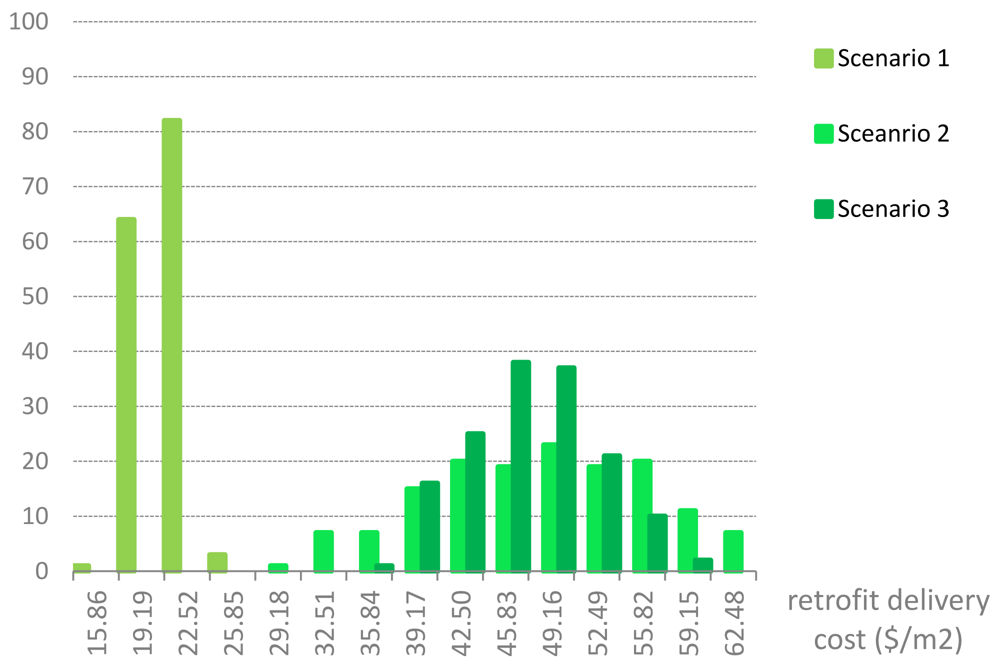


Figure 25: Histogram for each retrofit cost scenario

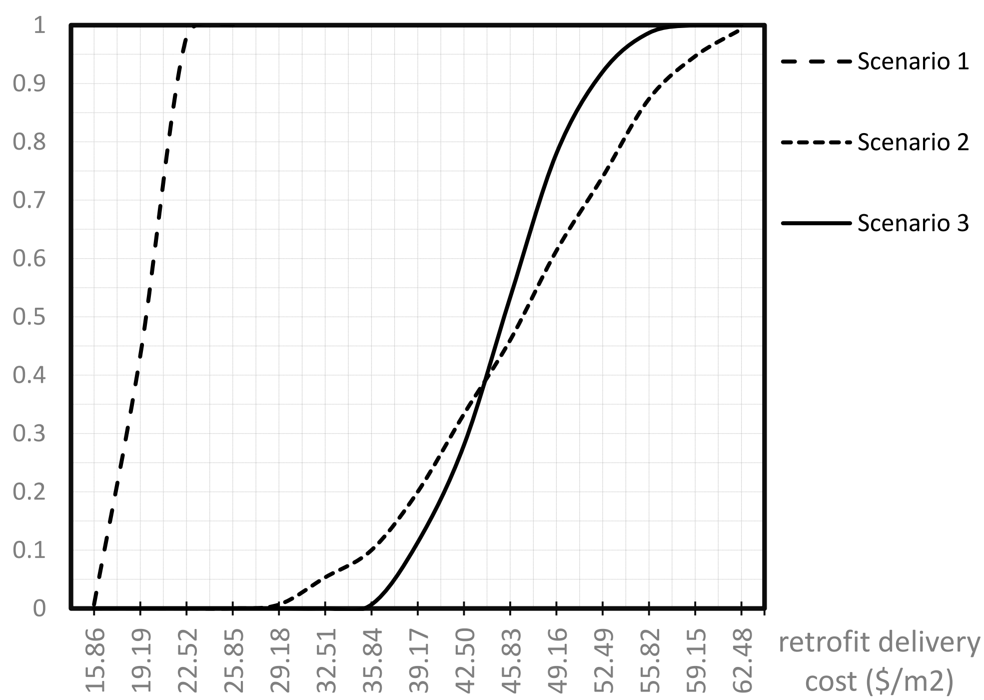


Figure 26: Cumulative frequency the retrofit delivery cost

Result observations for retrofit costs:

- Retrofit scenario 1, which adds a new low-e storm window and reduces air leakage by approximately 25%, has the lowest cost and the narrower margin of error.
- Retrofit scenario 2, has the largest margin of error among the three options.
- There is a lot of overlap in the cost results between scenarios 2 and 3, which means that in terms of costs, adding a new low-e storm window and with an air leakage reduction of 60% will cost as much as replacing the window and changing the PTHP window unit.

4.3.2. Annual Energy Savings

Figure 27 shows the raw outcomes per sample (horizontal axis) with the spread in results for the energy use for the base case and the three retrofit scenarios. Results were normalized by the conditioned area of the building. The energy savings for each scenario are calculated as the difference between the energy use between the case and each retrofit scenario. Table 13 compares the expected value, tendency, and spread for each energy savings scenario. Figure 28 shows the frequency distribution and Figure 29 the cumulative frequency for the percentage energy savings in each retrofit scenario.

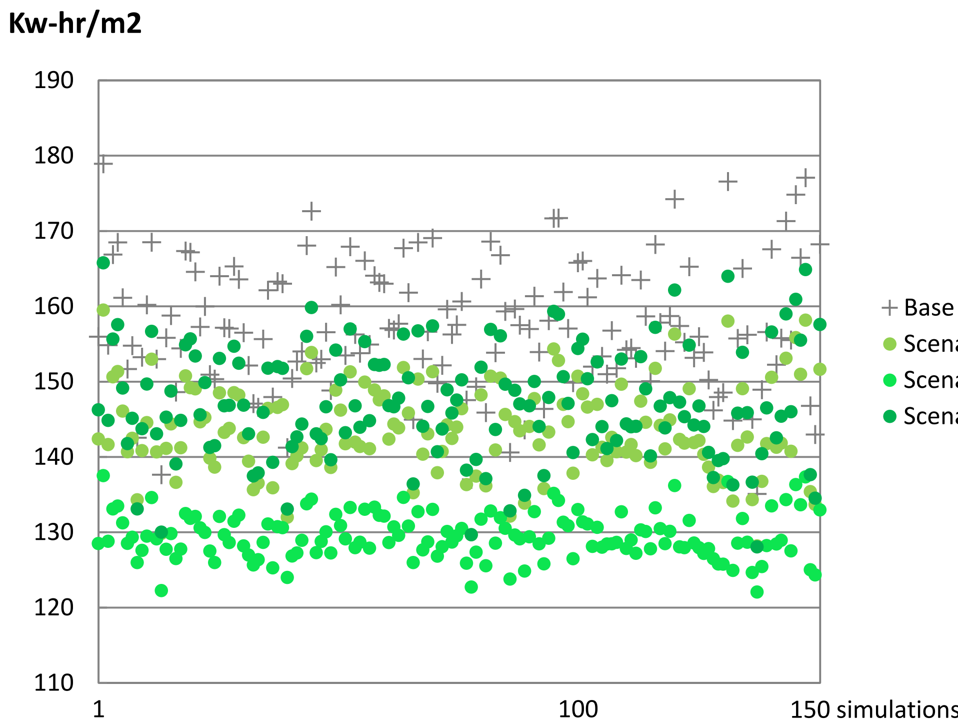


Figure 27: Estimated annual energy use per building floor area

Table 13: Mean (μ), standard deviation (σ), kurtosis (k), and skewness (s) for each energy saving scenario

% energy savings	μ	σ	k	s
Scenario 1	8.69	1.20	0.064	-0.391
Scenario 2	17.57	2.60	0.078	-0.370
Scenario 3	6.47	0.45	0.502	0.154

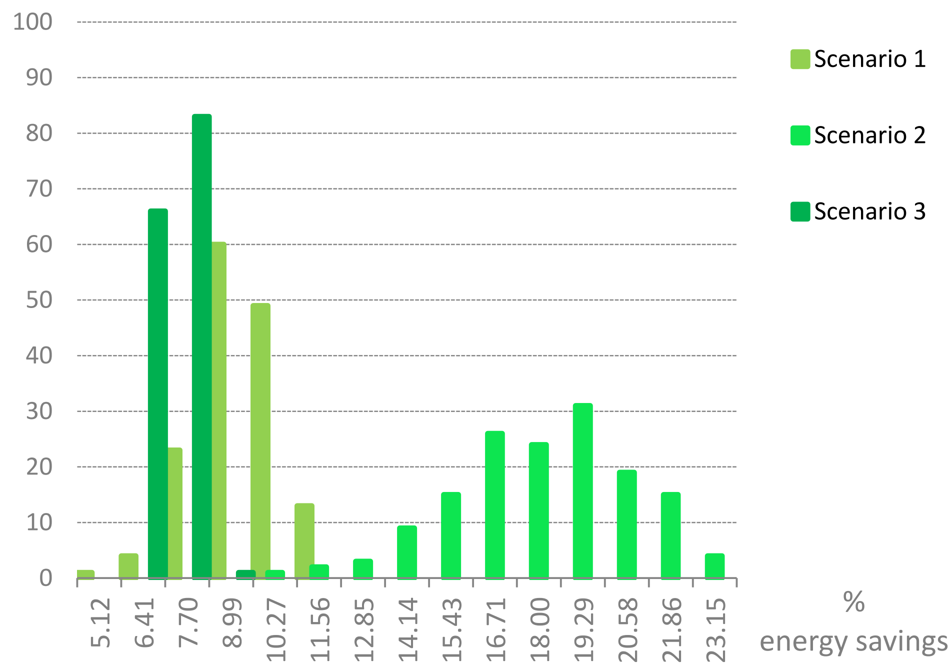


Figure 28: Histogram for each retrofit savings scenario

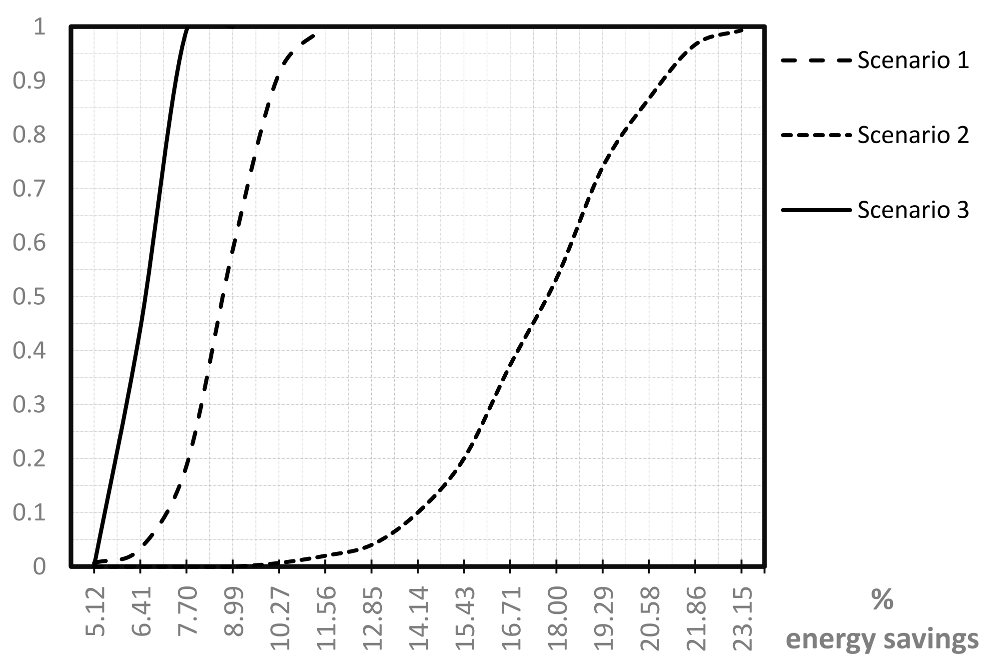


Figure 29: Cumulative frequency for the percentage energy savings

Result observations for annual energy savings:

- Retrofit scenario 2, which adds a new low-e storm window and with an air leakage reduction of 60%, has the largest percentage of energy savings, ranging between approximately 10 to 23%.
- Retrofit scenario 3, which replaces the windows and the PTHP units, has the narrower margin of error.
- There is a lot of overlap in the results between scenarios 1 and 3, which means that in terms of savings, adding a new low-e storm window and with an air leakage reduction of 25% has the potential of producing the same amount of energy savings' as replacing the window and changing the PTHP window unit.
- There is also overlap in the results between scenarios 1 and 3, and the base case results.

4.3.3. Thermal comfort

The month of January and August were selected as the peak months for the winter and summer calculation respectively. Figure 30 shows the raw data with the spread in results for the hours of comfort in the winter for one apartment in the building (apt c). Table 12 through Table 17 show the results for 6 selected apartments to compare heating and cooling comfort in different locations in the building.

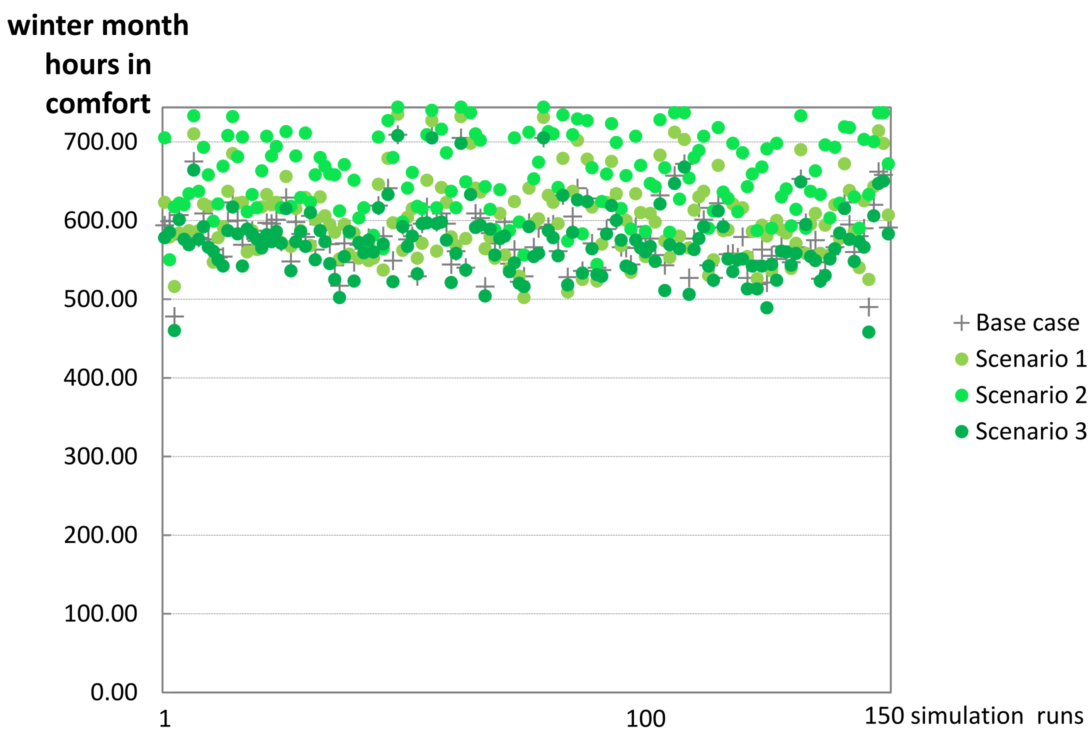


Figure 30: Hours in comfort for peak winter month in one apartment

Table 14: Mean (μ) and standard deviation (σ) for the level of heating comfort in each scenario

	Apt. a		Apt. b		Apt. c		Apt. d		Apt. e		Apt. f	
WINTER hourly average % satisfied (100-PD)	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
Scenario 1	78.05	3.19	81.64	3.82	81.83	3.07	82.26	2.39	83.96	2.45	75.06	2.96
Scenario 2	81.71	4.34	86.06	3.59	85.08	3.64	85.18	2.87	86.71	2.61	77.36	4.31
Scenario 3	76.62	2.71	79.05	3.20	79.95	2.50	80.83	2.19	82.42	2.14	74.80	3.05
Base Case	76.97	2.62	80.28	3.20	80.65	2.42	81.72	2.08	83.08	2.02	74.61	3.03

Table 15: Mean (μ) and standard deviation (σ) for the level of cooling comfort in each scenario

	Apt. a		Apt. b		Apt. c		Apt. d		Apt. e		Apt. f	
SUMMER hourly average % satisfied (100-PD)	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**	**μ**	**σ**
Scenario 1	97.34	0.33	97.25	0.33	97.06	0.34	96.96	0.34	96.80	0.33	97.52	0.31
Scenario 2	97.23	0.35	97.13	0.33	96.97	0.35	96.89	0.34	96.73	0.33	97.40	0.32
Scenario 3	97.48	0.30	97.41	0.32	97.20	0.31	97.08	0.35	96.95	0.33	97.65	0.30
Base Case	97.32	0.31	97.27	0.33	97.02	0.32	96.89	0.36	96.73	0.34	97.51	0.31

Table 16: Mean (μ) and standard deviation (σ) for the percentage of time comfortable in winter

	Apt. a		Apt. b		Apt. c		Apt. d		Apt. e		Apt. f	
WINTER % hours satisfied (PD< 20%)	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Scenario 1	74.11	7.63	82.19	7.47	80.93	6.79	81.31	5.17	83.90	5.54	67.23	6.57
Scenario 2	82.03	9.12	90.76	6.05	88.32	6.82	87.93	5.68	89.93	5.06	72.61	9.84
Scenario 3	69.89	6.10	76.28	7.08	76.83	5.68	77.73	4.38	80.46	4.46	65.43	5.49
Base Case	70.66	5.85	78.83	6.78	78.22	5.40	79.57	4.28	81.57	4.50	65.08	5.19

Table 17: Mean (μ) and standard deviation (σ) for the percentage of time comfortable in summer

	Apt. a		Apt. b		Apt. c		Apt. d		Apt. e		Apt. f	
SUMMER % hours satisfied (PD< 20%)	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Scenario 1	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00
Scenario 2	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00
Scenario 3	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00
Base Case	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00	100.00	0.00

The next set of results focus the winter comfort: Table 18 compares the level of comfort and Table 19 compares the number of hours in comfort for the six selected apartments. Figure 31 shows the frequency distribution and Figure 32 the cumulative frequency for the thermal comfort improvement.

Table 18: Mean (μ), standard deviation (σ), kurtosis(k), and skewness (s) for the percentage comfort level in the winter month across 6 selected apartments

WINTER % satisfied (100-PD)	μ	σ	k	s
Scenario 1	80.47	4.25	-0.244	-0.031
Scenario 2	83.68	4.86	-0.416	-0.542
Scenario 3	78.95	3.69	-0.129	-0.061
Base Case	79.55	3.88	-0.147	-0.215

Table 19: Mean (μ), standard deviation (σ), kurtosis(k), and skewness (s) for the percentage of time comfortable in the winter month across 6 selected apartments

WINTER % hours satisfied (PD< 20%)	μ	σ	k	s
Scenario 1	582.40	65.38	-0.177	-0.149
Scenario 2	634.36	71.86	0.340	-0.840
Scenario 3	553.82	56.57	-0.012	-0.089
Base Case	562.87	59.10	0.0197	-0.197

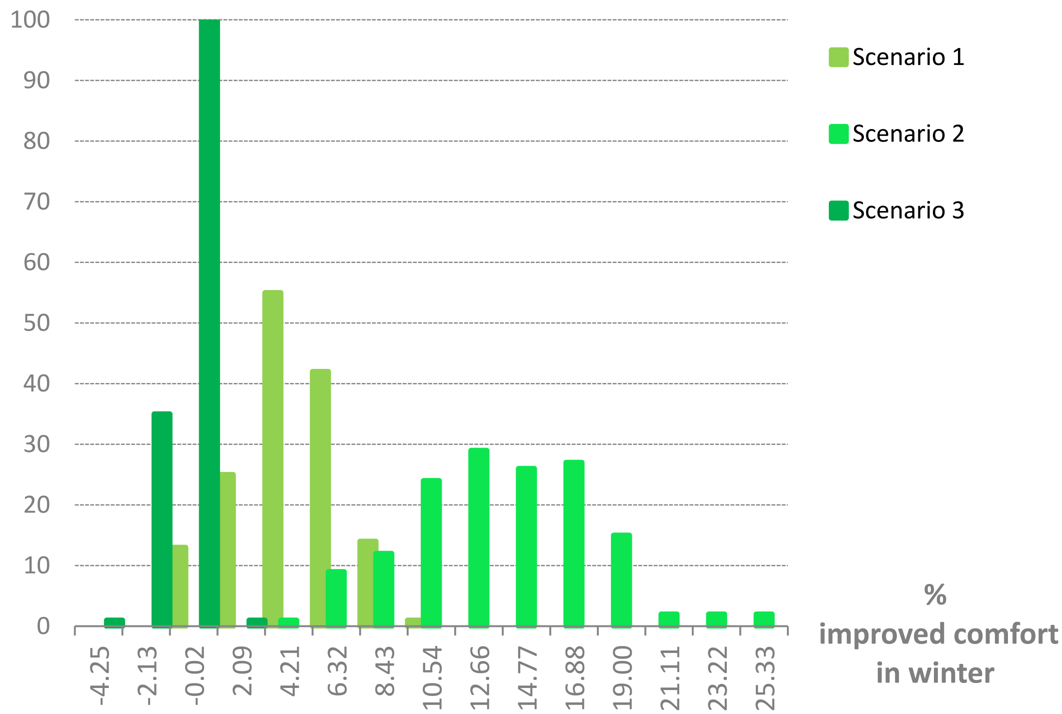


Figure 31: Histogram distribution for thermal comfort in winter for each retrofit scenario

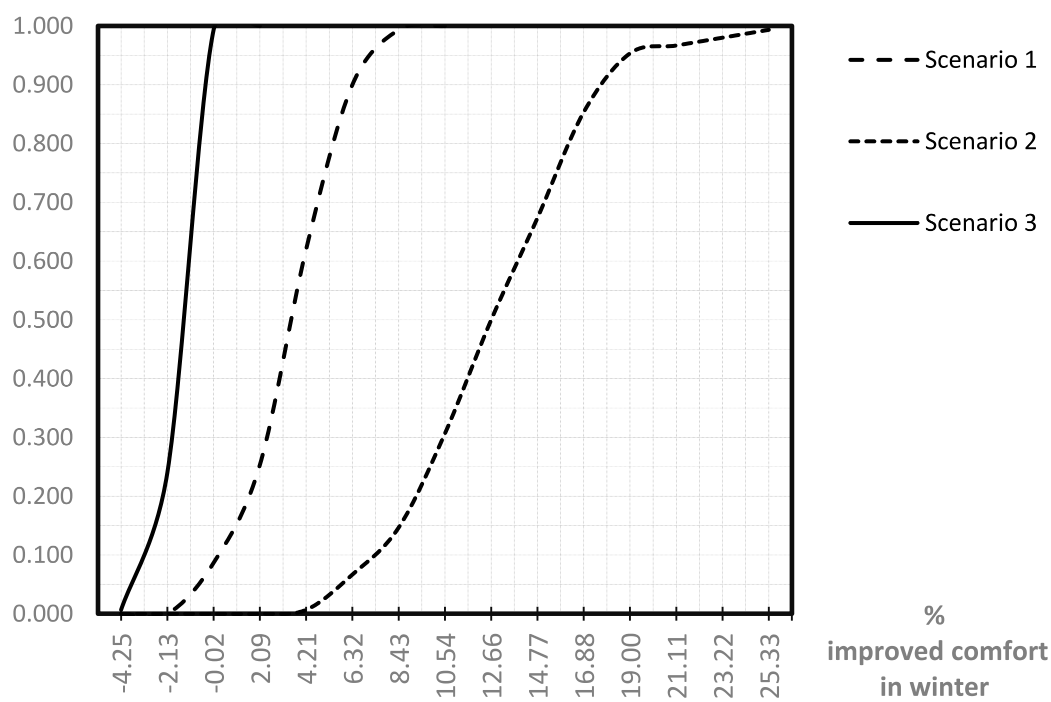


Figure 32: Cumulative frequency for the percentage improvement in thermal comfort

Result observations for thermal comfort in each retrofit scenario:

- For the selected peak summer month, the set of apartments evaluated show a high level of cooling comfort.
- Retrofit scenario 2, which adds a new low-e storm window and with an air leakage reduction of 60%, has the largest average percentage improvement in heating comfort, approximately 15% compared to the base case.
- There is a lot of overlap in the results between scenarios 1 and 3, which means that in terms of thermal comfort, adding a new low-e storm window and with an air leakage reduction of 25%, have the potential of producing the similar levels of comfort as replacing the window and changing the PTHP window unit.
- Results for Scenario 3 also show a decrease in the number of hours in winter comfort compared to the base case.

4.3.4. Net Present Value

This section presents the results for the present value of the cash flow after a 20-year period. Results for the building operation and scenario financial models are normalized per floor area, to facilitate comparison among cash flow components: energy use and Net Present Value (NPV). Appendix B provides a graphic description of the calculation.

Figure 33 shows the raw outcomes per sample (horizontal axis) with the spread in results for estimated present value of energy user after a 20-year period. Table 20 compares the expected value, tendency, and spread for each scenario. Figure 34 shows the frequency distribution and Figure 35 show the cumulative frequency for the present value of energy use. Figure 36 shows the frequency distribution for estimated reduction in energy use for each scenario.

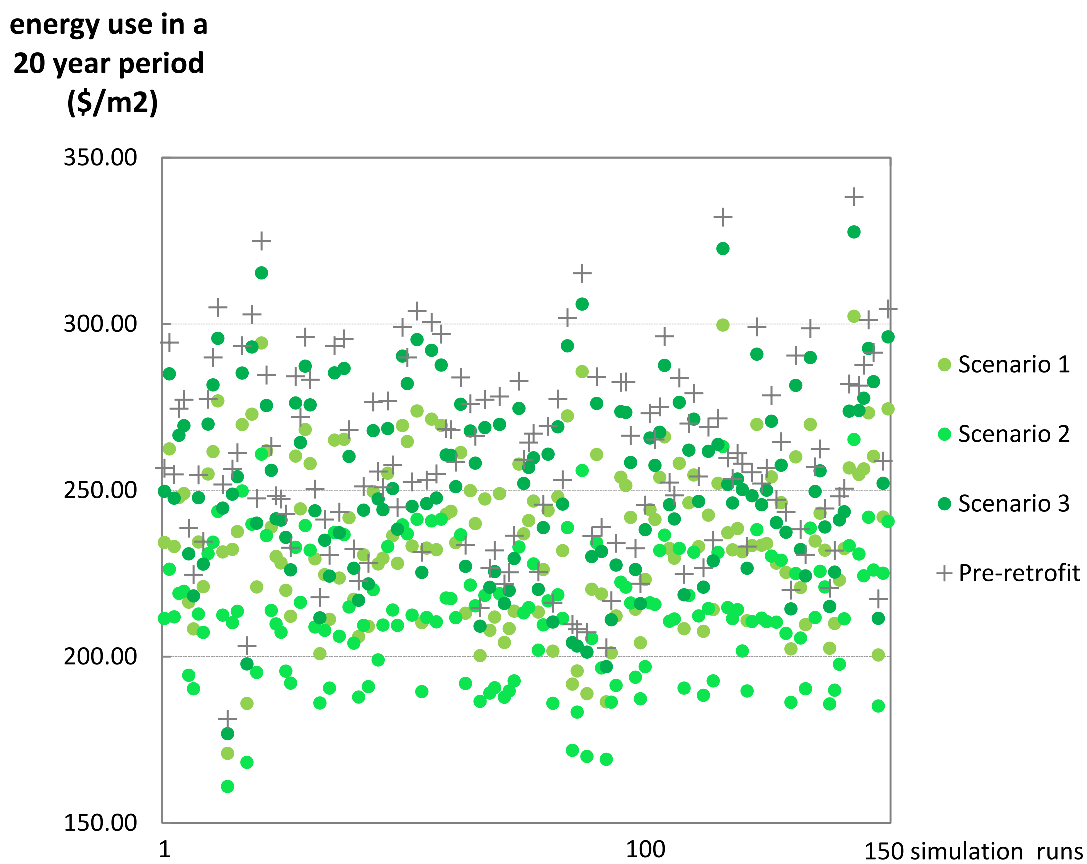


Figure 33: Aggregated cash outflow for the present value of energy use for a 20-year period

Table 20: Mean (μ), standard deviation (σ), kurtosis (k), and skewness (s) for the present value of energy use

PV energy use	μ	σ	units	k	s
Scenario 1	236.38	24.32	$/m2	-0.178	0.084
Scenario 2	213.12	20.01	$/m2	-0.163	0.011
Scenario 3	251.76	27.41	$/m2	-0.202	0.110
Base Case	259.09	28.46	$/m2	-0.211	0.108

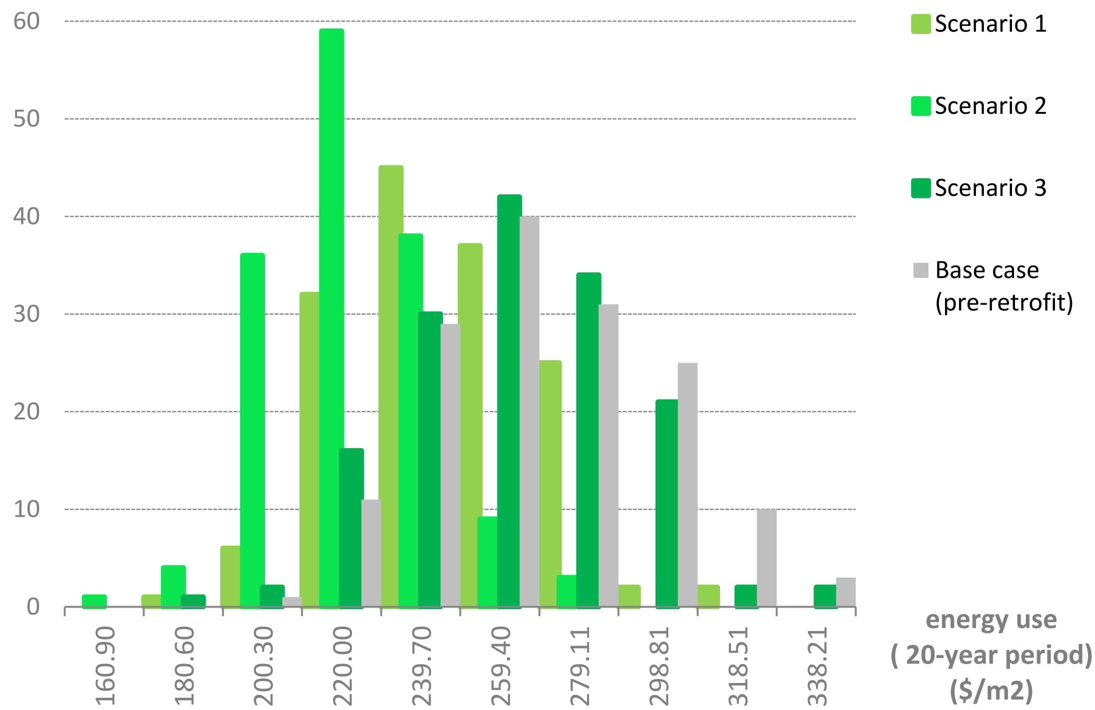


Figure 34: Histogram for present value of energy use

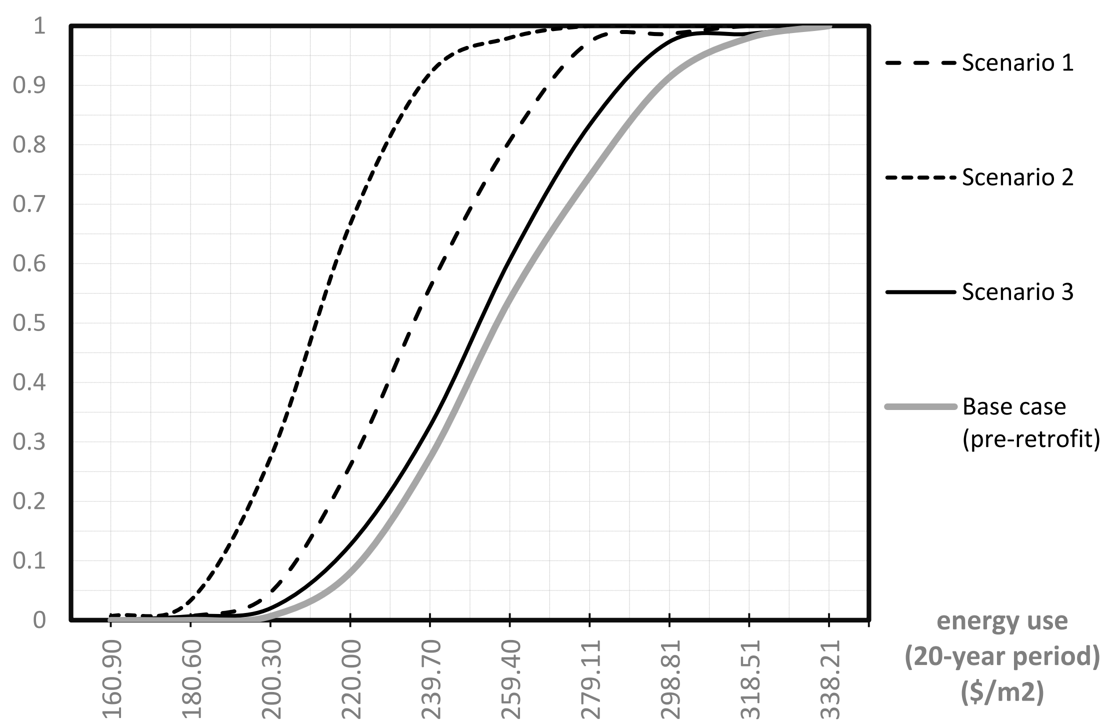


Figure 35: Cumulative frequency for present value of energy use

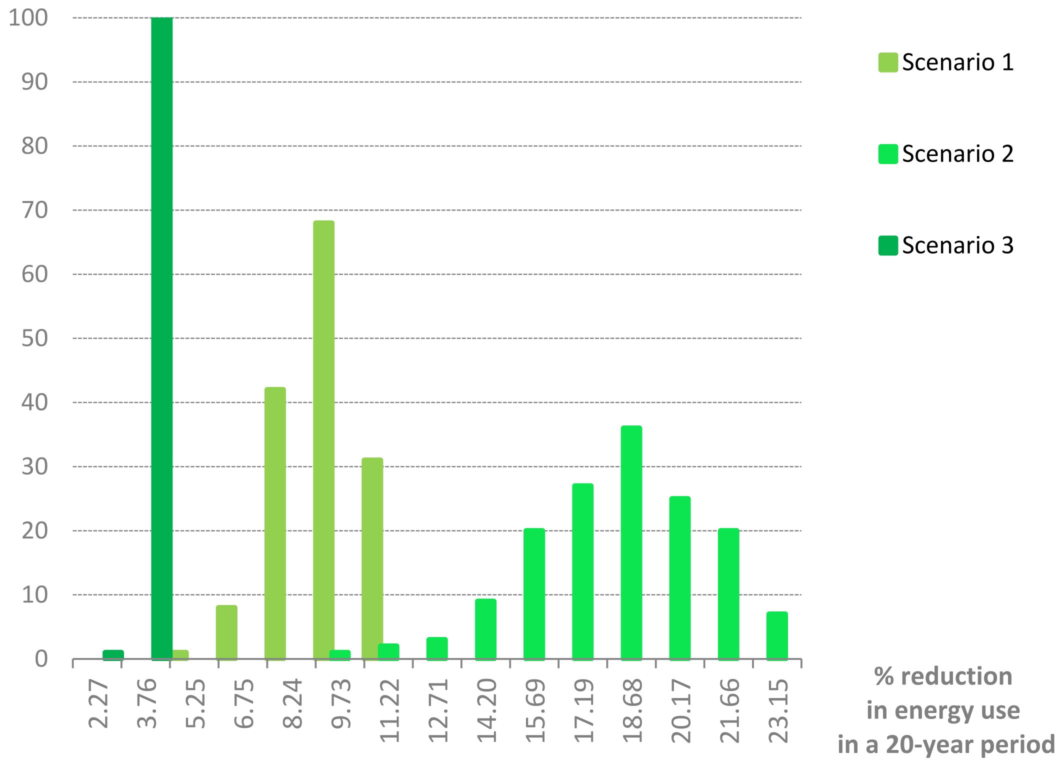


Figure 36: Histogram for the reduction in energy use for each scenario

Figure 37 shows the raw outcomes per sample (horizontal axis) with the spread in results for the present value of the retrofit investment for each scenario after a 20-year period. Table 21 compares the expected value, tendency, and spread for each scenario against the pre-retrofit base case. Figure 38 shows the frequency distribution function for estimated increase in revenue.

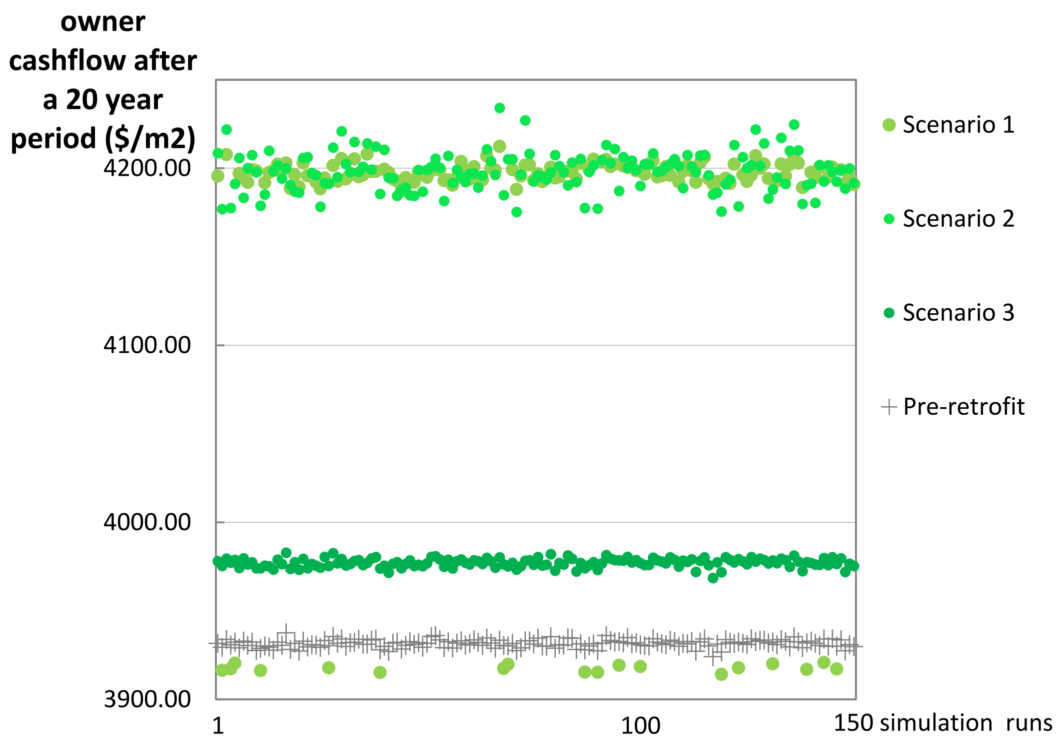


Figure 37: Aggregated cash flow after 20 years

Table 21: Mean (μ), standard deviation (σ), kurtosis (k), and skewness (s) for the present value of the retrofit investment

owner cash flow	μ	σ	units	k	s
Scenario 1	4163.93	91.11	$/m2	3.601	-2.351
Scenario 2	4197.94	10.89	$/m2	0.408	0.268
Scenario 3	3977.12	2.45	$/m2	0.270	-0.374
Base Case	3931.47	2.18	$/m2	0.330	-0.204

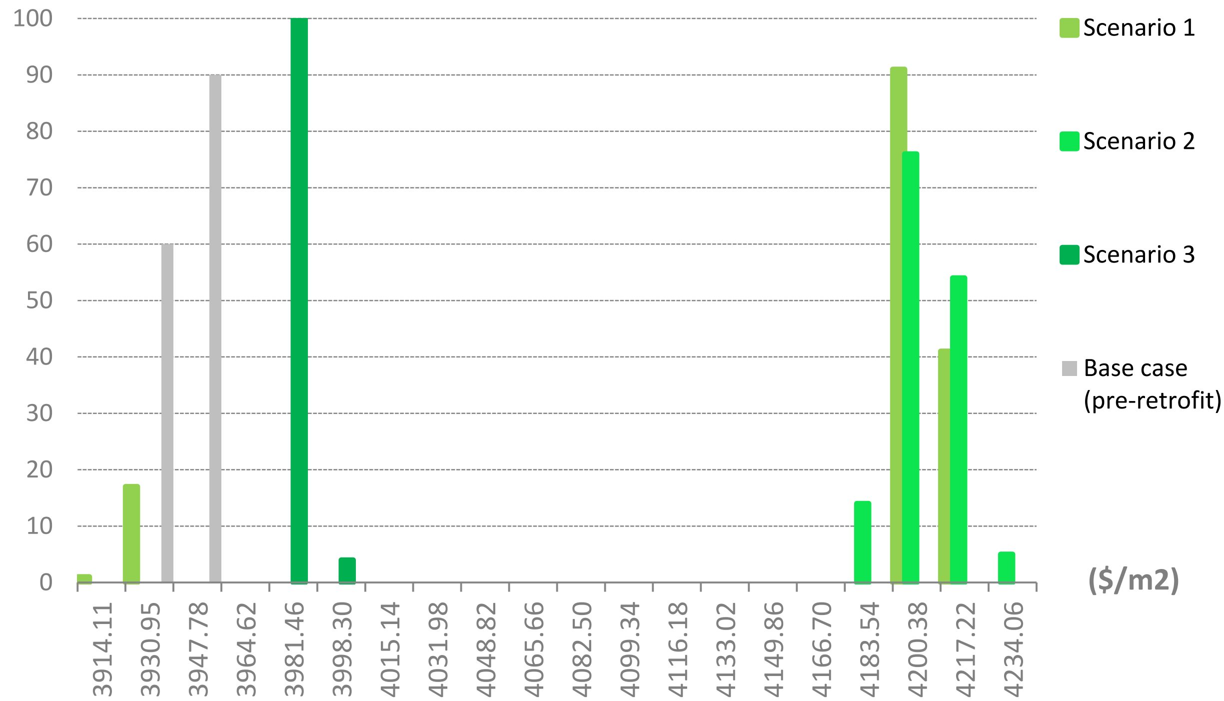


Figure 38: Histogram comparing the increase in income for each scenario after a 20-year period

Observations for the aggregated NPV results:

- In terms of energy efficiency, Scenario 2 shows the highest improvement. After a 20-year period it show a probability to achieve approximately a 20% reduction in energy use, Scenario 1 show a 10% reduction and Scenario 3 show a 5% reduction compared to the pre-retrofit base case.
- In terms of revenue, Scenario 1 and Scenario 2 show the highest increase in income. Scenario 1 shows a 7.64% increase, and Scenario 1 shows a 6.75% increase when compared to the revenue from the base case. This demonstrates that the rent premium in these scenarios would probably lead to more revenue for the owner.
- However Scenario 3 has the lowest overall cash flow of all three scenarios with a strong probability of an approximate 2% benefit after 20 years.

4.4. **Retrofit decision analysis**

Figure 39 compares the NPV results for each retrofit scenario in terms of the probability of improvement compared to the base case. The improvement in the NPV is calculated to measure the probability to be below a risk-threshold of 2% improvement, and the probability to be above a 7% confidence target.

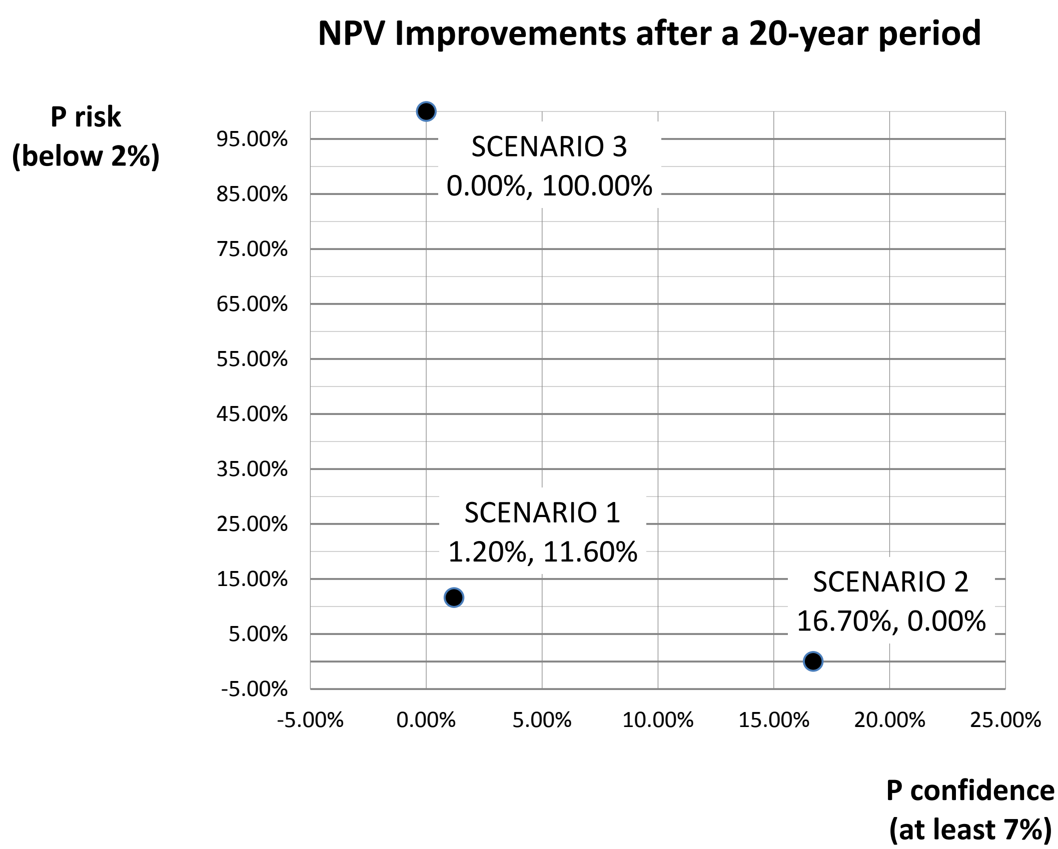


Figure 39 NPV comparison based on probability of confidence target and risk threshold

Observations for the retrofit performance results:

- Scenario 2 gets the top ranking, with a 16.7 % confidence in meeting the target NPV improvement and 0% risk of being below 2%.

- Scenario 1 has a 1.2 % confidence in meeting the target NPV improvement and 11.6% risk of being below 2%.
- Scenario 3 is the riskiest option because there is a 100% probability of being below 2% improvement.

4.5. **Discussion**

This case study tests the framework introduced in chapter 3 to analyze the performance of 3 retrofit scenarios in a residential façade retrofit. The case study is not intended to be representative of all the potential retrofit options in a residential building, nor does in resolves all issues related to multi-criteria decision making. The risk-based decision-making process is carried out using an uncertainty analysis at for façade model. The output distributions for the façade models were part of the parameter for an energy model using the building simulation engine Energy Plus to quantify the retrofit cost and energy consumption. A normative calculation was used to quantify thermal comfort associated to the cold draft due to the façade glazing. These comfort results are "monetized" but quantizing comfort to the rent premium factor that can be expected after the retrofit (see details in Appendix B). The net present value of the retrofit investment was calculated in terms of three cash flow components: rent revenue, retrofit cost and energy use. The predicted improvement in comfort was used in the quantification of rent premium based on the predicted improvement on comfort associated with each retrofit scenario.

To model and analyze the data for a residential façade retrofit case, models are created for the baseline case (pre-retrofit model) and three façade retrofit scenarios. Two simulation models of varying resolutions are combined: a detailed building façade was pre-analyzed and aggregated into the whole building energy model. These models provide data for the quantification of physical performance, which was then used in the quantification of financial performance. The estimation of risk in the retrofit performance assessment begins with uncertainty quantification. In an investment perspective, mean-risk models are typically used for performance assessments. In this research, we consider the asymmetry of the spread, by quantifying the skewness and kurtosis of the distribution (Figure 40).

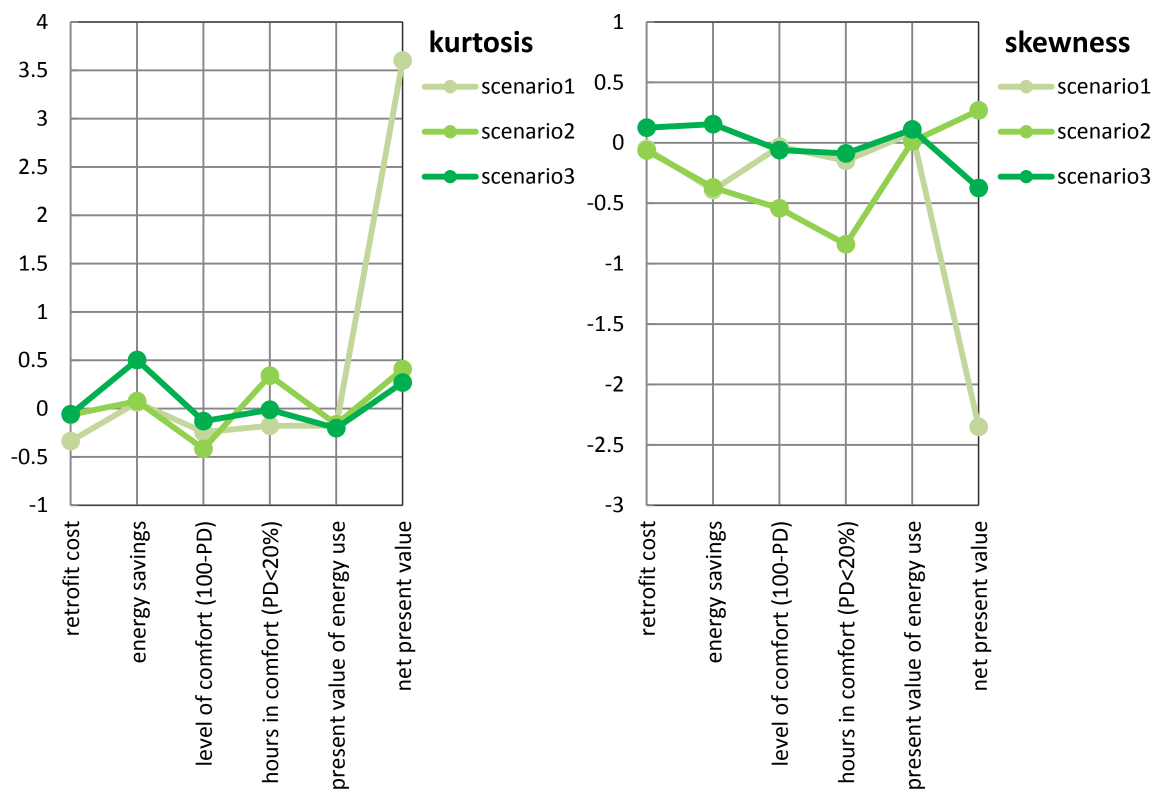


Figure 40: Plot of risk values for the performance indicator distributions a) kurtosis, b) skewness

The results confirm that a reduction in the façade air leakage will positively impact the energy efficiency of the building (Figure 41). Scenario 2 with an approximate 60% air-leakage reduction to the façade provides the most improvement in energy use. After a 20-year period, Scenario 3 shows the least improvement in energy use.

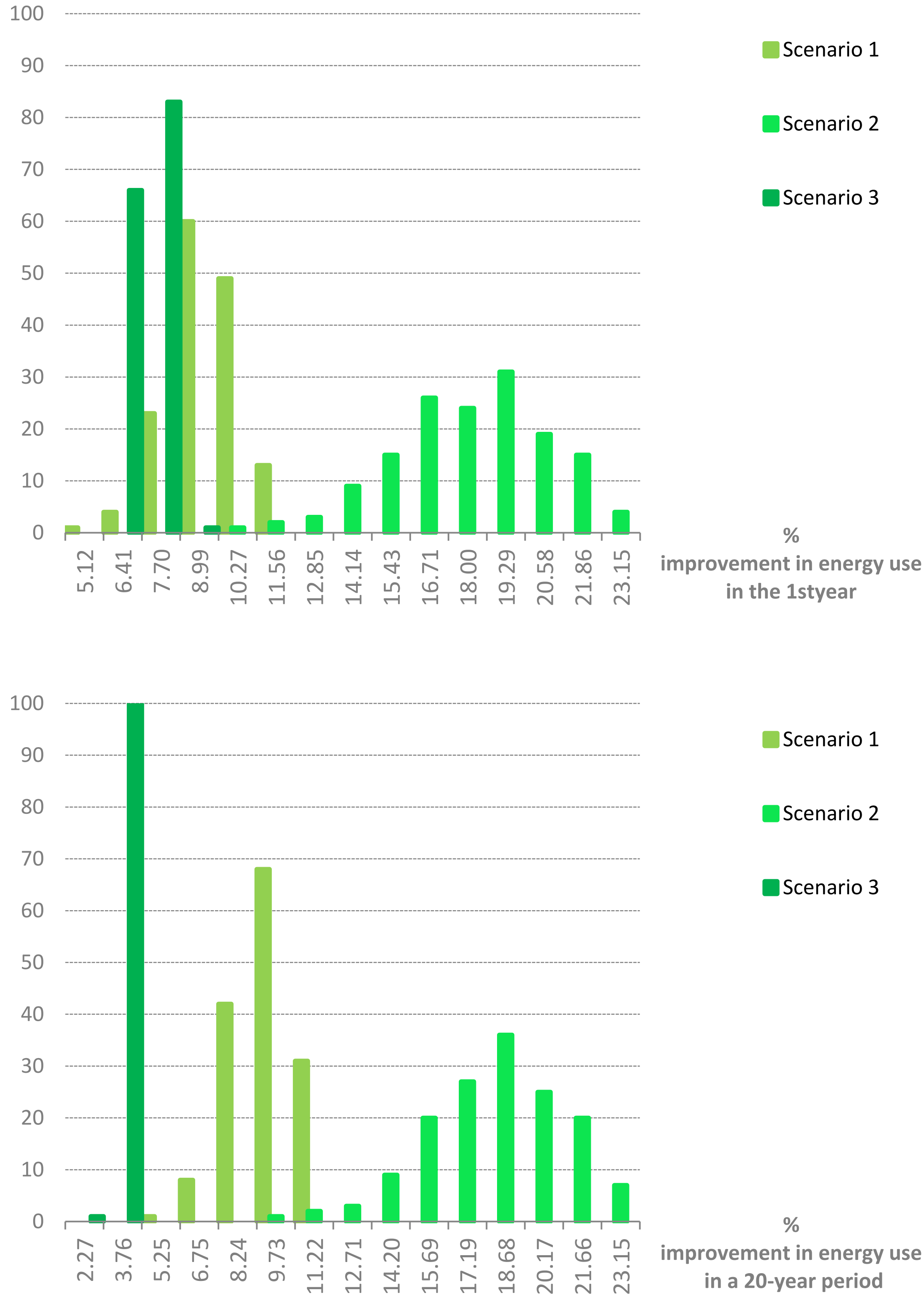
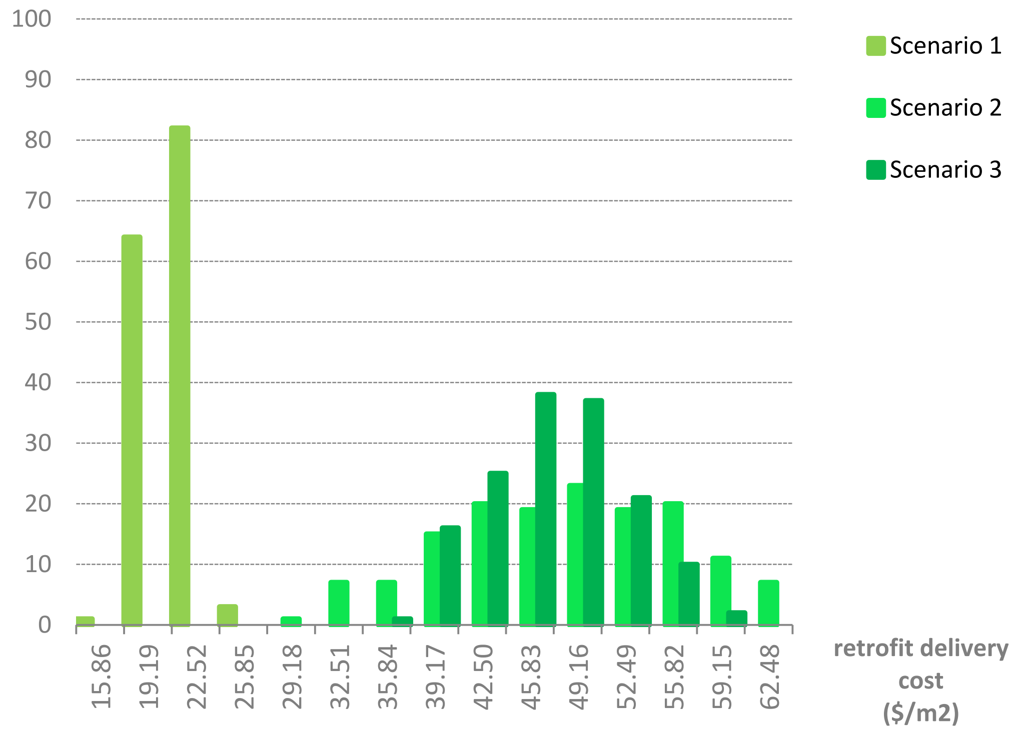


Figure 41: Histograms comparing energy saving predictions a) after 1 year and b) after 20 years



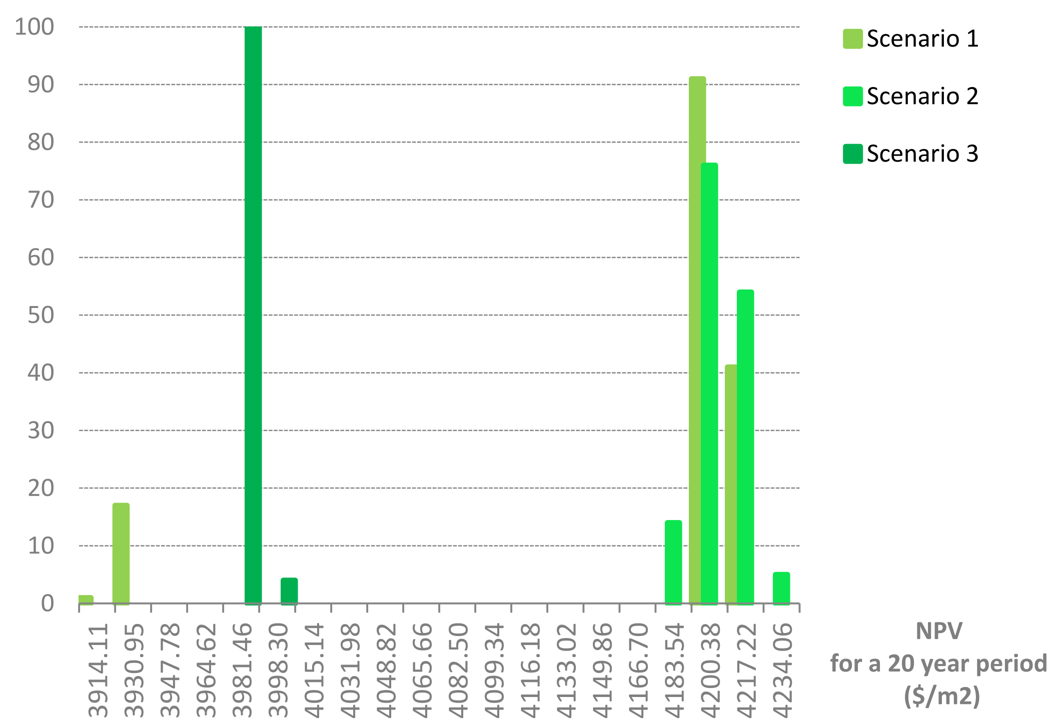


Figure 42: Histograms comparing a) the initial retrofit cost and b) the net present value of the investment after 20 years

The case study shows that the consideration of retrofit cost within an investment perspective can be used to compare the cost of the initial investments with the predicted cash flow in a 20-year study. Although there is a visible overlap in the prediction of retrofit delivery cost for Scenarios 2 and 3, the predicted revenue for scenario 2 is approximately 5% more than Scenario 3 (Figure 42). Scenario 1 also shows a similar difference in revenue, which suggests that the financing model is a critical consideration in investment decisions as well as the quantification of rent premium volatility in tenant-occupied buildings. The output results present relatively "flat" distributions and small levels of asymmetry, except in the case of the net present value results for retrofit scenario1 (Figure 40).

In the final step, the retrofit decision is analyzed to evaluate both the level of confidence and risk in the improvement to the NPV in each scenario. The evaluation method for this study is intended as a first approach to test the integrated framework proposed in this thesis and support the discussion of its applicability in the next chapter.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study is to provide a methodological framework for performance evaluation and stakeholder feedback when considering façade retrofit decisions. The objective is to avoid reproducing the limitations of a single perspective. The research is driven by three questions

- **How to best support performance evaluation for façade retrofit?**
- **How reliable are energy performance predictions for façade retrofits?**
- **How to quantify risks to support façade retrofit decision-making?**

In this chapter the findings are reviewed in the context of the research problem and the literature. On the strength of the proposed integrated framework, the final section provides recommendations for further study.

5.1. Research summary

The need for a more sustainable built environment has led to new policies and financial incentives focused on retrofitting the existing building stock. Financial models like the Property Assessed Clean Energy (PACE) and Managed Energy Services Agreement (MESA) provide alternatives to reduce the impact of first costs to property owners interested in building retrofits. In addition to these new financing models, the sustainability of an existing building involves a more comprehensive investigation of all areas of improvement including the building facade and its direct link to energy efficiency. This new approach to energy retrofits provides great opportunities for reduction in energy consumption in existing buildings with facades designed and built when the cost of energy was not an issue. Although the main source of consumption varies by building type, in both residential and commercial buildings, the major sources of consumption, heating and lighting, could potentially be reduced with an improvement in the building facade.

Despite strong opportunities on both the demand and supply side, the retrofit market faces some key barriers influenced by the performance criteria selection and the reliability of the performance data. In general, retrofitting a building facade is a complex decision problem. Stakeholders approach the retrofit project with different performance expectations. On the demand side, the problem is approached from an investment perspective. One of the barriers to retrofit investments is the issue of “split incentives” between the stakeholders who pay for the investment and those who benefit from it. On the supply side, the process to find an optimum solution between project cost and energy benefit is not transparent. In a given retrofit scenario, the façade design options can range from window upgrades to more complex changes involving renewable and passive technologies. There is an inherent complexity in modeling these options because of the incomplete knowledge of the physical and cost parameters involved in the performance evaluation. In addition, the thermal comfort of the building occupant is an important component of the retrofit performance assessment. These parameter uncertainties, combined with the new financing models to stimulate the retrofit market and diverse stakeholder perspectives, demand a closer look at decision-making process.

Research in the AEC field has focused on the development of strategies, tools, and products to improve the performance of building and meet sustainability goals. Other studies in the AEC domain (the building supply side) have mainly focused on the quantification of performance assessment to support the designer perspective. Some have developed decision making tools to support LCA decisions from the building manager decision. Within the literature on building retrofit, researchers study the selection of a solution as a design optimization or a financial investment problem. The key question in the investment approach is how to compute the financial benefit in relationship to the volatility of the cost of energy. In contrast, this dissertation is focused on the evaluation and selection of façade retrofit using an integrated framework. A review of the literature shows the important relationship between performance and risk for decision-making. Previous research in decision analysis provides various methodologies to support decisions characterized by a definition of performance criteria and stakeholder values to be part of the evaluation process, In addition, risk must be quantified as part of the decision making process. Although researchers offer various measures of risk specific to their discipline, these approaches can be generalized as the estimation of probability based on uncertainties in the quantification of performance.

The utilization of any of the current models for façade retrofit evaluation informs the decision by privileging a perspective over another. Approaches that incorporate expanded performance indicators such as productivity and human comfort still utilize simple models for the financial performance quantification. In the field of real estate management and other domains that view the building retrofit as an investment, the physical parameters that affect performance are over simplified. However, the physical performance dimension is crucial to any analysis of façade retrofit. Therefore facades retrofit solutions require a more holistic approach. The methodology proposed in this thesis research integrates three dimensions of performance, delivery process, environmental performance, and investment performance where the performance indicators for delivery process affect the calculation of environmental performance.

The main contribution of this research is the application of this integrated performance framework to a specific retrofit type, the building façade. This type of retrofit is a complex problem which could potentially make a significant impact on the overall valuation of the building. In contrast to other studies, this research attempts to fill a gap in the approach to façade retrofit decision by quantifying uncertainties in three dimensions of performance, considering the current financing models, and incorporating the risk attitude of the decision-maker. The objective is to provide a methodological approach to support façade retrofit decision with more confidence, insight and risk-awareness. This study in performance assessments for façade retrofit decisions confronts a major challenge that has not been resolved in prior research: the role of model uncertainty on the confidence level of retrofit decision making. Research on façade retrofits has focused on the physical behavior of the system. Other research has focused on prioritizing options to support decision making. We find that risk-conscious selection of retrofit measures should include quantification of both physical and financial uncertainties.

5.2. **Implication of findings**

To evaluate the feasibility of the integrated façade retrofit performance framework, a case study is conducted. Three retrofit scenarios are examined where a) a new layer is added to the façade in the form of a low-e storm window with a small reduction to air leakage, b) a low-e storm window is added with a 60% percent reduction to air leakage, and c) the windows and the through the wall heat pump units are replaced on the façade. The following performance indicators are quantified: retrofit cost, annual energy savings, thermal comfort, present value of energy use and net present value after a 20-year period. Each façade retrofit scenario is then evaluated based on the level of confidence to meet or exceed a specific target NPV improvement and the risk to fall below a minimum improvement threshold.

Table 22 and Table 23 are used to compare a determinist vs. a risk-aware approach to the façade retrofit decision. Both tables show that Scenario 2 has the highest expected NPV after 20 years. However, a stakeholder making a decision, by comparing the expected cost of the retrofit, the energy use after 20 years, and expected return on investment shown in Table 22, could also select retrofit Scenario 1 as the viable option. In the deterministic approach Scenario 1 shows a) the lowest retrofit delivery cost, and b) a 6% improvement in revenue, which is very close to Scenario 2 of 7%. In a risk-aware approach, the stakeholder making the investment decision looks at the probability of meeting a specific target or falling below a minimum threshold. Scenario 2 is the preferred option and Scenario 1 is a very distant second, because of the 1% level of confidence in meeting the target, as well as the 12% risk in falling below the minimum acceptable improvement in revenue.

Table 22: Deterministic approach to façade retrofit decision

$/m2	Scenario 1	Scenario 2	Scenario 3	Base case
Cost µ	19.65	46.4	45.39	
Energy-use µ	236.38	213.12	251.76	259.09
NPV µ	4163.93	4197.94	3977.12	3931.47

Table 23: Risk-aware approach to façade retrofit decision

Probability of improved NPV	Scenario 1	Scenario 2	Scenario 3
P confidence (revenue > 7%)	1.20%	16.70%	0.00%
P risk (revenue < 2%)	11.60%	0.00%	100.00%

The case study findings confirm the two hypotheses presented in section 1.5, suggesting that that performance assessments based solely on the expected value would not be very reliable and risk must be examined for more reliable façade retrofit decision-making.

5.3. **Recommendations for further study**

The framework for integrated façade retrofit assessment has been tested with one residential case study. Further case studies are needed to expand the understanding of the interdependencies among uncertain parameters. For example, the complexities associated with other façade construction types should be considered in conjunction with commercial building types. The current study could be expanded to include other financial investment models in order to identify the most sensitive input parameters. In addition, the calculation of project delivery performance could be enhanced by including other sources of uncertainties such as the unforeseen delays due to lead times or weather conditions. The next sections identify three directions of study for further contribution toward an integrated performance framework.

5.3.1. Stakeholder approach to risk

In an investment decision, risk has two sides; it is as much about the probability of loss as the likelihood of high revenue. In the current economic context, it is important to clearly understand which condition, loss vs. gain, is of highest priory for each decision-maker when considering a value-system for energy efficiency investment. Future application of the framework for facade retrofit decision-making should differentiate between the selections of confidence target and risk threshold driven by varying sustainability objectives.

5.3.2. Tenant behavior and rent premium

In this dissertation, two financing models are examined as part of the case study to test the façade retrofit analytic framework. More research is needed to understand the relationship between a façade retrofit scenario and its financing model, and the thermal impact on energy use. For example, research in the residential energy efficiency measures has found that occupants willingness to pay for façade energy efficiency measures vary from 3% for an insulated façade to 13% for window upgrades or replacements (Banfi et al. 2008). In commercial buildings, tenants' willingness to pay for energy efficiency features varies due to the effects of policy and technology on the tenant's valuation (Yoshida et al. 2012). Further study is needed to examine more closely the impact of thermal comfort on investment performance. In addition, other aspect of occupant comfort could be incorporated. A commercial façade retrofit could be used to expand the current framework to include other aspects of occupant comfort, proven to impact productivity and profitability, such as visual comfort.

5.3.3. Coupling models of varying resolutions

In this dissertation a two-dimensional dynamic model of the building façade is coupled with a zonal building energy model. The aggregation of deep source uncertainty of the façade is propagated in the whole building simulation. These types of model aggregation and loose couplings should be closely examined and more thoroughly validated, They promise to greatly to reduce the computational complexity of propagating uncertainties through loosely coupled models of varying resolutions, rather than building fully integrated but computationally intensive models. For example the development a series of façade models based on a typology of retrofit strategies could facilitate the detail analysis of façade retrofit options. More research is needed to identify modeling issues in a façade retrofit scenario which could lead to better design-analysis integrated models used to explore probable outcomes in façade retrofit decision-making.

5.4. **Conclusion**

The research community has responded to the push for innovation in sustainable buildings. Research has focused on the development of tools and practices to facilitate the design process and integrate evaluation throughout the building lifecycle. This dissertation contributes to the emerging literature on retrofit investments by proposing a risk-aware approach to façade retrofits and implementing an integrated analytic framework to examine different façade retrofit options and reach a rational risk-conscious decision. The broad impact of this research is in the retrofit decision-framework to integrate three performance dimension, incorporate risk quantification, and support decision making.

The assessment of a façade retrofit technology is complex, and dependent of the decision-stakeholder value system. The relationship between predicted performance and risk begins as a collection of data, analyzed in a process of statistical inference. To better support decision and future actions, it is important to empower the decision-maker with quantification of her risk, resulting from uncertainty in the models and parameters used in the evaluation. In addition, it is important to convey this information as a reflection of the decision-maker’s subjective perspective. In terms of new innovative technologies, more research is needed, focusing on the interactions between the retrofit delivery process and environmental and financial performance. In particular, capturing these interactions requires detailed process modeling to understand the drivers and interplay among these three dimensions when making a decision.

APPENDIX A
MODELING APPROACH FOR THE CASE STUDY

Data collection and analysis procedures

Figure 43 shows the three main tasks to model and analyze the data for the cases study. A detailed façade model is coupled with simplified building model for the base case and each of facade retrofit scenarios. An uncertainty analysis is conducted in two steps: 1) as part of a sensitivity analysis to identify the dominant parameters in the façade model, and 2) as part of the risk analysis for each retrofit scenario. Performance indicators for cost, energy savings, thermal comfort, and net present value were quantified. Figure 44 shows the study variables and analysis procedures.

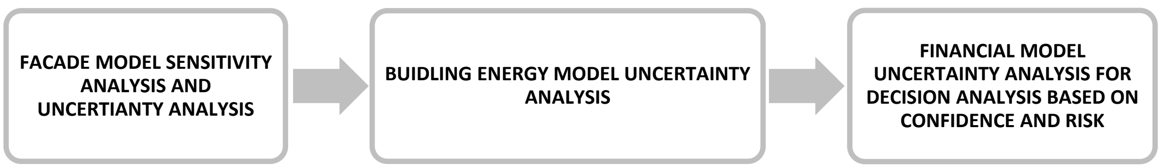


Figure 43: Research process

Model coupling process

To examine the impact of a façade retrofit on the overall energy performance of the building, two simulation models of varying resolutions were combined. The building façade was modeled using THERM 6.1, a computational fluid dynamic modeling tool to calculate heat transfer at the window frame and glazing edges (Figure 45). In addition, WINDOWS 6.2 was used to aggregate the THERM output for the u-values for the frame and the glass, as well as Solar Heat Gain Coefficient, SHGC. The output of distribution for the U-value and the SHGC from the façade model are then used as input parameter in the building model. Energy Plus was used to create a model of one typical floor in the building. Energy plus is a transient energy simulation engine, which can be accessed from various user interfaces. In this research, two interfaces were used: Open studio to visualize the building geometry, and EP-Launch to complete the rest of the modeling process. Information on the calculation and validation of these simulation tools can be found in (DOE 2012).

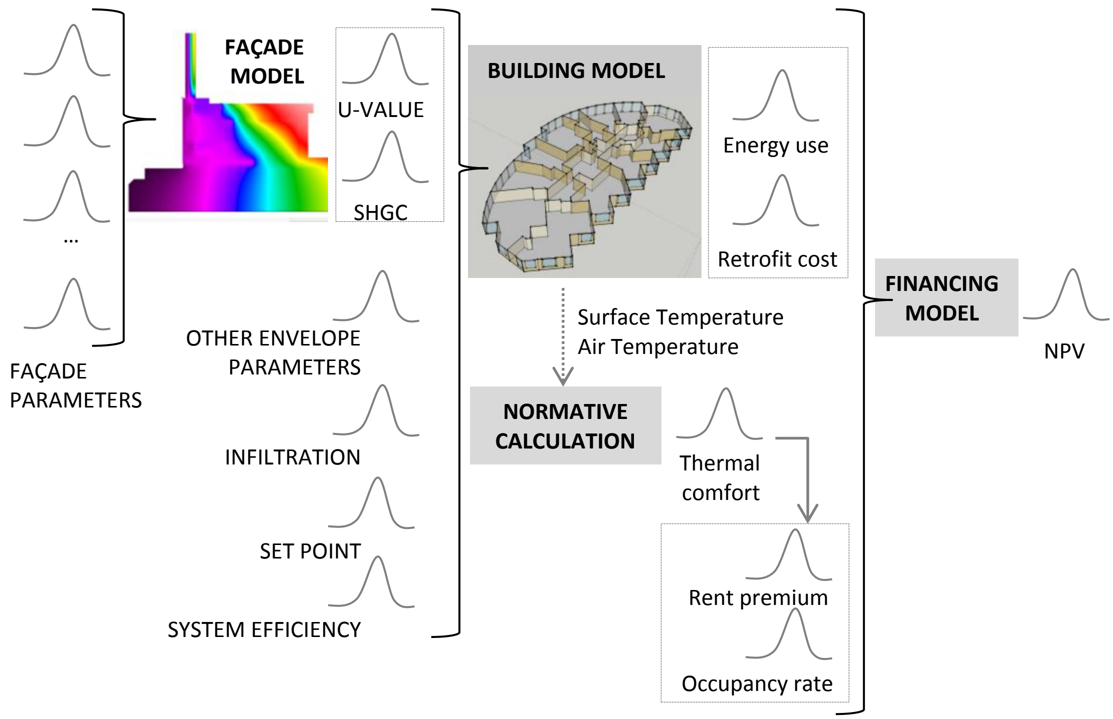


Figure 44: Uncertainty propagation for the performance evaluation of the façade retrofit case study

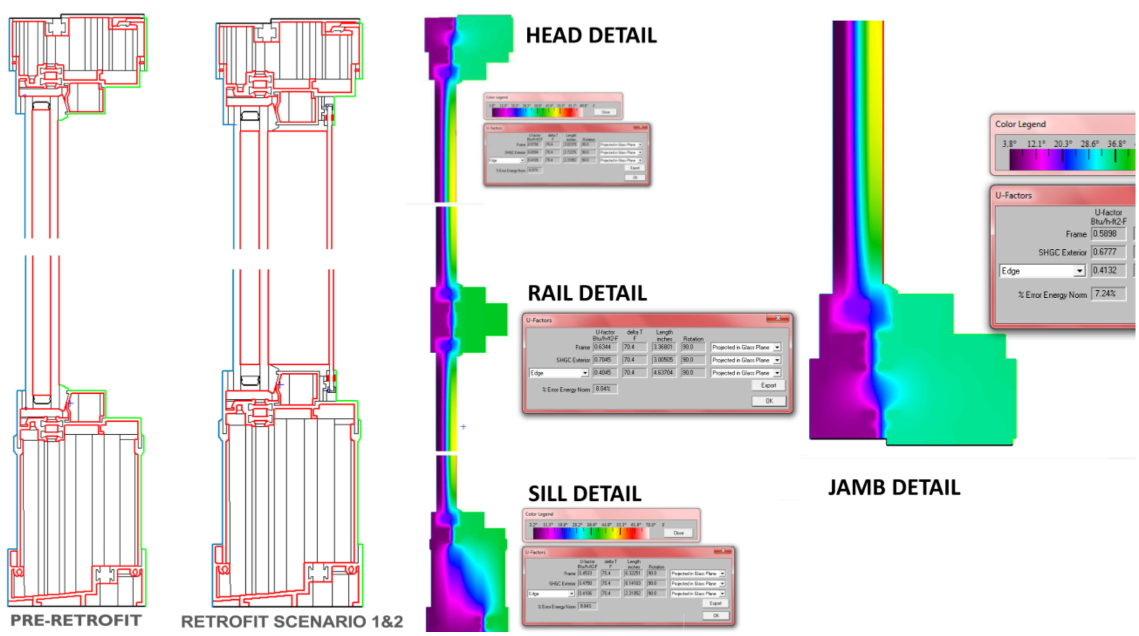


Figure 45: Example visualization of façade details and heat transmission results, modeled in THERM

Sensitivity analysis for Façade model

The façade was modeled in Therm (LBNL 2012) to examine the impact of thermal bridges on the U-value of the window before and after the retrofit. Parameter screening, is a sensitivity analysis method that changes one parameter at a time (Morris 1991). In this case study, the Morris Method is used to identify the most dominant parameters in the Façade model. Table 24 lists the parameters included in the uncertainty and sensitivity analysis. Table 25 shows the top 10 dominant parameters affecting the U-factor of the frame and the edge of glass in the window wall façade.

Parameter uncertainty propagation

SimLab is used for sampling parameters. The Latin Hypercube Sampling technique is used to propagate parameter uncertainty (Saltelli 2008). The Latin hypercube sampling requires a smaller set of samples and therefore reducing the computational burden. For the façade, samples as generated as input for the Therm model of the head, jamb, rail, and sill conditions of the window (Figure 49). For the building models, 150 set of samples samples are generated for the energy model and the lifecycle cost performed in energy plus. Information on the calculation and validation of these tools can be found in SAMO2004, LBNL 2012, and DOE 2012.

Table 24: Facade parameters considered in parameter screening process

Building façade parameters	**mean or expected value**	standard deviation				
Residential building – base case	**μ**	**σ**	**min**	**max**	**unit**	**source/comments**
emissivity-Glass_9923F-1	**0.8400**	0.0168	0.8064	0.8736		outside
emissivity-Glass_9923F-2	**0.1580**	0.0032	0.1517	0.1643		low-e side
emissivity-Glass_103-1	**0.8400**	0.0168	0.8064	0.8736		inside
emissivity-Glass_103-2	**0.8400**	0.0168	0.8064	0.8736		interior side
frame gas air KEFF	**0.0370**	0.0019	0.0333	0.0407	W/m-K	ITEM KEPT CONSTANT
butyl rubber conductivity	**0.2400**	0.0120	0.2160	0.2640	W/m-K	from MacDonald, 2002
butyl rubber emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
silica gel conductivity	**0.0300**	0.0015	0.0270	0.0330	W/m-K	from MacDonald, 2002
silica gel emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
anodized aluminum conductivity	**237.0000**	11.8500	213.3000	260.7000	W/m-K	from MacDonald, 2002
anodized aluminum emissivity	**0.8000**	0.0160	0.7680	0.8320		from Ruff et al, 1997
silicone filler conductivity	**0.5000**	0.0250	0.4500	0.5500	W/m-K	from MacDonald, 2002
silicone filler emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
EPDM-conductivity	**0.2500**	0.0125	0.2250	0.2750	W/m-K	from MacDonald, 2002
EPDM-emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
aluminum frame conductivity	**160.0000**	8.0000	144.0000	176.0000	W/m-K	from MacDonald, 2002
aluminum frame exterior emissivity			0.8340	0.8560		from Arild Gustavson
aluminum frame interior emissivity			0.0550	0.8200		from Arild Gustavson
urethane- thermal brk -conductivity	**121.0000**	6.0500	108.9000	133.1000	W/m-K	from MacDonald, 2002
urethane- thermal brk -emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
concrete slab conductivity	**0.7530**	0.0377	0.6777	0.8283	W/m-K	from ASHRAE + dev. from MacDonald, 2002
concrete slab emissivity	**0.9400**	0.0188	0.9024	0.9776		from Branco & Mendes
Foam weather stripping-conductivity	**0.0300**	0.0015	0.0270	0.0330	W/m-K	
Foam weather stripping-emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
glass wool conductivity	**0.0380**	0.0019	0.0342	0.0418	W/m-K	
glass wool emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
hardwood conductivity	**0.1600**	0.0080	0.1440	0.1760	W/m-K	
hardwood emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997
plywood conductivity	**0.1700**	0.0085	0.1530	0.1870	W/m-K	
plywood emissivity	**0.9000**	0.0180	0.8640	0.9360		from Ruff et al, 1997

Table 25: Ranking of top dominant parameters affecting the façade model output

Importance	Parameter effect on the U-value of the edge of glass	Parameter effect on the U-value of the window frame
1	Aluminum frame exterior emissivity	Aluminum frame exterior emissivity
2	EPDM emissivity	EPDM emissivity
3	Aluminum frame conductivity	Aluminum frame conductivity
4	emissivity-Glass_103-2 (low –e film surface)	emissivity-Glass_103-2 (low –e film surface)
5	emissivity-Glass_103-1(interior surface)	emissivity-Glass_103-1(interior surface)
6	Urethane thermal break conductivity	Urethane thermal break conductivity
7	EPDM conductivity	EPDM conductivity

APPENDIX B
NPV CALCULATION DIAGRAMS

$$\text{savings} = \text{NPV}_{\text{Pre-retrofit}} - \text{NPV}_{\text{Post-retrofit}}$$

$$\text{NPV} = \text{NET PRESENT VALUE}$$

$$\text{NPV} = \sum_{t=1}^{n} \frac{\text{Annual cash flow}_t}{\text{compound discount}}$$

Figure 46: Net Present Value calculation for a facade retrofit

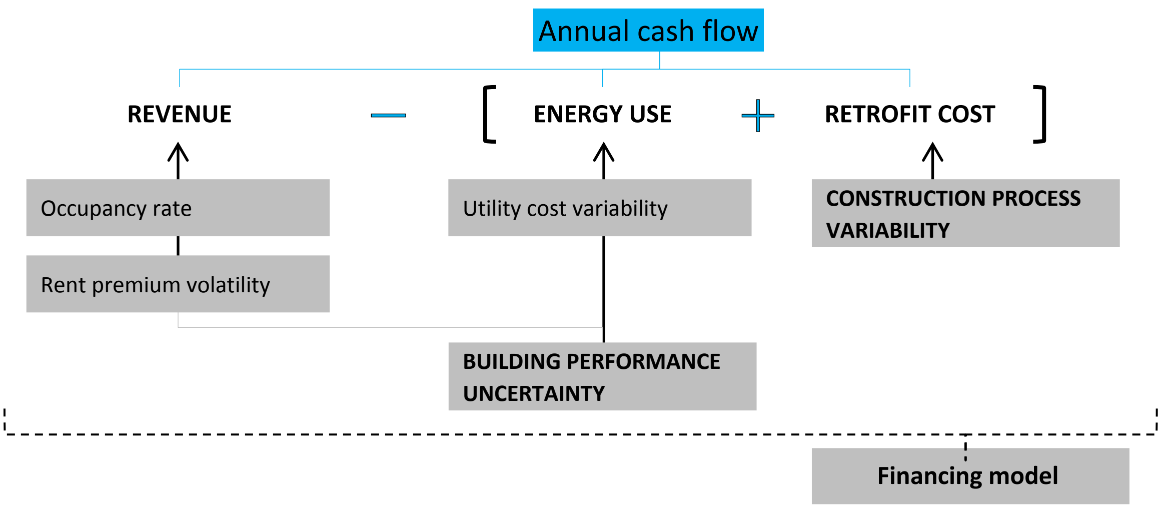
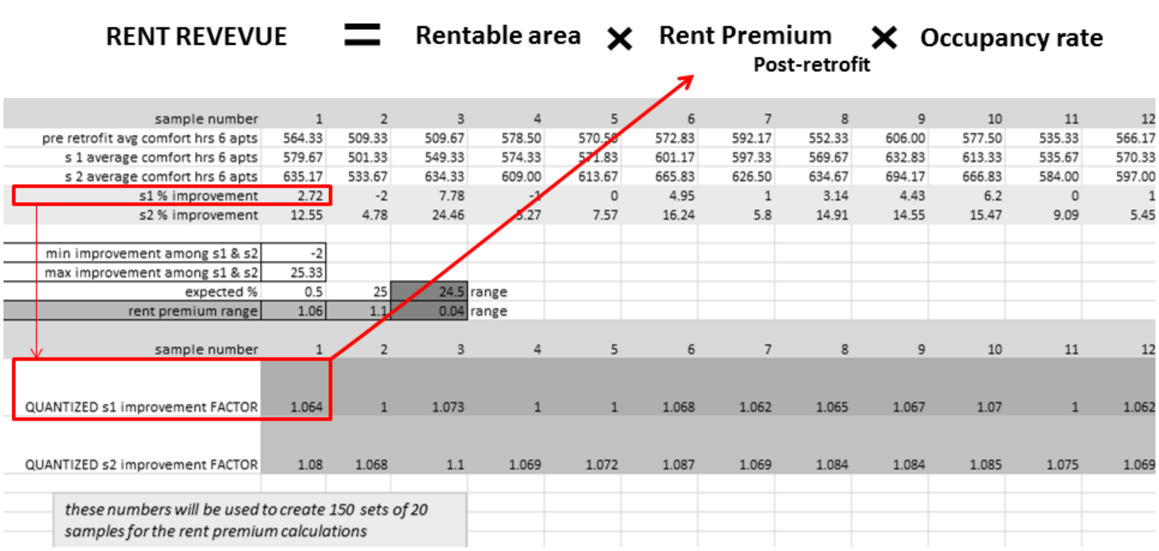


Figure 47: Factors impacting the annual cash flow calculation



sample number	1	2	3	4	5	6	7	8	9	10	11	12
pre retrofit avg comfort hrs 6 apts	564.33	509.33	509.67	578.50	570.50	572.83	592.17	552.33	606.00	577.50	535.33	566.17
s 1 average comfort hrs 6 apts	579.67	501.33	549.33	574.33	571.83	601.17	597.33	569.67	632.83	613.33	535.67	570.33
s 2 average comfort hrs 6 apts	635.17	533.67	634.33	609.00	613.67	665.83	626.50	634.67	694.17	666.83	584.00	597.00
s1 % improvement	2.72	-2	7.78	-1	0	4.95	1	3.14	4.43	6.2	0	1
s2 % improvement	12.55	4.78	24.46	5.27	7.57	16.24	5.8	14.91	14.55	15.47	9.09	5.45
min improvement among s1 & s2	-2											
max improvement among s1 & s2	25.33											
expected %	0.5	25	24.5	range								
rent premium range	1.06	1.1	0.04	range								
sample number	1	2	3	4	5	6	7	8	9	10	11	12
QUANTIZED s1 improvement FACTOR	1.064	1	1.073	1	1	1.068	1.062	1.065	1.067	1.07	1	1.062
QUANTIZED s2 improvement FACTOR	1.08	1.068	1.1	1.069	1.072	1.087	1.069	1.084	1.084	1.085	1.075	1.069

these numbers will be used to create 150 sets of 20 samples for the rent premium calculations

Figure 48: Example mapping comfort improvement to rent premium factor within a 6% to 10% range

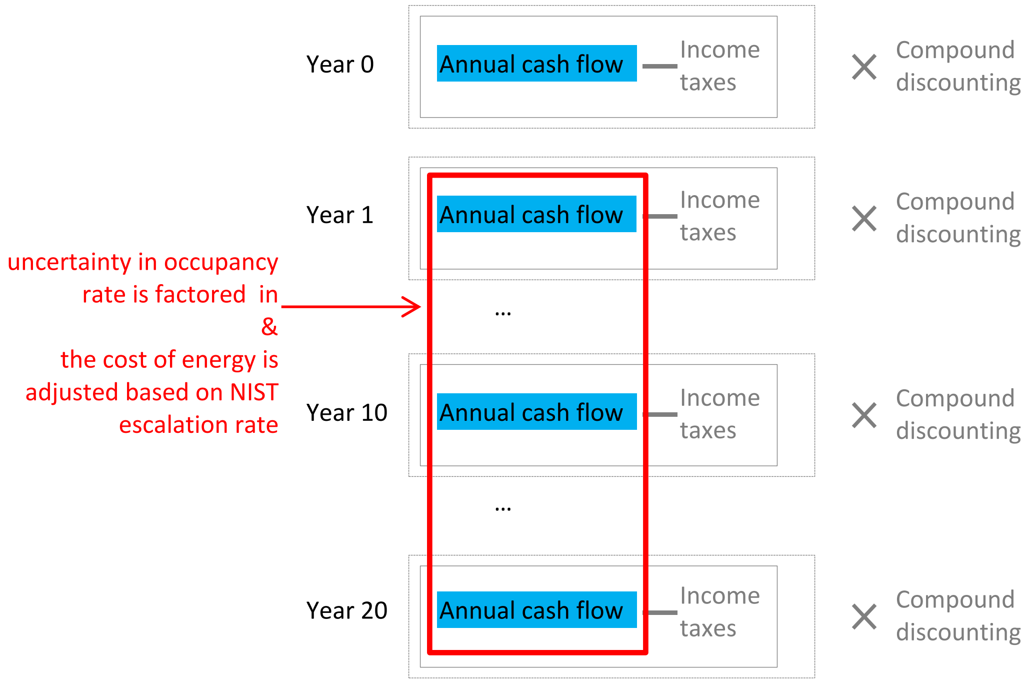


Figure 49: NPV calculation for the pre-retrofit base case scenario and MESA financing model

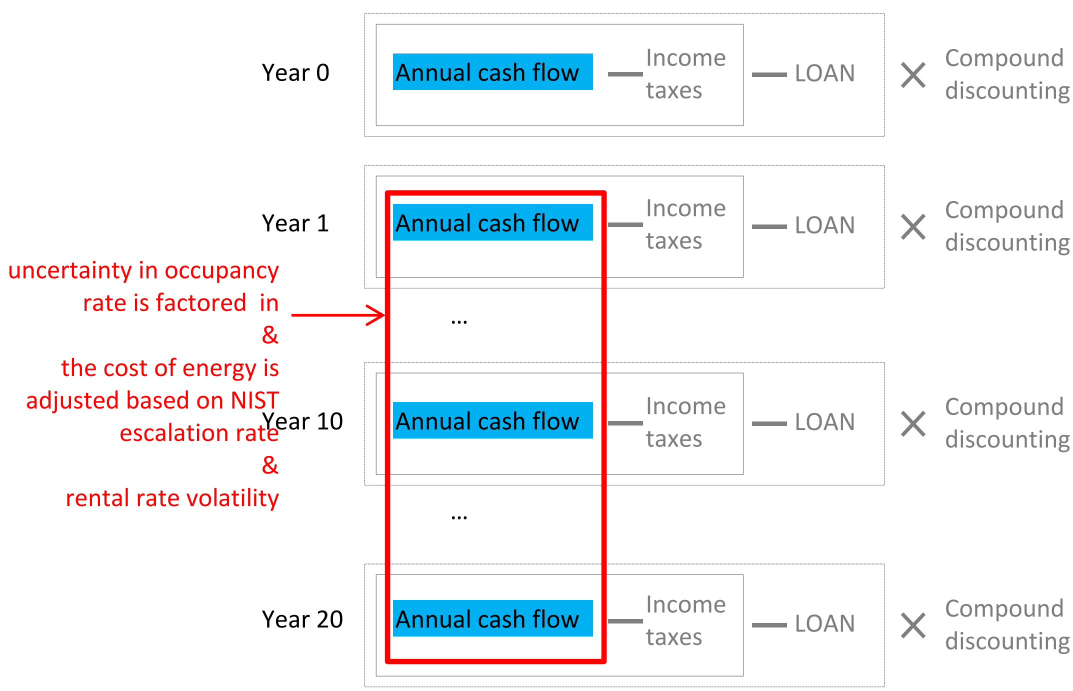


Figure 50: NPV calculation for retrofit scenarios 1 and 2 with the PACE financing model

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