An Approach Towards Sustainable Building

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AN APPROACH TOWARDS SUSTAINABLE BUILDING

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Abstract

The motivation for development of energy efficiency and implementation of novel advanced materials applied in buildings can be traced to increasing energy costs in conjunction with an enhanced environmental awareness among people. This doctoral dissertation presents contributions towards sustainable building, where factors such as building technology, energy efficiency in buildings, workers' health issues during construction measures, and certain economic considerations for renovation of buildings have been considered.

The research study aims to provide a knowledge base for motivating building owners to renovate buildings based on energy efficiency and improved indoor environment. The initial phase of the research study identifies a detailed description of common drivers, expected in renovation projects by building owners. In the second phase, an information base is identified which may facilitate the bidding processes for decision makers by means of technological, social and economic aspects. The aforementioned information base can also contribute to attentive decisions regarding sustainable renovation and energy saving measures.

A strategy was developed within the Renovation Workshop of Riksbyggen, in order to promote energy saving measures concurrent with major renovations in residential buildings. This operational decision support process was applied in a tenant owners' cooperative in Sweden. The objective of this process was to showcase and more importantly to implement energy saving measures, based on knowledge transfer between different parties involved in the renovation project. For the conducted case study, this process was shown to be of great importance when decisions regarding energy saving measures in conjunction with scheduled renovations are being planned.

A unique case study was conducted on two of the most commonly used environmental certification programs for buildings in Sweden; Environmental Building (Miljöbyggnad) and GreenBuilding. Following a granted access to a limited database of submitted applications to Sweden Green Building Council, the most common mistakes in these were identified and categorized. This study contributed to further understanding about the level of ability among building consultants, comprehension of environmental certification, and enhancement of the ability to produce high-quality calculations concerning building-related energy usage. In addition, this insight can provide a basis for planning of continuing education of consultants within the field of building technology.

For a church building, a study was conducted subsequent to an exchange of an existing electric coil heating system to a hydronic ground source heat pump system. Analyses of the energy demand and energy signature, prior to and after installation were carried out. The replacement of the original heating system with a ground source heat pump system for the church building constitutes a reduced energy consumption level of approximately 66%, at the average outside temperature of -2.30 °C. This study demonstrated, that data from a detailed electric bill, can be utilized in order to obtain the energy signature of the building and henceforth assess the energy savings.

One aspect of the research, examined the decision making process related to sustainable renovation and refurbishment in buildings. The utilized methodology identified three distinct phases in order to instigate an engagement in sustainable renovation, by means of questionnaires and semi-structured interviews. In particular, the attitudes of stakeholders in Sweden, Denmark and Cyprus to sustainable building were studied through three separate case studies. Within the framework of this study, it was identified that building physics and durability are among the most important drivers for energy renovation. The results provided an insight into the renovation process in the aforementioned countries and identified that drivers such as improvement of indoor air quality and elimination of moisture in the building envelope are also of crucial importance.

Another aspect of the conducted research highlights workplace accidents occurring within the Swedish construction sector. The purpose of this study was to serve as a useful tool to track the working environments of construction workers in order to reduce health and safety issues within the construction sector. The findings of this research suggest that despite laws, regulations or additional factors that seek to ensure a safe and healthy environment for construction workers, the Swedish construction work force still faces challenges. Moreover, it is identified that construction workers participating in the study call for additional measures to ensure occupational health and safety.

Improved knowledge of economic performance and technical results of renovations can contribute to a snowball effect, with more property owners recognizing the value of energy aspects and thus provide an increased level of energy savings.

Sammanfattning

Motivationen för utveckling av energieffektivitet och implementering av nya avancerade material för användning i byggnader, kan spåras till ökande energikostnader i kombination med en ökad miljömedvetenhet om miljöfrågor. Denna doktorsavhandling presenterar bidrag till hållbart byggande, genom att behandla faktorer som byggnadsteknik, energieffektivitet i byggnader, frågor rörande byggnadsarbetares hälsa under byggnadsåtgärder, samt överväganden och kunskapsspridning om förbättrad funktion för renovering av byggnader.

Forskningsstudien syftar även till att presentera en kunskapsbas för motivering av fastighetsägare till renovering av byggnader baserad på energieffektivitet och en förbättrad inomhusmiljö. Den inledande fasen av forskningsstudien behandlar de drivkrafter som påverkar en fastighetsägare inför ett renoveringsprojekt. I den andra projektfasen, identifieras en informationsbas som kan underlätta anbudsprocesser för beslutsfattare genom att beakta tekniska, sociala och ekonomiska aspekter. Denna informationsbas kan även bidra till uppmärksammade beslut om hållbar renovering och energibesparande åtgärder.

En strategi utvecklades inom Riksbyggens renoveringsverkstad, i syfte att främja energisparåtgärder i samband med större renoveringar i bostadshus. Denna operativa beslutsstödsprocess, tillämpades i en bostadsrättsförening i Sverige. Syftet med denna studie var att visa hur kunskapsöverföring mellan olika aktörer i renoveringsprojekt kan resultera i energibesparing i samband med schemalagda renoveringar.

En unik fallstudie genomfördes på två av de mest använda miljöcertifieringsprogrammen för byggnader i Sverige, Miljöbyggnad och GreenBuilding. En databas av inskickade ansökningar till Sweden Green Building Council granskades och de vanligaste bristerna i ansökningarna identifierades och kategoriserades. Denna studie ökar förståelsen kring de färdigheter som förekommer hos byggkonsulter samt visar behovet att kunna genomföra högkvalitativa beräkningar av byggnaders energianvändning. Den ger också ett underlag för planering av fortbildning av konsulter inom området byggnadsteknik.

För en kyrkobyggnad, utfördes en fallstudie där energissignaturmetoden användes för att värdera energibesparingen efter utbyte av ett befintligt uppvärmningssystem med direktverkande el, till ett vattenburet bergvärmesystem. Resultatet blev en minskad energianvändning på cirka 66% räknat vid den genomsnittliga utomhustemperaturen på -2.30 °C. Denna studie påvisar även att data från en detaljerad elräkning, kan nyttjas för att ta fram byggnadens energisignatur och användas för att värdera energibesparingar.

En aspekt av forskningen utredde beslutsprocessen relaterad till hållbar renovering och ombyggnation av byggnader. Den använda metoden identifierade tre olika faser i syfte att inleda ett engagemang i hållbar renovering, med hjälp av frågeformulärer och semistrukturerade intervjuer. I synnerhet studerades attityden till hållbart byggande hos

beslutsfattare i Sverige, Danmark och Cypern med hjälp av tre separata fallstudier. Inom ramen för studien noterades det att byggnadsfysik och hållbarhet är bland de viktigaste drivkrafterna för energirenoveringar. Resultaten ger även inblick i renoveringsprocessen för de nämnda länderna och identifierar att önskemål om bättre luftkvalitet och eliminering av fukt i klimatskalet är viktiga drivkrafter.

En annan aspekt av forskningen belyser arbetsplatsolyckor inom den svenska byggsektorn. Syftet med denna studie var att framställa ett användbart verktyg för bedömning av byggnadsarbetares arbetsmiljöer för att kunna minska hälso- och säkerhetsproblem inom byggsektorn. Resultaten av denna forskning tyder på att den svenska byggarbetskraften ännu möter utmaningar trots förekomst av lagar och ytterligare faktorer som syftar till att garantera en säker och hälsosam miljö för byggnadsarbetare. Dessutom visar studien att de byggnadsarbetare som deltog i studien önskar att ytterligare åtgärder vidtas för att säkerställa hälsa och säkerhet på arbetsplatsen.

Bättre kunskap om ekonomiskt och tekniskt resultat av renovering kan bidra till en snöbollseffekt, där fler fastighetsägare ser värdet i att inkludera energiaspekter och sålunda ge upphov till att volymen av energibesparingar blir allt större.

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Dedication

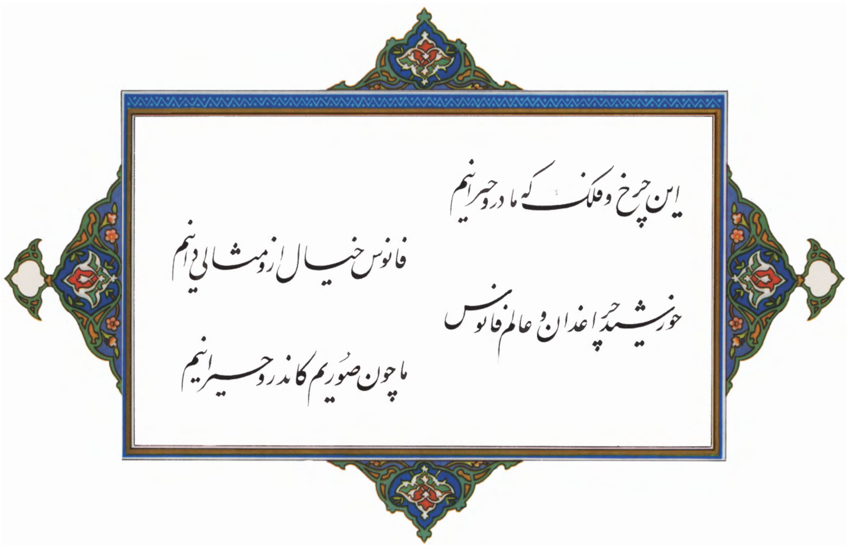
This doctoral dissertation is lovingly dedicated to my dear mother and father for their infinite love, guidance and support which have sustained me throughout my life. Their precious presence adds another dimension to the blissful paths of my destiny. This dissertation is moreover dedicated to my beloved brothers Dr. Amir Shahram Gohardani, Dr. Omid Gohardani and Doctor of Medicine candidate Avid Gohardani. Thank you for embellishing my life with your presence and for the joyous journey you share with me.

Navid Gohardani
Stockholm, Sweden

We are no other than a moving row
Of visionary Shapes that come and go
Round with this Sun-illumined Lantern held
In Midnight by the Master of the Show;

Hakim Omar Khayyam Neyshabouri (1048−1131)

Persian astronomist, mathematician, philosopher, poet



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The invaluable support of Prof. Björk and Associate Prof. Gudmundsson as my mentors along this scientific journey, has served as my inspirational source and their helpfulness, encouragement and assistance have helped me to stretch my abilities and surpass challenges as a researcher.

Finally, the Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS) is acknowledged for funding the research project.

Nomenclature

Greek symbols

δ	=	Vapor permeability
η	=	The ratio between total gross production of electricity and the primary energy consumption for electricity
	=	Efficiency of the heating system for the ground source heat pump
η_t	=	Heat exchange efficiency of heat recovery of ventilating air
λ	=	Thermal conductivity
χ	=	Energy saving
Φ	=	Total normal heat flux
Ψ	=	Linear thermal transmittance
	=	Ratio between the energy use per hour prior and after the GSHP installment

Latin characters

f_B	=	Base load factor
$f_{Del,i}$	=	Primary energy factor for delivered energy from energy carrier, i
$f_{Exp,i}$	=	Primary energy factor for exported energy from energy carrier, i
$f_{SP,h}$	=	Estimated average seasonal performance factor
f_T	=	Temperature dependent factor
f_{Tf}	=	Temperature factor
h	=	Heat transfer coefficient
k	=	Number of replacements or refurbishments
m	=	Mass per unit area
	=	Number of cost elements
n	=	Number of years (expected life of project)
r	=	Interest rate per annum
t	=	Thickness
A	=	Perpendicular reference area for solar radiation
A_{Net}	=	Useful floor area
A_{temp}	=	Area enclosed by the inside of the building envelope of all storys including cellars and attics for temperature-controlled spaces, intended to be heated to more than 10 °C
Cc	=	The capital cost (design/build cost)

Dc = Disposal cost
E = Primary energy usage of a building
$E_{f,i}$ = Electrical energy received from the district, during the time increment i
$E_{t,i}$ = Electrical energy returned to the district, during the time increment i
$E_{Del,i}$ = Delivered energy for energy carrier, i
$E_{Exp,i}$ = Exported energy for energy carrier, i
$E_{Tot,i}$ = Total energy usage of a building, for each energy carrier, i
F = Density flux
$H_{f,i}$ = Thermal energy from the district, for each energy carrier, i
$H_{t,i}$ = Thermal energy returned to the district, for each energy carrier, i
I = Solar radiation against a reference plane
Mc = Maintenance cost (reactive and preventive)
N = Integer
$N_{C,Off}$ = Collection of delivered non-renewable energy carriers
$N_{C,Exp}$ = Collection of exported non-renewable energy carriers
Oc = Operating cost
Q = Energy use per hour
Q_u = Estimated total heat delivered by the heat pump
R = Thermal resistance
$\tilde{R}$ = Renewable energy ratio
Rc = Replacement cost
$R_{C,On}$ = Collection of renewable energy produced on site
$R_{C,Exp}$ = Collection of renewable energy produced on site and exported
$R_{C,Off}$ = Collection of imported non-renewable energy produced off-site
R_w = Sound insulation index
T = Temperature
T_{indoor} = Indoor air temperature
$T_{outdoor}$ = Outdoor air temperature
$\overline{T}$ = Average temperature
U = Overall thermal transmittance/overall heat transfer coefficient
$\dot{V}$ = Airflow
Z = Vapor resistance

Abbreviations

AC	= Alternating Current
ACES	= A Concept for promotion of sustainable retrofitting and renovation in Early Stages
AGM	= Annual General Meetings
AIA	= American Institute of Architects
ASHRAE	= American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	= American Society for Testing and Materials
BEMS	= Building Energy Management Systems
BIM	= Building Information Modeling
BRI	= Building-Related Illnesses
CERBOF	= Center for Energy and Resource Efficiency in Construction and Management
CHP	= Combined Heat and Power
COP	= Coefficient Of Performance
CSCDT	= Construction Sector Chain Disaster Theory
CSR	= Corporate Social Responsibility
DC	= Direct Current
DOE	= U.S. Department of Energy
DOT	= Design Output Temperature
EB	= Environmental Building (Miljöbyggnad in Swedish)
EE	= Energy Engineer
EPBD	= Energy Performance of Buildings Directive
EPA	= Environmental Protection Agency
EPIQR	= Energy Performance Indoor environmental Quality Retrofit
ESPEET	= Early Stage Primary Energy Estimation Tool
EU	= European Union
FORMAS	= Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
FR	= Financial Representative
GB	= GreenBuilding
GSHP	= Ground Source Heat Pump
GUI	= Graphical User Interface
HDD	= Heating Degree Days
HVAC	= Heating, Ventilation and Air Conditioning
IARC	= International Agency on Research on Cancer
IDP	= Integrated Design Process
IR	= Infrared
LAT	= Latitude
LCA	= Life Cycle Analysis
LCC	= Life Cycle Costing
LCI	= Life Cycle Inventory
LON	= Longitude
MCS	= Multiple Chemical Sensitivities

MDR	= Mean Daily Range
MEDIC	= Méthode d'évaluation de scénarios de dégradation probables d'investissements correspondants
NNZEB	= Nearly Net Zero Energy Building
NZEB	= Net Zero Energy Building
NZEBs	= Net Zero Energy Buildings
OSHA	= National Institute of Occupational Safety and Health
PM	= Project Manager
PT	= Project Team
PV	= PhotoVoltaic
PVC	= PolyVinyl Chloride
RB	= Riksbyggen
RDI	= Research, Development and Innovation
ROI	= Return On Investment
RWR	= Renovation Workshop of Riksbyggen
SBS	= Sick-Building Syndrome
SDB	= Summer Dry Bulb
SWB	= Summer Wet Bulb
SGBC	= Sweden Green Building Council
TOC	= Tenant Owners' Cooperative(s)
USGBC	= U.S. Green Building Council
VIPs	= Vacuum Insulation Panels
VOCs	= Volatile Organic Compounds
WDB	= Winter Dry Bulb
WLC	= Whole Life Cost analysis
WVTR	= Water Vapor Transmission Rate
ZEBs	= Zero Energy Buildings

Subscripts

$coup$	= Coupling effect
cv	= Gaseous convection
g	= Gaseous
$leakage$	= Leakages through the building envelope
r	= Relative to radiative thermal
se	= External
si	= Internal
$vent$	= Ventilation

Symbols

$^\circ$	= Degrees

Used terminology

Some of the distinct terms used in this thesis are explained further, as outlined below.

Data triangulation	The use of different sources of information in order to increase the validity of a study
Energy efficient buildings	Concerns new built or renovated buildings and can be defined as buildings that are designed to provide a significant reduction of the energy need for heating and cooling, independently of the energy and of the equipments that will be chosen to heat or cool the building
EPBD	Energy Performance of Buildings Directive Directive 2010/31/EU of the European Parliament and Council of energy efficiency of buildings
Ethnography	The branch of anthropology that deals with the scientific description of individual human societies
Fossil fuel	Any fuel source, such as natural gas, fuel oil, or coal, that has a finite supply
Green building	A comprehensive process of design and construction that makes use of techniques in order to reduce energy consumption and minimize environmental impacts of a building, while contributing to the health and productivity of the occupants
Greenhouse gas	The entrapment of heat within Earth's atmosphere by gases such as carbon dioxide and methane, covering the heat inside the atmosphere

Ground source heat pump	A system of underground pipes extracting natural heat from the ground and increasing the temperature by means of a heat pump which provides hot water or heating to the building
High-efficient insulation materials	A general understanding is that air filled thermal insulation materials with thermal conductivity values below 0.025 W/(mK) and evacuated thermal insulations with thermal conductivity below 0.015 W/(mK) can be considered as high-efficient insulation materials for buildings
Hydronic	A heating system for a building in which circulating water acts as the medium for carrying heat throughout the structure, in particular when the circulation is aided by a pump
Life Cycle Analysis (LCA)	An environmental impact tool utilized in order to compare the environmental performance of two or more scenarios
Life Cycle Costing (LCC)	A procurement evaluation technique that determines the total cost of acquisition, operation, maintenance and disposal of items, which potentially are under procurement
Photovoltaic	Solar photovoltaic collectors comprise of arrays of a material which converts solar radiation into electricity
Sustainable building	Buildings that comply with core business needs (usability, viability) over time (adaptability) to the lowest possible use of resources (economy, energy, water consumption)
Sustainable development	A development that meets the needs of the present without compromising the ability of future generations to meet their own needs

Chapter 1

Introduction

The concept of sustainable development gained a broad acceptance subsequent to the 1987 Brundtland Commission's report, *Our Common Future*, at the request of the United Nations (United Nations, 1987). The report established an ethical principle: *"We must satisfy our generation's needs without destroying the opportunities for future generations to satisfy their needs"*. The task the United Nations gave to the countries of the world was to merge technology, economics and sustainable development with a new lifestyle based on equity. The United Nations General Assembly called attention for two key ideas:

- That sustainable development engages co-operation on a global scale
- That well-being of people, economies and the environment is completely interlinked

Sustainable development involves integration and growth in a way that benefits the widest range of sectors and between generations. Our actions today will have a significant impact elsewhere and on future generations. To reduce energy consumption and emissions of greenhouse gases is an overarching societal goal concerning all.

Construction and buildings account for 40% of Sweden's energy use and about 25% of the country's carbon emissions (United Nations Environment Programme, 2007). According to the Swedish government's set targets for energy use and environmental quality, the total energy consumption per heated unit area in residential and commercial buildings should be reduced with 20% by 2020 and 50% by 2050 compared to the annual consumption of 1995 (Scheurer, 2011). According to the Swedish Energy Agency (2013), if current policy instruments continue to 2050, the energy (total energy purchased) per square meter, will decrease by 22-30 percent by 2050 compared to 1995. Furthermore it is necessary for the Swedish building sector to completely act independently of fossil fuels for energy purposes, in line with the continuous increasing amount of renewable energy by 2020 (Swedish National Board of Housing and Planning, 2009). To cope with current energy efficiency requirements, the building owners' desire to improve the existing housing stock ties in with the Swedish government's goal of achieving the standards of new buildings. In parallel, the building code of today is very largely focused on energy, so new buildings have to be built with energy efficiency as a main target.

There are currently about four million dwellings in Sweden (Statistics Sweden, 2013). About 1.4 million new dwellings were constructed between 1961 and 1975 as a part of the political vision of a modern welfare state (Hall and Vidén, 2005). Considerable state loans made way for the immense building projects that ensued, subsequently labeled as the Million Homes Program (1965−1974). The Million Homes Program was the Swedish government's incentive to remedy the housing shortage and for that time period, bad living conditions. The aim of the program was to increase the current building stock with one million apartments during a 10 year period.

Societal targets for moisture, mold and other factors in buildings are significant for achieving healthy buildings and improved indoor environment. In 2006, the Swedish government commissioned the Swedish National Board of Housing, Building and Planning to conduct a survey of the Swedish building stock in order to assess measures and expenses for amending damages or deficiencies required to reach existing targets and to set new ones concerning the built environment (BETSI, 2011). A number of approximately 1800 buildings were statistically chosen to be representative of the complete building stock and were investigated by specialists and building experts. The outcome of the investigation was first presented in 2009, with more extensive results in 2010. The Swedish National Board of Housing, Building and Planning estimates that approximately 66% of all buildings in Sweden are damaged in some sense. Most damages/defects are however, not of serious nature. From the detected damages approximately 45% are moisture related and can adversely affect the indoor climate (BETSI, 2011b). This study furthermore examined the driving factors in decision making for new renovation projects.

1.1 Research Scope and Limitations

The scope of the undertaken research study in this thesis is based on the hypothesis set forth in the ACES project ("A Concept for promotion of sustainable retrofitting and renovation in Early Stages"). These factors are believed to influence sustainable renovation most within the scope of this project. For this purpose, four distinct aspects: technical, economic, workers' health issues, and energy, leading to development of a framework for an approach to sustainable renovation, have been undertaken in this study, as shown in Figure 1.1.

Figure 1.1. The scope of the research study.

The benefit of utilizing this approach stems from the independency of these topics and their overall interdependency. The independent assessment of each of the aforementioned aspects of the project will provide an overall framework for a sustainable approach within the built environment that encapsulates all the mentioned features. Hence, this framework will not suffer from potential shortcomings of targeting only single features.

Hence, the following factors have only been considered partially or entirely omitted in this study: site planning and building orientation, ventilation systems, building materials, renewable and alternative energy sources. Equally, the scope of this research is not an in-depth analyses of a single metric and an optimization thereof, as such an approach would not necessarily contribute to a more profound understanding of the entire research scope.

In this thesis, the terminology of restoration, refurbishment and renovation have the same meaning and therefore been utilized interchangeably.

Technical Approach

The technical approach in this study is concerned with the establishment of the technical means which facilitate the actualization of sustainability within the built environment. One aspect of the technical approach deals with the usage of high-efficient insulation materials such as Vacuum Insulation Panels (VIPs) and aerogels, which are explained in further detail in Chapter 2. Moreover, the technical aspects of this study relate to development of a novel tool for estimating the required primary energy for a building (ESPEET), an operational decision support process for renovation, and energy analysis of a church building, all found in Chapter 4 are included. In light of this background, the technical approach also includes the identification of two suitable high-efficient insulation materials to be used for refurbishment purposes of buildings and appropriate means for application of the aforementioned technologies.

Economic Approach

The economic approach is one of the most important implementations regarding sustainable refurbishment within the built environment. Regardless of the benefits provided by the technical solution, the cost must be justified for each corresponding technical solution. In the context of the ACES project, this thesis has focused its scope on some of the economic benefits of utilizing high-efficient insulation materials, as the main economy related aspects were explored by other researchers in the research team.

Workers' health

Despite current laws, regulations or additional factors that seek to ensure a safe and healthy environment for construction workers, the Swedish construction work force still face challenges. In this study the Construction Sector Chain Disaster Theory (Gohardani and Björk, 2013b,c) is employed in order to obtain an insight into preventive measures against injuries or death within the construction sector. Furthermore, the importance of statistical data pertaining to accidents and injuries is highlighted, for future prevention of such incidents or accidents and in order to promote a healthier and safer working environment for Swedish construction workers.

Energy Approach

In this study a tool for providing a simplified insight into calculation of the primary energy and exergy in new or existing buildings has been developed. Additionally, the energy efficiency of high-efficient insulation materials has been considered by utilizing a simulation tool. Furthermore, assessment of energy calculations related to environmental certification of buildings in Sweden is studied. The results indicate how occurred calculation errors may influence submitted applications to Sweden Green Building Council (SGBC).

The topics included for each of the abovementioned aspects have been chosen as suitable contributing factors to the hypothesis of the ACES project, following consensus among the involved researchers. The choices however do not imply that these topics are more important than other relevant topics within the same discipline.

1.2 Hypothesis

The hypothesis of the ACES project is based on the idea that there are rational reasons depending on ”sound economy” for carrying out renovation that will make a building operate in a sustainable manner. The renovation work will hence be a value-driven process, which contributes to sustainable development. In the conducted study, contributions towards testing of this hypothesis are made related to processes that contribute to sustainable development. In order to substantiate this hypothesis, a number of research questions/sub-hypotheses have been formulated, in order to highlight the scientific contributions of this study.

Research Questions

The research topic of this thesis is partially synergistic with the research questions of the ACES project. In particular, the motivation of restoration by economic reasons, workers’ health issues and production of documents that can spark the interests of stakeholders in order for them to make attentive decisions regarding sustainable building, have been addressed within the framework of this thesis. The conducted study relies on rational reasons for buildings to operate in a sustainable manner, while preserving a sound economic approach, resulting in sustainable development. The only deviation not addressed in this thesis in relation to the ACES project is how quality assurance can contribute to sustainable development. This particular aspect of the research was examined by other researchers involved in the project (Frangou et al., 2013).

The following research questions have been addressed in this thesis:

- **Q1**: What approaches are taken towards sustainability in early project stages related to the built environment and why are these of importance?
- **Q2**: Can building owners/stakeholders utilize the findings of this study in order to make sustainable decisions concerning renovation in early project stages?
- **Q3**: Do the findings of this research have applications within the realm of real-life situations?
- **Q4**: Which parameters constitute common inaccuracies in applications for environmental certification of buildings in Sweden?
- **Q5**: Can this study motivate building owners to renovate a building for improved performance concerning energy efficiency and indoor comfort?
- **Q6**: What is the attitude of construction workers within the built environment in Sweden, concerning current health and safety related measures at their workplaces?

1.3 Structure of the Thesis

List of appended articles

The following articles are appended in this thesis:

- **Article I:** Navid Gohardani, Folke Björk. ”Sustainable refurbishment in building technology”, Smart and Sustainable Built Environment, Volume 1, Issue 3, pp. 241−252, Emerald, 2012.

  Contributions: Gohardani performed the research and the literature review. Björk contributed with an overall view about the topic and with a number of references.

  This article features a thorough literature review of the topic of sustainable refurbishment in the built environment. In this article, selected refurbishment tools and methods are outlined in further detail and a regional glance at building refurbishment is presented. In addition, a suggested path forward is shown for continuous sustainable refurbishment projects.

- **Article II:** Navid Gohardani, Tord Af Klintberg, Folke Björk. ”Turning Building Renovation Measures Into Energy Saving Opportunities”, Structural Survey. (Submitted for publication)

  Contributions: Gohardani assembled the research findings and the literature review and designed the methodology. Af Klintberg contributed with data to the study and useful sources implemented in the study. Björk improved the methodology and contributed with improvements to the manuscript.

  This study describes initiatives that promote energy saving measures in conjunction with planned major renovations in residential buildings, owned by tenant owners' cooperatives. This article presents a proposal for a developed strategy; the operational decision support process.

- **Article III:** Navid Gohardani, Folke Björk, Per Anker Jensen, Esmir Maslesa, Stratis Kanarachos, and Paris A. Fokaides. ”Stakeholders and the Decision Making Process Concerning Sustainable Renovation and Refurbishment in Sweden, Denmark and Cyprus”, Architecture & Environment. Volume 1, Issue 2, pp. 21−28, Sciknow Publications, 2013.

  Contributions: Gohardani assembled the research findings related to Sweden and edited the manuscript. Björk contributed to the overall analyses of the data from Sweden. Jensen and Maslesa contributed to the research findings of Denmark. Kanarachos and Fokaides contributed to the research findings of Cyprus.

This article outlines the decision making process related to sustainable renovation in buildings with emphasis of the attitudes and priorities of stakeholders in Sweden, Denmark and Cyprus based on case studies.

- **Article IV:** Navid Gohardani, Ivo Martinac, Folke Björk. ”Common inaccuracies in environmental certification applications in Sweden", Smart and Sustainable Built Environment. (Submitted for publication)

  Contributions: Gohardani assimilated the data for the case study and edited the manuscript. Björk and Martinac, reviewed the manuscript and provided insights and suggestions for improvement.

  The purpose of this study has been to contribute to further understanding about the level of ability among building consultants and energy experts, comprehension of environmental certification of buildings, and enhancement of the ability to produce high-quality calculations concerning building-related energy usage.

- **Article V:** Amir S. Gohardani, Navid Gohardani, Folke Björk. ”One Facet of the Swedish Construction Industry and Applications of the Construction Sector Chain Disaster Theory”, Management & Marketing Journal. (Submitted for publication)

  Contributions: Gohardani A.S. established the basis of the theory and edited the manuscript. Gohardani N. contributed with application of the inventory and conducted the surveys. Björk reviewed the manuscript and provided suggestions for improvement of the analysis.

  The purpose of this study has been to highlight and minimize health hazards, injuries and fatalities among Swedish construction workers by employing the Construction Sector Chain Disaster Theory (CSCDT).

- **Article VI:** Navid Gohardani, Folke Björk. ”Improvement of the energy performance of a church building by the exchange of an electric coil heating system to a hydronic ground source heat pump system”, Energy and Buildings. (Submitted for publication)

  Contributions: Gohardani conducted the research and assimilated the data for the case study. Björk contributed to the processing of data and reviewed the manuscript.

  In this article, the energy performance of a church building subsequent to an exchange of an existing electric coil heating system to a hydronic ground source heat pump system, is assessed and discussed. Furthermore, the energy *demand and the energy signature of the building is analyzed prior to and after installation of the ground source heat pump system.*

- **Article VII:** NAVID GOHARDANI, Kjartan Gudmundsson. "Sustainable building renovation and refurbishment with applications of Vacuum Insulation Panels", SB11 World Sustainable Building Conference, Proceedings Vol. 2, Helsinki, Finland, 18 – 21 October, 2011.

  CONTRIBUTIONS: Gohardani conducted the research and simulations. Gudmundsson provided the graph on page 3 and the simulations on page 8 of the article and also contributed with improvements to the manuscript.

  In this study, the usage of Vacuum Insulation Panels for building renovation and refurbishment is considered. In particular, simulations of the thermal performance for a number of different configurations of insulation material placements in building envelopes are actualized. Similarly a supplementary insulation of balcony slabs is studied.

- **Article VIII:** NAVID GOHARDANI, Folke Björk. "Economic and environmental benefits related to a sustainable building refurbishment", Proceedings of the 1st International Conference on Building Sustainability Assessment, Porto, Portugal, 23 – 25 May 2012.

  CONTRIBUTIONS: Gohardani conducted the research and performed the simulations. Björk provided improvements to the manuscript.

  An insight into the economic and environmental benefits related to a sustainable building refurbishment is outlined in this article.

- **Article IX:** NAVID GOHARDANI, Folke Björk. "A Simulation Approach Towards A Sustainable Building Design Based on Energy Analysis", Proceedings of the 2012 International Conference on Sustainable Design, Engineering, and Construction, Fort Worth, Texas, U.S.A., November 7 – 9, 2012.

  CONTRIBUTIONS: Gohardani conducted the simulations and produced the research findings. Björk contributed with assessment of the results and a review of the manuscript.

  This study seeks to explore the influence of a modified building geometry and different geographical locations on a generic building structure within the context of sustainability, by usage of Building Information Modeling.

- **Article X:** Navid Gohardani, Folke Björk. "A Simplified Approach Towards Net Zero Energy Buildings: The Early Stage Primary Energy Estimation Tool", BESS-SB13 California: Advancing Towards Net Zero. Pomona, California, U.S.A., June 24 – 25, 2013.

  Contributions: Gohardani conducted the research and simulations. Björk contributed with an assessment of the results and a review of the manuscript.

  In this article, an insight into a tool developed for estimation of the primary energy in early stages of retrofitting/new built projects has been provided.

Chapter 2

Research Background

2.1 The ACES Project

There are a number of motivating factors for the undertaken research study. In particular, the fact that energy efficiency of buildings built during the last decades have contributed to an inefficiency within the building sector (Ryghaug and Sørensen, 2009), which ultimately contributes to high greenhouse gas emissions and other environmental hazards and to a waste in energy. Additional motivation stems from the fact that both building owners and building occupants ultimately seek to reduce their energy expenses, particularly in times of increasing energy costs. Hence, the combination of the aforementioned factors together create incentives for energy efficiency in buildings and serves as a good motivational platform from which the conducted study has evolved.

The work presented in this study is part of the ACES project, which is a joint research project between Royal Institute of Technology (Sweden), Danish Technical University (Denmark) and Frederick Research Center (Cyprus). The reasoning behind the ACES project is related to the fact that more than 40% of the total energy in Europe is spent within the building sector, which significantly contributes to greenhouse effects and air pollution. Further, approximately 85% of the 160 million buildings in EU are thermally inefficient (European Commission, 2012). Hence, it is crucial for the existing building stock to be refurbished.

The essence of this project is based on the idea that decisions about upcoming renovation and energy saving measures should be undertaken at an early design stage, when usually the focus of the project team is devoted to measures that uphold basic functionalities. Hence, by employing this approach a plan is made for renovation measures that will result in the building operating in a more sustainable manner. This project seeks to underpin the motivation of building owners to renovate a building for improved performance with regard to energy efficiency and indoor comfort (Swedish ScienceNet, 2010). The objectives of the ACES project can be summarized as follows:

- To exhibit that restoration resulting in a sustainable development can be motivated by economic reasons
- To explain how quality assurance can contribute to a sustainable development
- To explain how workers' health issues can contribute to a sustainable development
- To produce documents that will motivate stakeholders to continue their development towards sustainable renovation

These objectives have been examined in further detail through different work packages by the countries involved.

2.2 Reflections in relation to the design process in architecture

Research endeavors in architectural design date back to the foundations of building construction itself. Remarkably, the true limitations of design procedures stem from the confined boundaries preset in the mind of mankind. Even the perceptions an architect holds throughout the complex process of designing an architectural wonder, contributes to a fundamental impact on the performed procedures commonly applied. Research methodologies in architecture and design, tend to primarily focus on architectural visions, trends or the actual design features of a construction, and not on the person behind it all. Following efforts directed towards a trajectory that encircles the architect and his or her perception regarding architecture and design research, this chapter aims to highlight the views of many prominent architects whose architectural wonders have served as crucial milestones in history and influenced generations of people.

It is essential to recognize that a complete image of the key issues influencing the mentioned research cannot be fully embraced, unless the underlying key points are treated. One of these relations concerns the authorial link between architects and buildings, shown in Figure 2.1.

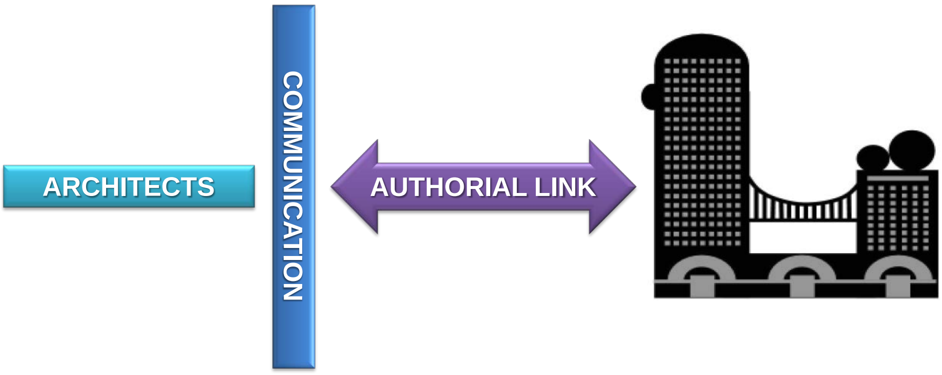


Figure 2.1. The authorial link between architects and buildings influences architectural design research.

Given an Albertian view (Unwin, 2010), the connecting lines between architects and their works of architecture are substantially influenced by the environment of the architectural action. Development of structural forms based on building materials, modifications of archeological reconstructions, structural analysis and maintenance requirements over the years, displays one trail towards architectural research. Frayling's dialogue (Frayling, 1993) on the topic of research and art design emphasizes further, three research paths: Research into art and design, research through art and design, and research for art and design, as depicted in Figure 2.2.

Another trail follows a completely different direction and has concentrated its research endeavors outside building projects and in particular on: structural and climate studies, energy conservation and different aspects of sustainability. Notwithstanding, the major role of architecture in any society, it has been argued that this topic is often treated as a separate subject. Once again, the essential injection of effective communication seems to serve as an access point to other disciplines and as a representative portrait of architecture in a multidimensional society. The overall assessment one could make about the impact of architecture is that it holds a nature that could include major contributions to so many other disciplines than stand-alone art, practice, teaching, and the design process.

Evidently, this view would only become reality under the condition that architects within an architectural domain reach out to other actors such as: city planners, builders, patrons etc., with critical and effective instruments of communication that seek to glance at the impact of ideas from a variety of different perspectives. Architectural design and research is thus not a straight path to perfection, but a convolution of elements that through measured efforts, pursuits, approaches, achievements and the delicacy, ingenuity in arts and literature hold one the largest impacts on human lives.

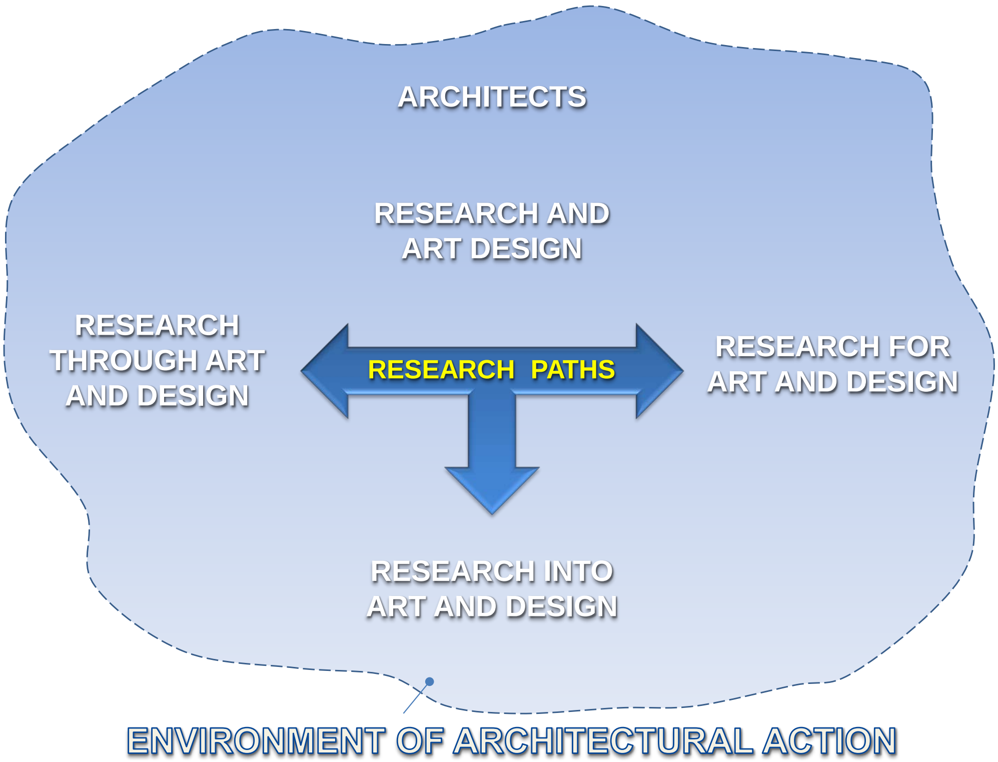


Figure 2.2. Three different research directions related to the topic of research and art design.

2.3 Sustainable Building

A great amount of the energy used in the world today, along with its greenhouse gases is connected to the building sector. The path towards sustainable development involves changes in the concepts of architecture, construction and spatial planning. Sustainable development further needs to take a broader approach incorporating the complete impact of a building on the well-being and health concerns of the occupants and the environment. One step along this journey is the drive to increase energy efficiency in heating and cooling systems in order to conserve energy. Moreover, it is essential to construct energy-efficient buildings with zero carbon footprints in order to reduce the environmental impacts of building construction.

2.3.1 Sustainable Development

Sustainable development is a term utilized for a collective of terminologies involving improvements related to social, economic, and the environmental conditions of individuals and a better quality of life (Ortiz et al., 2009). Realizing this goal for current and future generations has however been addressed as one of the great challenges of the 21st Century (Sachs and Warner, 1995). As a global emerging sector, the construction industry is very attractive in both the developed and developing countries. This sector however, is equally responsible for generation of greenhouse gas emissions, high-energy consumption, environmental damage, resource depletion, and external and internal pollution (Zimmermann et al., 2005; Ortiz et al., 2009).

2.3.2 Early Project Stages

The early stages of a project within the built environment is according to Kolltveit and Grønhaug (2004), defined as *"the process and activities that lead to, and immediately follow, the decision to undertake feasibility studies and to execute the main project"*. In effect, this entails that the early stage is initiated prior to the instant when a decision has been made about the main project. Its duration lasts until decisions are made for activities and processes needed for executing the project. The term early stage in regards to the built environment is a subject for different interpretation based on the observer's perspective with different initial points (Ryd, 2008). In this context, the true early stages occur upon a market condition which is conducive to a business opportunity. The early stages are then apparent prior to the project formulation and further existent in connection with each individual subproject. Nonetheless, it is notable that cost reduction and efficiency in employed processes are contributing factors to a shortened time limit for conducting the outlined processes. Ryd (2008) provides an insight to planning in the early stages, goals and visions, identification of needs and stakeholders, collaboration, and procurement in early stages.

One of the main challenges related to early phases of projects in the built environment is related to a high level of uncertainty (Chapman and Ward, 1995) related to the development of the technical concept, which per definition of Kolltveit (1988) describes an approved idea of the technical solution that satisfies the functional, quality and capacity requirements. The importance of effective execution of early stages of a major project and its related decisions, have a profound effect on decisions intended for future value generation and may otherwise result in conceptual changes during the implementation phase as exhibited by Baker (2002) and Andersen et al. (1999). Hence, from an economic perspective, it is noteworthy that decisions made during the early stages of a building project can significantly influence the costs and efficiencies of subsequent phases.

The purpose of the early stages, can be summarized as expressed by Ryd (2008): *"through creative work transform the users (construction client's) requirements concerning function and quality as well as other desires into an architectural and engineering solution and a basis for production which is economical for both the user/client and contractor/supplier and which also allows for other requirements stipulated by society and affected parties (stakeholders) and the existence of existing buildings regarding safety and the environment also to be met"*.

Schade et al. (2011) outline that for the client the early phase is initiated when a business opportunity or a societal demand arises. The commencement of a building project often includes a business planning phase for the client where goals, budget, time frame and organization are determined before other stakeholders from the Architecture, Engineering and Construction (AEC) sector are involved. The main objective of sustainable design is to determine architectural solutions that guarantee the welfare and coexistence of humans, other living organisms, and inorganic elements as described by Kim and Rigdon (1988). The authors discuss that sustainability in architecture can be associated with three principles; economy of resources, life cycle design and humane design, as shown in Table 2.1. Economy of resources is concerned with the reduction, adaptive reuse, and recycling of the natural resources that are used as inputs to a building. Furthermore, life cycle design provides a methodology for analyzing the building process itself and its influence on the environment (Malmqvist et al., 2011). Finally, humane design focuses on the interactions between humans and the natural world.

Economy of resources	**Life Cycle Design**	**Humane Design**
Energy Conservation	Pre-Building Phase	Preservation of Natural Conditions
Water Conservation	Building Phase	Urban Design Site Planning
Material Conservation	Post-Building Phase	Design for Human Comfort

Table 2.1. Sustainable design and pollution prevention (Kim and Rigdon, 1988).

The principles described in Table 2.1, result in different methods. Reducing the expenditure of resources will lead to a decrease in the utilization of non-renewable resources in the construction and operation of buildings. There is a continuous flow of both natural and manufactured resources in and out of a building. This flow commences with the production of building materials and continues all through the life span of the building. A building also requires a regular flow of energy input during its operation. The environmental impacts of energy consumption by buildings occur primarily aside from the building site, through extraction of energy sources and generation of power. Subsequently, the process of heating, cooling, lighting, and the operation of other apparatus included in the building's energy consumption is not recoverable.

The pre-building phase includes finding of an appropriate site for the building, building design, and building material processes. The stage in a building's life cycle when it is physically being constructed, is referred to as the building phase. With the vantage point of sustainability, during this phase, construction and practices are optimized in order to reduce the environmental impact of resource consumption. The continuous health effects of the building environment on the building occupants are also considered.

The post-building phase commences at the time when the useful life of a building has ended. Thus, building materials are recycled to be used as resources for other buildings or are discarded as waste. The objective is to decrease construction waste by recycling and reusing buildings and construction materials. Humane design is concerned with the survival expectancy of all elements of the global ecosystem, including plants and wildlife, whereas economy of resources and life cycle design deal with efficiency and conservation. For modern societies it is estimated that more than 70% of a person's lifespan is spent indoors. Therefore, an essential role of a sustainable building design is to provide built environments that sustain the well-being of building occupants including health, physiological comfort, psychological welfare, and productivity.

A successful sustainable design strategy relies much on the manner which the occupants use their building. For example; a building which is highly well-insulated may still consume considerable amounts of heating energy if its windows are constantly kept open by the building occupants. Additionally, the building performance is probable to be compromised if not the occupants are informed and educated about the operation of the building and the motivation behind sustainable design.

2.3.3 Decision making and stakeholders

The building sector consists of a wide segment of decision makers at various levels, ranging from government entities to building owners, architects, engineers, developers, builders, and home owners. The built environment in return is divided into various market segments. As a result, legislation and policies need to be able to cover all the barriers faced by the mentioned stakeholders during the entire decision making process. Some of the present barriers include:

- Greater initial costs for the parties involved
- Higher market risks with emerging technologies
- Uncertainty regarding regulatory, policy and technical issues
- Inadequate available information

All parties involved in the decision making process play a significant role in the long-term visions of the building sector, employing policies and technologies to meet set goals. However, stakeholders faced with significant uncertainty regarding regulatory, policy and technical issues are likely to hesitate and delay the decision making process. Consequently, regulations and policies need to be planned to address uncertainty in a systematical manner. Furthermore, consumers need to be provided with adequate incentives that address the environmental costs of energy usage, otherwise they are unlikely to make optimal economic and environmental decisions.

Some of the aforementioned market barriers can be eliminated by:

- Removing regulatory, fiscal and policy barriers
- Providing stakeholders with more available and relevant information
- Improving the knowledge base for architects and engineers involved with heating and cooling systems concerning energy-efficient technologies
- Execution of regulations and policies leading to deployment and reduction of expenses by attaining cost advantages due to expansion

It should be noted that some stakeholders do not have the long-term interests as other decision makers when they make decision in early design stages (Susniene and Vanagas, 2005). These can consist of developers seeking to minimize initial construction costs without considering the interests of building owners/occupants. Moreover, some markets such as the one for cooling and heating systems for buildings, are characterized by information that differs significantly. In such markets usually the seller benefits from a better or more complete information than the buyer. Regulations and policies are necessary to make certain that governments, policy makers, and consumers become aware of the potential of energy-efficient technologies, in order to save energy and reduce CO_2-emissions. Additionally, governments can lead the way for policies to direct the public procurement of low and zero-carbon technologies. Decision making during early design stages points out the direction of a project with cost-effectiveness in mind. An apparent developed project framework, directs the decision making process throughout the project; the building design and its systems, the construction process and building operations and maintenance.

An integrated project delivery is built on collaboration between the different parties involved in a design project (AIA, 2007). In an integrated project, the key participants are involved from the earliest practical moment. Decision making is improved by the incursion of knowledge and expertise of all key participants. Their combined knowledge and expertise have the largest impact during the project's early stages where educated decisions have the greatest effect. In a fully integrated project, definitive decision making abilities are not delimited to a single team member. Instead, all decisions are made unanimously by a defined organization of decision makers. Regardless of how the parties decide to structure the decision making organization, in an integrated project all decisions are made in the best interest of the project (AIA, 2007). The structure of the decision making organization differs from project to project, but always consists of some combination of the primary participants and key supporting participants working collaboratively to provide decisions in the best interest of the project. A multidisciplinary approach by a design and construction team allows its members including building owners, site planners, landscape architects, architects, engineers, contractors, interior designers, lighting designers, tenants, management companies, builders etc. to share specialized proficiency and synchronize their individual design efforts to accomplish a well operated integrated building (AIA, 2007).

Integrating input from all key stakeholders and members of the design team before schematic design commences is essential, particularly since 70% of the decisions related to environmental impacts are made during the initial 10% of the design process (Boecker et al., 2011). Decisions made early in the design process have a significant impact on how the building will perform over its lifetime, affecting not only how much energy will be required to operate it, but also how comfortable it will be to live in.

The majority of building projects are in the end limited by the available budget, regardless whether they are refurbishment or new construction projects. Budgets will constrict both sustainability measures and functional design solutions. For example, limiting the space provision for the building occupants will most likely be seen as a reduction in quality from the occupant's point of view, but may well improve the energy use per occupant. Similarly, a measure may create benefits altogether, for instance, improving access to daylight will decrease energy consumption for lighting and be regarded as a positive progress towards sustainability by most building occupants.

2.3.4 Sustainable Restoration and Adaptive Re-usage

In this section, the role of restoration pertaining to sustainable development is examined. A macroscopic approach regarding this task encompasses multi-dimensional aspects in regards to combined contributions ranging between the impact of quality assurance, workers' health issues and written evidence that would encourage stakeholders to make and maintain their investments in sustainable renovation. In light of the complex considerations within the aforementioned research domain, a key issue centralizes around the economic and environmental evaluation of restoration. Moreover, a crucial question that arises within this context is: What drives the economic and environmental aspects of restoration?

Evidently, the current insight of this rather bilateral evaluation remains ambiguous and a basic dissection that would further reveal any contributing factors is beneficial. In this research study, an initial step that pinpoints the necessity for restoration and a motivation for its role, serves as a starting point for further progress. Additional details regarding renovation needs may also include current renovation measures in different countries and considerations regarding renovation for a number of typical buildings.

Through additional pieces of information that investigate the advantages and disadvantages of restoration, both from an economic point of view and an environmental facet, the basis for further discussions into the subject matter is set. Provided that an adequate flow of information is shared for further evaluation of the advantages and disadvantages for a combined economic and environmental evaluation outlook, a few emerging factors will be considered throughout the course of this research. Demands for restoration might seem rather trivial in certain instances and not distinctly evident in others. A word check for the noun restoration in a dictionary returns the following wording: "a reconstruction of an ancient building, showing it in its original state" (Random House Dictionary, 2010). Even though reconstruction of historical buildings (Cox, 2010) does include a major part of building restorations, restoration itself extends far beyond the premises of heritage restoration. Fire, flooding, acid rain and natural disasters such as earthquakes are a few selected phenomena, affecting the condition of buildings.

One of the trade-offs in building preservation is the choice between complete restoration and adaptive reuse. Given the expensive process of a complete building restoration, an adaptive reuse procedure can be regarded as an alternative practical approach of preserving parts of a building's historical fabric (Hein and Houck, 2008). In the United States, a historical building is not necessarily removed from an economic profitability domain, as preserving such a building involves many greater aspects. In fact, in many cases building restoration is a vital economic vehicle. In 1997, it was shown that historical preservation activities generated $580 million annually in direct economic activity for the state of New Jersey (Garbarine, 1997). A total demolition of a historical downtown building, with aims to build a new building is comparable to the waste of approximately 1.3 million recycled aluminium cans and that does not even include the impact on the landfill or the embodied energy that has been lost (Rypkema, 2007).

Thus, on the one hand the environmental aspects of demolition efforts versus restoration efforts are noteworthy, yet on the other hand, one may argue that construction of new high-performance green buildings may very well contribute to the global green agenda, by meeting all the necessary requirements for sustainability (OPRHP, 2009). Having stated this fact, there is indeed a disparity in the demands for sustainability for different countries. Within this context, one could link the retrofitting needs of typical building complexes to sustainability. Retrofitting costing estimates can be made by EPIQR (Energy Performance Indoor Environmental Quality Retrofit), a methodology capable of enabling apartment owners interested in refurbishment measures with detailed cost analyses (Caccavelli and Genre, 2000). As discussed earlier, the aim of this research study is to investigate the role of renovation and refurbishment with particular attention to the drivers of economic and environmental aspects.

Upon further reflection about the key question that seeks to find the drivers behind economic and environmental aspects of restoration, a theory needs to be formulated. The author's own theory regarding the choices between economic and environmental evaluations of refurbishment should be based on the outlook for a potential snowball effect, i.e. a scenario where the effects of these factors become increasingly significant with time. Further details about the snowball effect can be illustrated by a number of examples through which the author makes arguments about the aforementioned supposition. Principally, the snowball effect refers to a specific decision that systematically contributes to a larger set of chain reactions capable of including both the responses to advantages and disadvantages.

The decision platform for making correct choices between the economic and environmental aspects of renovation is rather vague and involves many degrees of freedom. Perhaps, the most significant issue raised within these rather convoluted choices is to recognize that sustainable and economic aspects are interrelated. In a nutshell, the overall impact of all made decisions is of vital importance. In order to place the snowball theory into practice, one can assume that a potential decision maker is given the option to consider the restoration of a public administration building as well as a residential building. Obviously the first consideration one has to make is the location of these two buildings, since the stand-alone location determines a number of factors regarding local attitudes versus sustainability. The restoration of a public administration building is most likely restricted in many ways as it may also involve preservation of certain structures of the building in harmony with the surrounding landscape. These restrictions may further impose additional economic burdens that prevent novel technical solutions to be implemented, such as probable damages to details of architectural value related to a historical building.

Conversely, some technical solutions may equally improve the desired building performance and therefore be suitable for integration even in cases where historical attributes for a certain building cannot be compromised. An example for such a technical solution can be related to for instance VIPs, which serve as a more efficient alternative to conventional thermal insulations used in buildings (Nemanic, 1995). Given their low thermal conductivity and suitability for refurbishment of historical and pristine buildings, these panels are more expensive than conventional thermal insulation pieces. Nevertheless, they also allow more living space due to their compactness (Baetens et al., 2010b).

Hence, if one would revisit the restoration ideas for a public administration building or even a residential building, it has already been demonstrated that modern technical solutions, such as implementation of VIPs, are readily available for a diverse set of applications that cover the entire spectrum of both modern and pristine buildings. Once the availability of a certain refurbishment technique has been established, the next level of analysis is to consider the overall effect for such an application. Ultimately, the overall decision has to be made in view of how many additional factors, a particular decision regarding a partial or complete renovation would activate.

Since refurbishment with VIPs has been discussed as a cross disciplinary approach for a wide range of buildings, it would be suitable to use this technical option as an exemplary case to uncover the discussed factors through seeking answers to a hypothetical scenario for which a number of selected questions are posed:

1. Is there adequate technical data available for considerations of demolition, restoration and adaptive reuse of this building?
2. Which role does preservation of this specific building complex have?
3. Is there a particular need to only consider the thermal insulation of this building or are there other refurbishment needs?
4. What are the economic benefits associated with demolition, total renovation and adaptive reuse of this building?
5. What are the implications on sustainability for a possible demolition, total refurbishment and adaptive reuse of this building?
6. From a macroscopic vantage point, how does a decision within this context impact the society?

Although, the list of these questions can be endless, the principal aim of this section is to utilize these questions as interesting starting points for further discussions. The first question essentially determines if there is enough data gathered, regarding preliminary decisions for further actions. This data could be related to climatic considerations and the needed energy efficiency measured for different building locations (Guertler and Smith, 2006). In order to answer the second question, one should reflect upon the imposed necessity to preserve the building as a historical building or alternative options. In many cases, a historical landmark will have more criterion for limitations than a residential building would have. Thus, further considerations of the answers to the third question, enable multiple assessments of the refurbishment needs. Within these settings the choices made are driven both from economic and sustainable agendas. Between the choices for demolition, total restoration and adaptive reuse of buildings, the ultimate decisions result in a number of chain reactions that incur the earlier discussed snowball effect.

Major considerations of these effects should reveal the number of adjacent programs estimated to be initiated, with such an initiative. Whether the goal is demolition, total restoration or adaptive reuse of a building, the final economic assessment should consider the total economic benefits incurred by such a decision. In other words, one should envision whether or not the made decisions would activate the global or local building activities, related entrepreneurial endeavors, export and import of building materials, tax deductions related to the building site and environmental considerations. The environmental issues concern all possible interactions with the surroundings and direct implication, such as preset emission reduction targets.

Furthermore, CO_2 emission reduction, which in part is directly related to effective thermal insulation, represents an exemplary case that could potentially be achieved through the implementation of VIPs or other high-efficient thermal insulation materials.

The answers to questions five and six are highly interrelated as sustainability cannot be treated in view of an isolated subject, independent of economic forecasts and vice versa. In many ways, the answer to the last question is a bold attempt to consider an isolated event such as demolition, refurbishment or the adaptive reuse of a building in a broader context. A historical, administrative or commercial building does not necessarily have the same demands for preservation as residential buildings, as the difference between these types of buildings is rather great. Therefore the different mechanisms involved within the snowball effect theory can very well vary greatly on a case by case basis. Possible limitations in the snowball effect could emerge for certain cases, confined to local politics. Consequently, if the findings from implementation of a snowball theory result in a moderate impact on a local level, many decisions that would encourage further advancement could be abandoned depending on the circumstances. Hence, it is rather expected that the overall impact of the rolling snowball should extend beyond the isolated problem and in the decision making process, the greatest impact that would benefit society (both in terms of sustainability and economy) should be endorsed.

Conclusively, in this section an attempt has been made to address a few viewpoints that are concerned with the economic and environmental aspects of renovation. Through the implementation of the snowball theory it has been demonstrated that choices regarding refurbishment are rather convoluted and should be considered from different angles and on different levels. Illustration of the aforementioned levels within the suggested snowball theory have been discussed with selected exemplary questions. It is suggested that the overall decision regarding the most appropriate choice of refurbishment is based on the total impact of the final snowball size that encompasses a notable impact on society, including both sustainable and economic aspects.

2.4 Economic Aspects of Building Refurbishment

Building owners, building occupants and the general public carry the cost of building construction. The main direct cost outflows are related to building construction, renovation, operation, and building-related infrastructure. Indirect costs can be associated to building-related occupant health and productivity issues as well as external costs, such as waste generation and air and water pollution. Often the individuals responsible for design, construction, and initial financing of a building are different from those operating the building and meeting its operational expenses. Nevertheless, the decisions made at the early stages of building design and construction can considerably influence the costs and efficiencies of subsequent phases.

Depending on the object in need of renovation, a positive attitude towards sustainability can further be completed by the preservation of architectural, historical and cultural values of a building. For residential buildings however, most building occupants are solely interested in the lowest housing cost as possible, regardless of the benefits that an early stage sustainability approach yields. In light of this discussion one has to convey the message that in order to cope with the increasing space heating costs and to meet today's building standards, a sustainable approach is indeed a necessity. It can thus be argued that even if the initial cost of renovation would be slightly higher than if such an approach would not be undertaken, the long term approach of sustainability helps both stakeholders and building occupants in economic savings.

The economic aspects of investment in for instance more efficient insulation materials is indeed an important discussion for stakeholders as legislations may introduce additional fees and environmental incentives that would result in higher penalty costs for stakeholders that do not subscribe to the new building standards (Fouquet, 2012). In light of this discussion it is further fruitful to convey that although the economic aspects of refurbishment indeed are extremely important for both stakeholders and building occupants, it remains with no substantial value, when viewed from a different perspective. From a historical or cultural perspective the refurbishment of a pristine building exhibiting a nation's heritage is indeed priceless if the building can be refurbished without major alteration to its original state and without diminishing its architectural values.

2.5 Service life of buildings and Life Cycle Assessment

The fact that the built environment is a growing technological sector in both developed and developing countries, has instigated its major impact on many different disciplines. In effect, the depletion of natural resources and environmental concerns associated with the building industry have placed more stringent demands on the usage of the correct choice of building materials with minimal environmental impact. Life Cycle Assessment (LCA) and service life of buildings are of great importance in light of the preceding discussion. These can enable a sustainable built environment with emphasis placed on longevity of buildings and minimization of their corresponding refurbishment costs.

Life Cycle Assessment (LCA)

The assessment of the overall environmental impacts of materials, from their manufacturing to their final disposal is often referred to as LCA. In essence, social and environmental impacts influence the production of new materials. In order to minimize the need for development of entirely new materials, it is crucial that existing materials are utilized to the extent possible. In this context three main courses of action can be employed with the first one being to reuse the materials in existing buildings. Secondly, a reuse of building components saved from a demolished buildings and thirdly the recycling of materials. In the design and recycling of building components, it is crucial to consider the life span and replacement frequency of these components. In this process, it is useful to determine the components with the likelihood of becoming replaced sooner than others. Similarly, it is important that their exchange is possible without the influence on the building as whole. It is customary that building components in functioning order are removed from a building.

An important condition pertaining to this removal is that these components are not damaged during the service life of the building. It is further crucial to facilitate the recycling of components by keeping the materials in the purest state possible, upon their removal from the building. For metallic components, this process is altogether well established, due to the established procedures associated with metal recycling, which in effect result in yield of recycled components and minimal effect of contaminants. Other building components are however more difficult to recycle, for instance timber which requires de-nailing and cleaning and may easily be prone to biological degradation. In addition, for certain composite materials, such as sandwich cladding panels and other materials which have been treated with toxic substances, recycling is quite intricate and in certain instances even impossible. The design of buildings with replaceable components and components that are easily removed, opens the gate into an approach of sustainability for the building, entailing in less expensive upgrade of building components, building refurbishment and general maintenance of the building. LCA has been used in the building sector since 1990 (Fava, 2006) and it can be utilized in the decision making process in order to serve as a motivating factor to deal with the evident depletion of natural resources. An overview of different steps in LCA related to buildings is shown in Figure 2.3 and is discussed below.

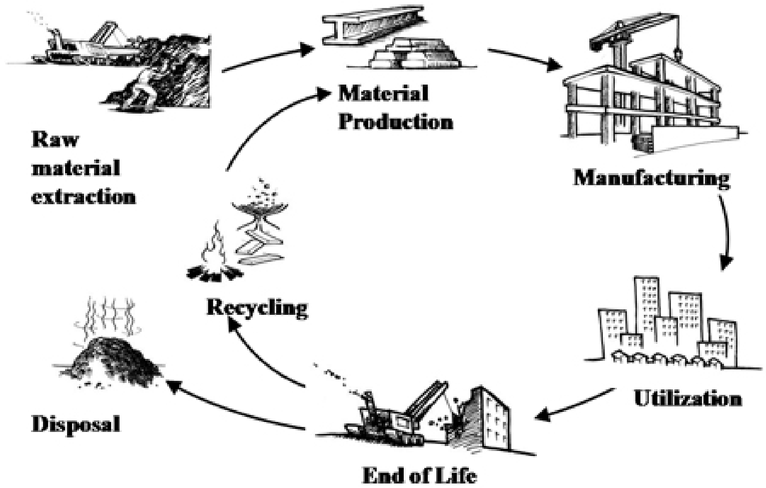


Figure 2.3. A schematic overview of LCA related to buildings (Fraunhofer Institute for Building Physics, 2013).

LCA consists of four steps according to the standard ISO 14040:2006 (Environmental management - Life cycle assessment - Principles and framework):

1. Definition of the goal and scope
2. Creation of the inventory
3. Assessment of the impact
4. Interpretation of the results

In the first step, the goal and scope involve the definition of the purpose, system boundary and audience. In the creation phase of the inventory, or the Life Cycle Inventory (LCI), data for each unit process is collected and the relevant energy and mass flow input and outputs are identified. In addition to these, data on emissions to air, water and land are collected and related the energy input/outputs and of the processes related to material. The third step consists of three subcategories in which, the impact categories are selected, classification of the life cycle impact is carried out and the characterization of the indicators is modeled for each category. Hence, the third step identifies the potential environmental impacts and establishes the needed resources for the modeled system. Essentially the problem-oriented and damage-oriented methods make up the life cycle impact assessment. Finally in the last step, the data is interpreted and the findings are evaluated. This stage also serves as the conclusive stage for all four steps of a life cycle assessment.

The LCA tools intended for environmental evaluation are additionally categorized into three distinct categories:

- Level I: Product comparison tools
- Level II: Whole building design decision or decision support tools
- Level III: Whole building assessment framework or systems

Examples of such tools for each distinct category are shown in Table 2.2.

Category	**Examples of LCA tools**
Product comparison tools	• Gabi (GER) • SimaPro (NL) • TEAM (FRA) • LCAiT (SWE)
Whole building design decision or decision support tools	• LISA (AUS) • Ecoquantum (NL) • Envest (UK) • ATHENA (CAN) • BEE (FIN)
Whole building assessment framework or systems	• BREEAM (UK) • LEED (USA) • SEDA (AUS)

Table 2.2. Examples of LCA tools in each category I−III (Haapio and Viitaniemi, 2008).

Kohler and Moffatt (2003) have highlighted that the focus of LCA was more confined to isolated buildings and specific entities and that due to the site-specific nature of the different factors affecting LCA, this application has from the start been confined to research groups. They also highlighted that a better approach was attained if the focus was shifted towards the built environment, which incorporated the relationship of mass flow and energy, between different buildings. This expansion of the focus provides at least two benefits. The first one will allow further development of integrated systems and actualize the cascade of resources. In such a system, the output of a process can act as an input to another system.

In addition, decision makers can be apprised about the main trade-offs for a sustainable development (Kohler and Moffatt, 2003). Regardless of the fact that LCA has been applied to a specific entity or the built environment as a whole, an integrated design process (IDP) needs to be considered. The advantage of utilizing an IDP is that a planning/design team is created and the inevitable trade-offs facilitated for experts and stakeholders by means of an effective communication. The influence of the design decisions on life cycle impacts and costs are shown in Figure 2.4.

Initially, at early stages of the design process the influencing potential is very high. This potential is however decreased significantly with the evolution of time. Early stages of the design process also enable the identification of synergies and possible use of unconventional technologies to a development towards sustainable solutions. Performance measurements/indicators can be used in order to identify critical thresholds and set targets. It is also recommended that the entire design team participates in a workshop concerned with the objectives of the project.

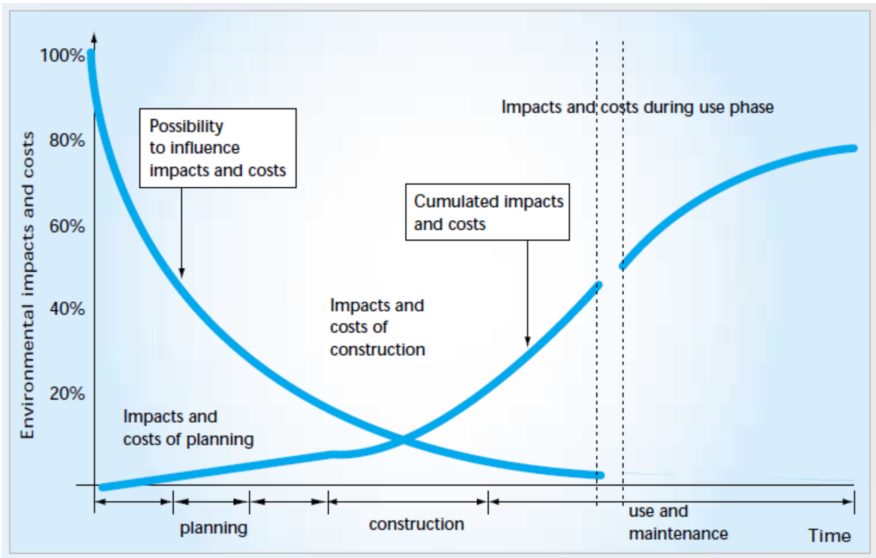


Figure 2.4. The influence of design decision on the life cycle impacts and costs of an average building in Europe or North America (Kohler and Moffatt, 2003).

The following conclusions can be outlined based on available literature (Dhillon, 1989; Kohler and Moffatt, 2003):

- In some cases the most sustainable building is no building at all. For instance, if care can be provided for individuals in their existing homes, a new hospital might not be needed.
- In a comparative study the system boundaries of LCA need to be clearly understood.
- The scope of the LCA can be specified by sensitivity analysis.
- An adaptive design is preferred from a LCA perspective because it enables performance despite of alterations in building use and technology.
- Specific spaces and structures that are appealing to occupants will more likely be longstanding, regardless of the efficiency and functionality.

- LCA seeks to explore the trade-offs between different phases of the life cycle and does not consider each individual phase. A misconception related to LCA is that it will ensue in reduction of the energy usage and emission reduction in a building or facility. In reality, the purpose of a LCA is to reduce the impacts of operation, refurbishment and replacement of the structure by for instance investment in additional insulation or more sophisticated building envelopes.

2.6 A Glance at Related Literature Regarding Sustainable Refurbishment

In consideration of the vast research areas in building technology, Article I was authored with the primary aim to identify a number of prominent research efforts related to available decision making tools employed in various building renovation and refurbishment projects. Focusing on energy conservation in the built environment, this review study identified selected approaches in the direction of sustainable renovation. Earlier in this chapter, it was established that refurbishment brings notable economic, social and environmental benefits in comparison to demolition (Power, 2008).

The debate regarding refurbishment of older housing and buildings versus demolition is continuously ongoing (Baker, 2005; Károlyi, 2007). There are many advantages with refurbishment over demolition and many disadvantages of choosing demolition over refurbishment (Power, 2008). Selected advantages of choosing housing refurbishment over housing demolition are as follows:

- Reduced transportation costs
- Reduced landfill disposal
- Retention of community infrastructure
- Greater reuse of materials
- Benefits in terms of local economic development and neighborhood renewal and management

Furthermore, selected disadvantages of choosing housing demolition over housing refurbishment follow as shown below:

- Higher capital costs
- Greater use of aggregates and embodied carbon inputs, noise and disruption
- Greater transportation need for materials and waste

Given that building refurbishment modifies the human living environment, it is critical that the financial and technical visions by engineers, architects and technical experts do not limit people's living environment (Gohardani, 2011). A number of decision making tools combining technical, economic, energy and comfort analyses for refurbishment were noted in this review study. A tool in this context is an instrument with a set purpose to alleviate the understanding of the refurbishment project and establish a set of actions and methods based on a defined workflow. The extent to which a tool is utilized is based on its real life application, usefulness and the purpose set for the reasoning behind the usage of the tool. For practically useful tools, this level of application is obviously higher than for those with a limited application extent. Some of the tools considered for building retrofits are:

- The Energy Performance, Indoor air Quality, Retrofit (EPIQR) (Genre et al., 2000), is a toolset and an instrument, with its own limitations.
- TOBUS denotes another decision making tool capable of investigating different indoor environmental quality aspects of office buildings and upgrade solutions (Caccavelli and Gugerli, 2002).
- XENIOS, is further a proposed decision making methodology and software for assessing refurbishment scenarios in hotels (Dascalaki and Balaras, 2004).
- MEDIC is developed on the theories of conditional probabilities to help assess the residual service life and thereby the necessary investments in refurbishment (Flourentzou et al., 2000a).

Adopting MEDIC, probability calculations for each element regarded in EPIQR for passing from one qualitative condition class to another can be made (Flourentzou et al., 2000a). A comparison between different systems or tools for building retrofits are shown in Table 2.3. In this table it is indicated that, the majority of the available tools only address a limited number of refurbishment criteria and thus a more robust approach is needed.

System or Tool	EPIQR	MEDIC	TOBUS	Hotel buildings (XENIOS)
References	$I^{a,b,c,d}$	II^{a}	$III^{a,b,c,d}$	IV^{a}
Building element degradation including residual life	✓	✓	✓	✓
Functional obsolescence of building			✓	✓
Fiber-Reinforced Polymer structure strengthening				
Indoor environmental quality	✓		✓	✓
Energy consumption	✓		✓	✓
Electromechanical installations			✓	✓
Solar system and desalination				✓

Table 2.3. A selection of systems or tools considered for buildings retrofits, with their corresponding features. Adapted from: Clark et al (2004). The number column refers to different publications by different authors, as follows: $I^{a,b,c,d}$: (Flourentzou et al., 2000b; Bluyssen, 2000; Wittchen and Aggerholm, 2000; Jaggs and Palmer, 2000), II^{a}: (Flourentzou et al., 2000a), $III^{a,b,c,d}$: (Caccavelli and Gugerli, 2002; Balaras et al., 2002; Flourentzou et al., 2002; Balaras, 2002), $IV^{a,b}$: (Balaras, 2004; Dascalaki and Balaras, 2005).

In this regard, one possible approach is to adopt a methodology for zero carbon refurbishment according to Figure 2.5.

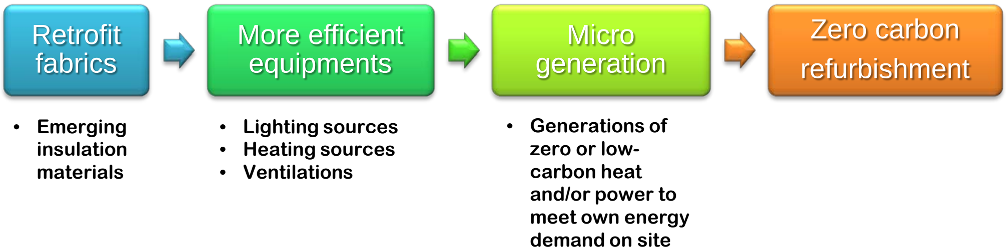


Figure 2.5. A hierarchical process towards zero carbon refurbishment. Adapted from Xing et al. (2011).

This methodology makes considerations of emerging insulation materials in its initial phases. Zero carbon refurbishment is however, not the only refurbishment option available. In fact, zero carbon is not entirely zero if embodied carbon is taken as a principal metric in consideration of whole-life sustainability (Ayaz and Yang, 2009). Despite these limitations, tailoring all the steps of the suggested methodology could lead to energy savings at the expense of increased embodied carbon. Adequate thermal insulation allows for a building to retain its generated heat within. The indirect heat generated sources are heat stored in thermal mass or direct solar gain, whereas human body heat and other heat generating activities such as cooking contributes to additional heat within a building. Hence, a further insight into the advantages and disadvantages of these thermal insulation materials is needed for a better understanding of the refurbishment needs in the built environment. A profound analysis of thermal insulation materials consequently provides an early step approach in the quest for zero carbon refurbishment. A detailed LCA study pertaining to a low energy family building conducted by (Blengini and Di Carlo, 2010), exhibits that material related impacts are of crucial importance with emphasis on life cycle potential.

2.7 High-Efficient Insulation Materials

Thermal insulation is one of the main solutions to energy conservation. Inadequately insulated buildings waste energy (U.S. Department of Energy, 2012). Well-insulated houses not only save energy, consequently lowering operating costs, but also keep the building occupants more comfortable. According to Papadopoulos (2005), advanced insulation materials are essential in order to achieve set goals for the European Union related to energy saving measures and energy performance limits. In this section, a number of properties associated with different insulation materials have been considered for comparison purposes. In particular, attention has been devoted to high-efficient insulation materials. Upon familiarization with the different insulation materials, the advantages and disadvantages of all considered approaches can be viewed in light of the objectives associated with this research project.

The demand for sustainability in the built environment has become an industry driver that affects both future and the existing building stock. High-efficient insulation materials are often distinguished by their low $\lambda-$value, which is a measure of the thermal conductivity in a building technology context. Other factors that influence the level of needed insulation are cost, ease of construction, building code requirements, durability, acoustical performance, air tightness, environmental impact, and availability (Al-Homoud, 2005). In this section, the advantages and disadvantages of high-efficient insulation materials, related to cost, environmental impacts and sustainability are discussed.

The analysis is confined to VIPs and silica aerogels. It is noteworthy that $\lambda-$values are often provided as a range, as one particular $\lambda-$value cannot be attributed to all forms of insulation, even within the same category. The choice of insulation materials are therefore not solely based on the materials with the lowest $\lambda-$values, but merely those that have the potential to address the challenges of a sustainable building refurbishment.

2.7.1 High-Efficient Insulation Materials - VIPs and Aerogels

In this section, the main criterion for the selection of the insulation materials has been attributed to materials with low $\lambda-$values. Table 2.4, outlines an estimate of the different $\lambda-$values for each corresponding material.

Insulation material	λ [W/mK]
Vacuum Insulation Panels	0.003 – 0.008
Aerogels	0.013 – 0.018

Table 2.4. Insulation materials with their corresponding $\lambda-$values. Sources: (Jelle, 2011; Xing et al., 2011; Aspen Aerogels, 2013a,b; Lawrence Berkeley National Laboratory, 2013)

Prior to considering the high-efficient insulation materials that might be of interest in future building applications, it is essential to outline the theory behind achieving a low thermal conductivity. Upon utilizing insulation materials with a low thermal conductivity, a thin building envelope is actualized with a low thermal transmittance. In essence, the overall total thermal conductivity, which is a measure of the ratio of a material's thickness to its thermal resistance, consists of the contribution of several factors as given by (Jelle, 2011)

$$\lambda = \lambda_s + \lambda_r + \lambda_g + \lambda_{cv} + \lambda_{coup} + \lambda_{leak} \qquad (2.1)$$

In Equation 2.1, λ_s is the solid state thermal conductivity, λ_r represents the radiation thermal conductivity, λ_g denotes the gas thermal conductivity, λ_{cv} is the convection thermal conductivity, λ_{leak} denotes the leakage thermal conductivity, and λ_{coup} represents the term accounting for second order effects between various λ_n. The $\lambda_{coup}-$parameter is usually quite complex to quantify and is in theoretical approaches for VIPs often neglected (Heinemann, 2008).

2.7.2 Vacuum Insulation Panels (VIPs)

VIPs consist of a filling material and an envelope (Fricke et al., 2008). The core structure is hence micro-porous and upon evacuation sealed in an envelope bag, which is gastight (Simmer and Brunner, 2005). A schematic of a VIP can be seen in Figure 2.6, where in particular the core of the panel, protective layer, barrier layer and sealing layer make up the multilayer envelope.

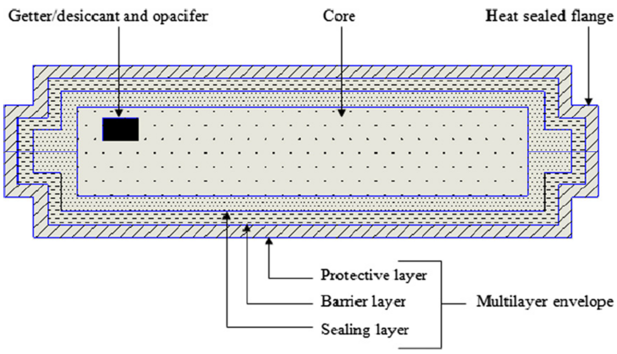


Figure 2.6. A schematic of a VIP (Alam et al., 2011).

Elements of VIPs

The kernel of the VIP consists of porous materials such as powders, fibers and porous foams. The purpose of the core is to maintain the vacuum under a threshold value and support the panel's envelope.

The protective layer
The function of the protective layer is as its name suggests, to protect the core and also the barrier layer of the VIP from damage caused by handling. Additionally, the protective layer also serves as a substrate for the barrier layer.

The barrier layer
The layer between the protective layer and the sealing layer is referred to as the barrier layer. The function of this layer is to serve as a barrier against water vapor transmission and air. A three layer structure is often utilized for a higher protection.

The sealing layer
The sealing layer is the inner-most layer, protecting the inner core of the VIP. One of the factors that contribute to gas passage is an improper sealing or perforation.

Thermal conductivity

The thermal transport in VIPs has the possibility to be exceptionally low since the vacuum makes λ_g and λ_{cv} in Equation (2.1) very low.

Acoustics

In their article Baetens et al. (2010a), differentiate between three different categories related to the acoustic properties of VIPs:

- Properties of a single VIP
- Properties of VIPs with insulated sandwiches
- Properties of insulated massive walls with VIPs

In general, the law of mass is often applied in order to estimate the sound insulation properties of a material or structure. This relation can be expressed as (Baetens et al., 2010a)

$$R_w \approx 20 \log(1 + 3.4m) \tag{2.2}$$

where R_w denotes the sound reduction index and m is mass per unit area. For a VIP with a 10 mm thickness, the sound reduction index has been estimated to $19 - 26$ dB and $10 - 15$ dB for perforated VIPs (Maysenholder, 2008). In order to account for the reduction in thickness, a thicker facing in terms of vacuum insulated sandwiches can be utilized.

2.7.3 Aerogels

The potential of utilizing aerogels in a wide range of applications has earlier been recognized by a number of researchers (Gesser and Goswani, 1989). For building applications the usage of aerogels is indeed promising as a complement and perhaps a substitute for existing insulation materials. The total market for aerogel products is expected to grow at a compound annual growth rate of 19.3% between $2012 - 2017$, reaching global revenues of \$332.2 million by 2017 (BCC Research LLC, 2013). Aerogels were originally discovered in 1930s (Kistler, 1931), but the interest for these materials have increased considerably with the incentives to abate greenhouse emissions (McKinsey & Company, 2009). Aerogels are essentially dried gels which are porous, a result from supercritical drying, allowing the sample to maintain its texture and wetstage (Baetens et al., 2011).

Acoustics

Regarding acoustic properties, monolithic aerogels can be characterized for their low sound velocity (down to 90 m/s) (Forest et al., 2001). The range is extended to approximately 100 m/s for commercial products of non-monolithic nature (Aspen Aerogels, 2010). For sound insulation purposes, layered structures of different granular sizes can reduce the sound level with as much as 60 dB, within a 7 cm thickness (Ricciardi et al., 2002).

Safety aspects

One of the safety concerns with aerogel insulation can be attributed to dust production, with an exposure limit of approximately 5 mg/m^3. Despite the mentioned concern, no studies related to human beings have been reported which would suggest that aerogels cause silicosis (lung disease caused by inhalation of mineral dust) upon prolonged exposure to synthetic silica (Baetens et al., 2011). In addition, the international agency on research on cancer (IARC) does not classify amorphous silica to act as carcinogen to human beings (Merget et al., 2002).

Together with VIPs, aerogels have emerged as promising candidates for thermal insulation applied in the buildings of the future. Presently, similar to any other new emerging technology, the production costs of aerogels are still high. The fragility of aerogels due to their low tensile strength is currently also a drawback. However, the implementation of carbon fiber matrices may be able to increase the tensile strength. The optical properties of aerogels are extremely interesting for building applications, as they offer opaque, translucent and transparent solutions (Jelle, 2011).

The transmitted light through and reflected by aerogels appears red and blue, respectively. The scattering of light in silica aerogels is due to Rayleigh-scattering (Sneep and Ubachs, 2005), which takes place due to present inhomogeneities in the solid upon interaction with the wavelength of the incident light and is more pronounced when the mentioned wavelength is of similar magnitude as the size of the particles. Depending on the number of pores in this range, the scattering efficiency is dependent upon the number of scattering centers. Moreover, the adding of opacifiers can reduce the transparency of aerogels (Reichenauer et al., 2004) and transparency can be achieved at the infrared spectrum. However, it should be noted that the overall thermal conductivity at high temperatures increases due to this transparency (Baetens et al., 2011).

High-efficient Insulation Materials — Summary

In summary, the following conclusions can be drawn from the featured high-efficient thermal insulation materials in the preceding sections:

- One requirement for insulation materials of the future is for them to present a thermal conductivity which is as low as possible.
- However, solely a low thermal conductivity is not sufficient as effects of ageing, building site adaption and perforation should be considered as well.
- For the two studied high-efficient insulation materials, a lower value of the thermal conductivity is exhibited by VIPs. However, in the long term perspective, this value will increase due to the influence of moisture and air penetration. Comparatively, aerogels have not shown to exhibit increasing thermal conductivity values with time.
- Perforation is indeed a major obstacle for VIPs, as an adaptation to a building site may become intricate for these materials.
- In a general sense, some of the novel insulation materials have mostly been studied towards thermal performance. Thus, one could argue that there most likely exists a paucity regarding results related to their actual implementation in a building technology context. One important aspect in this regard, is the acoustic performance study. This specific consideration is often lacking, even in very thorough literature reviews regarding high-efficient insulation materials.

2.8 Net Zero Energy Buildings

Amid the economic challenges within the built environment, one vision shared by the majority of the building community is to develop buildings that produce the same amount of energy as they utilize. These buildings are called net zero energy buildings (NZEBs). In the U.S. only, the energy usage within the commercial sector is expected to grow by 1.6% annually. In addition, buildings are responsible for 40% and 70% consumption of primary energy and electrical energy, respectively. These factors all contribute to energy conservation measures which include both energy conservation and refurbishment. ASHRAE has a vision of implementing market-viable NZEBs by 2030. This measure calls for implementation of the NZEB−strategies in existing and new buildings (ASHRAE Vision 2020 Ad Hoc Committee, 2008). Other programs which have shown a great interest in fulfilling similar goals are U.S. Department of Energy's (DOE) Building Technologies Program and the Energy Performance of Buildings Directive Recast (EPBD) within the European Union (2010/31/EU). These incentives essentially seek to explore the route ahead for addressing energy related issues for buildings, in accordance with the Kyoto Protocol (United Nations, 2013).

2.8.1 Definition of a Net Zero Energy Building

There has been a great discrepancy related to the definition of a net zero energy building. Therefore, some of the different definitions of this concept are explored herein. These definitions have dissimilar metrics and hence allow for a discussion of the general perception of a net zero energy building. There are essentially four different definitions where net zero energy buildings are described as:

- Net zero site energy building
- Net zero source energy building
- Net zero energy cost building
- Net zero energy emissions building

Net zero site energy building

For a net zero site energy building, according to this definition the usage of energy when measured at the site, equates the produced energy. Therefore, this definition can easily be verified by on-site metering. The beneficial aspects of this definition are energy-efficient designs and the drawbacks are related to non-distinguishable fuel types and that no consideration is devoted to inefficiencies in utilizing the grid.

Net zero source energy building

This definition accounts for the energy usage of the building in comparison to the energy level at the energy sources from an annual perspective. It represents the total energy impact, as the system boundary encapsulates the building, the transmission system, the power plant, and the consumed energy required for providing the fuel source to the power plant. One of the obstacles for this definition is related to conversions related to site to source and their difficulties.

Net zero energy cost building

This type of building often utilizes energy-efficient and renewable energy solutions and hence is attractive for building owners. This definition is usually determined from the utility bills. Approaching zero level per this definition may however be an intricate task, due to the existing charging structures for electricity cost which do not allow the credit to become less than zero annually, despite the energy that will be returned to the grid.

Net zero energy emissions building

This building type considers the produced energy needs of the building and serves as a good model for ”green” energy. The employed calculation for this definition is actualized by multiplying the building’s total imported and exported energy by the appropriate emission multipliers. The aforementioned factors are based on on-site generation emissions and the utility's emissions.

2.8.2 Towards A Single Definition for NZEBs

Despite the number of different definitions for NZEBs, a single definition is of interest, in order to facilitate the terminology and assessment of such buildings. As the most significant element regarding NZEBs is occurring as an energy transfer across the boundary, site energy measurements at least in the U.S. have become the main point of interest for organizations such as the American Institute of Architects (AIA), U.S. Green Building Council (USGBC) and ASHRAE (ASHRAE Vision 2020 Ad Hoc Committee, 2008). In light of the preceding discussion, it is important to emphasize that in the matter of sustainability concerning NZEBs, solely the energy flows of the building does not concern the overall sustainability of the building. Hence, it is important that other aspects of sustainability is viewed from this perspective, but also that this view is expanded to include other facets of the building, apart from the energy flows. Kurnitski et al. (2011) propose two definitions for in particular the net zero energy building (NZEB) and the nearly net zero energy building (NNZEB). Their proposal is for any building that has a primary energy use of 0 $kWh/(m^2a)$, to be considered as a NZEB. In addition, they propose that buildings with the national cost optimal energy use of > 0 $kWh/(m^2a)$ primary energy, to be classified as NNZEB. Primary energy is the energy embodied in natural resources prior to undergoing any human-made conversions or transformations (Kydes, 2011).

2.8.3 Grid Connection

ZEBs often make use of electricity and natural gas in order to obtain the heating and cooling loads, when on-site generation of the energy is not sufficient. In the event where the on-site generated energy exceeds the loads of the building, the remaining energy is to be exported to the power grid, hence allowing an offset in future energy use. It is therefore important to emphasize the role of the grid, as the achievement of ZEBs without its presence is intricate due to limited storage technologies (Torcellini et al., 2006). This limitation further entails that the energy generated from renewable sources often needs to be oversized for instance during the summer, as it cannot be fully utilized. Given the fact that excess on-site energy generation from solar or wind power can not always be utilized and sent to the grid, the presence of on-site energy becomes even more emphasized. A summary of the different definitions and their advantages and disadvantages, as well as other identified issues related to these definitions is presented by Torcellini et al. (2006), as shown in Figure 2.7. The connection between the building and the energy grids is further shown in Figure 2.8.

2.8.4 Physical boundary

This boundary is usually concerned with the energy analysis and the flow of energy at the connection point to the supply grids. The physical boundary furthermore is inclusive of the on-site generation systems such as photovoltaic (PV) and micro combined heat and power (CHP) and is defined as the boundary between the building and the grid. Due to the technical limitations, the energy generation from a solar thermal system is often utilized entirely on site, distinguishing this system as a demand-reduction technology. In terms of energy generation, a wind energy turbine is an adequate option, but should be treated against the primary energy factor (Voss et al., 2012).

2.8.5 The balance boundary

The balance boundary incorporates a classification of the considered energy services. Examples of such, are technical services for ventilation, cooling, heating, charging of electric vehicles on site, and domestic hot water.

2.8.6 The weighting system

This system seeks to convert the energy forms into physical units such that the balancing process can be achieved towards a common metric, which often in terms of ZEBs is the primary energy, while other countries besides the U.S. utilize carbon emissions for this purpose. An example of this factor can be governmental decreasing factors to electricity in order to instigate a discounting of systems based on electricity for heating such as heat pumps, etc. (Voss et al., 2012).

2.8.7 Photovoltaic systems

Solar energy can be utilized directly through solar collectors for generation of electricity or heat. In essence, thermal solar collectors consist of an absorber and a heat insulated shell. By means of high-efficient materials like vacuum insulation or a gas filling, the collectors can be tailored to the most varying requirements. In photovoltaic collectors, sunlight is converted into electricity. The collectors use silica in monocrystalline and polycrystalline form as well as in amorphous form. When the solar collector is hit by sunlight and the amount of accumulated energy exceeds a certain threshold, electrons are freed from the silica bonds, creating moving electrons leading to extraction of electrical current. Solar collectors have a lifetime of approximately 40 years. They generate direct current and thus require a battery or inverter that is plugged into the electrical grid (Bauer et al., 2010; Bokalders and Block, 2010). An overview of a PV system is shown in Figure 2.9.

Definition	**Advantages**	**Disadvantages**	**Other issues**
Site ZEB	• Easy to implement • Verifiable through on-site measurements. • Conservative approach to achieving ZEB. • No externalities affect performance, can track success over time. • Easy for the building community to understand and communicate. • Encourages energy-efficient building designs.	• Requires more PV export to offset natural gas. • Does not consider all utility costs (can have a low load factor). • Not able to equate fuel types. • Does not account for non-energy differences between fuel types (supply availability, pollution)	
Source ZEB	• Able to equate energy value of fuel types used at the site. • Better model for impact on national energy system. • Easier ZEB to reach.	• Does not account for non-energy differences between fuel types (supply availability, pollution) • Source calculations too broad (do not account for regional or daily variations in electricity generation heat rates). • Source energy use accounting and fuel switching can have a larger impact than efficiency technologies. • Does not consider all energy costs (can have a low load factor).	• Need to develop site-to-source conversion factors, which require significant amounts of information to define.
Cost ZEB	• Easy to implement and measure. • Market forces result in a good balance between fuel types. • Allows for demand-responsive control. • Verifiable from utility bills.	• May not reflect impact to national grid for demand, as extra PV generation can be more valuable for reducing demand with on-site storage than exporting to the grid. • Requires net-metering agreements such that exported electricity can offset energy and non-energy charges. • Highly volatile energy rates make tracking over time difficult.	• Offsetting monthly services and infrastructure charges require going beyond ZEB. • Net metering is not well established, often with capacity limits and at buyback rates lower than retail rates.
Emissions ZEB	• Better model for green power. • Accounts for non-energy differences between fuel types (pollution, greenhouse gases). • Easier ZEB to reach.		• Need appropriate emission factors.

Figure 2.7. The summary of ZEB definitions and their respective advantages and disadvantages. Adapted from Torcellini et al. (2006).

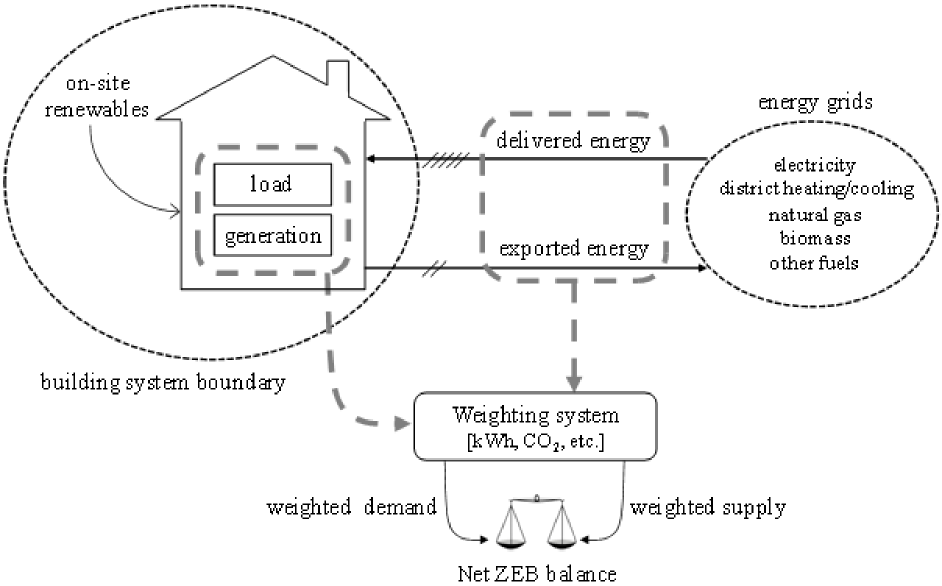


Figure 2.8. The connection between the building and the energy grids (Sartori et al., 2011).

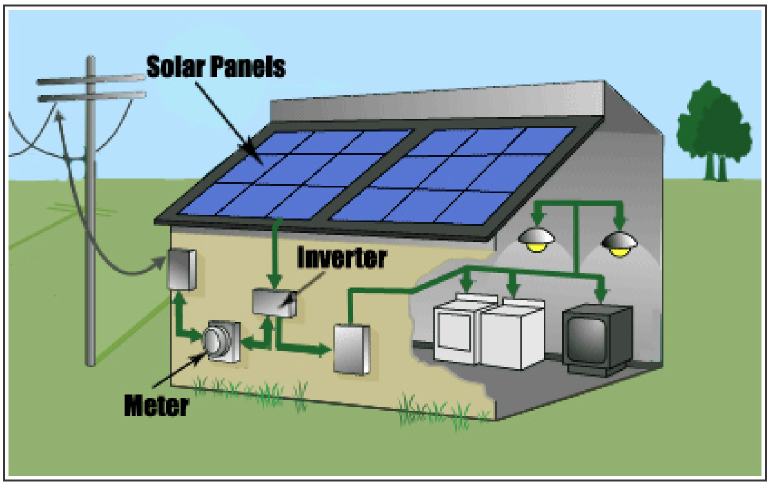


Figure 2.9. An overview of a photovoltaic system consisting of solar panels, inverter and meter. The power from the PV array is initially converted from DC to AC by means of the inverter which in return is connected to the utility grid. Reprinted with kind permission of Pacific Solar Technologies LLC (2013).

Chapter 3

Research Methods

This chapter describes the employed research methods of the conducted study more explicitly. Specific details pertaining to the utilized methods are however presented in Articles I−X. Figure 3.1 provides an overview of the employed research tools and corresponding articles in this study.

Figure 3.1. The employed research tools and corresponding articles.

This Ph.D. study was undertaken within the ACES project as part of the Eracobuild program (Strategic Networking of RDI Programs in Construction and Operation of Buildings) on value driven processes, more detailed in Section 2.1. Following the initial stage of the conducted research which resulted in a licentiate thesis (Gohardani, 2012), some features of the main hypothesis of the ACES project which reflect reality still remained unexplored. Hence, these features served as the initial basis for analysis for the research presented in this thesis. Given that the considered topics of this study originate from reality based problems encountered within the built environment, without emphasis on the theoretical assumptions, render their empirical support evident, as explained by Ghoshal (2005).

The main focus of this study has been concerned with the ongoing challenge and problem associated with motivating stakeholders to make attentive decisions regarding sustainable building measures at early project stages. This problem was evident at the initial stage of the study (during the phase towards the licentiate of engineering degree) and remained unexplored with regards to certain aspects such as workers' health issues, the attitude of stakeholders in Sweden, Cyprus and Denmark regarding sustainable refurbishment and environmental certification of buildings in Sweden, at the time of initiation of the Ph.D. project. As this study was carried out in collaboration with both academia and industry, selected aspects related to the abovementioned have been addressed. The utilized research methods in this study have emerged based on discussions with the author's supervisors, faculty members and domestic and international research colleagues. The research design in this study has been based on the following:

- Literature review
- Generation/re-evaluation of research questions
- Survey(s)/collection of data
- Selection and assessment of research methods
- Analysis of data

Apart from the methods above, certain approaches have also been taken to ensure the trustworthiness of the data, as described further in this chapter. The abovementioned research methods have been applied in three different phases; the initial phase, the intermediate phase and the final phase of the research project. As shown in Figure 3.2, initially a literature review was carried out with the aim to cover the main focus of this study and in order to gain understanding of available decision making tools and refurbishment methods leading to energy efficiency in buildings. These formed a basis for the study and assisted in obtaining an illustrative view of available decision making tools for refurbishment of buildings, at the initiation of the conducted research. One of the conclusions from this review was that despite

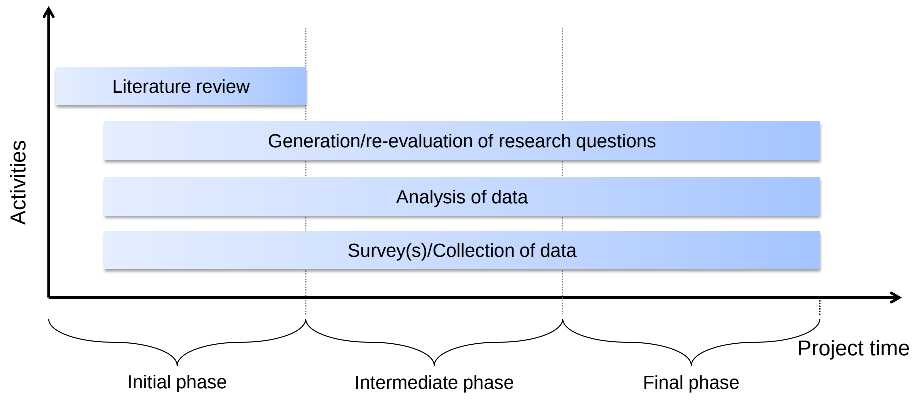


Figure 3.2. The allocation of tasks in different phases of the research project.

the widening range of sustainability criteria for refurbishment, a great deal of decision making tools and refurbishment methods only address a limited number of common criteria. Furthermore it was concluded that multinational studies which identify national differences and drivers for sustainability were of special interest. While the literature review was mainly confined to the initial project stages, the remaining activities were carried out over the entire timeline of the project, depending on resource availability, time constraints, and a sound basis for data evaluation.

According to Baszanger et al. (2004), for a study, three different cases can be distinguished from an ethnographic viewpoint. The first of these occurs when the phenomena of interest can not be deduced logically and empirical observations are needed. In the second case, the field worker needs to maintain openness without reverting to predefined rules set to meet prior schemes. The final context in which ethnographic studies become crucial are those where observed facts are interlinked with cultural/historical aspects. In essence, ethnography emphasizes the importance of understanding matters from the point of view of those involved (Denscombe, 2007). While it would be interesting to consider the conducted research in this study through an ethnographic approach, time restriction and some disadvantages of this approach such as stand-alone descriptions, resulted in the rejection of this approach. The latter refers to a case where a number of scattered ”pictures” co-exist but remain as isolated stories with the potential weakness of poor reliability and little generalization prospects from an ethnographic account of the event.

In this study a mixed method approach has been employed, which essentially implies that qualitative and quantitative research approaches have been undertaken within the same research project. According to a number of published reviews (Bryman, 2006; Collins et al., 2006; Rocco et al., 2003), the mixed method approach can result in a more complete description of the phenomenon being studied and places emphasis on the integration of alternative approaches. In addition, this approach makes good use of the potential of triangulation and provides a practical problem-driven approach to research.

In Article III, the mixed method approach was used with a triangulated approach consisting of a literature review which provided a basis for the design of questions in the questionnaire for each country and the semi-structured interviews. The benefits of questionnaires can be expressed in terms of large amount of research data produced at a low cost and short amount of time. Questionnaires provide standardized answers to posed or pre-coded questions. Equally, such pre-coded questions can be restricting as well as frustrating for the respondents (Denscombe, 2007). In this study however, as a questionnaire was combined with interviews featuring open-ended questions together with semi-structured interviews, the mixed method approach has been used as a means to move the analysis forward with the literature review acting as input to the remaining methods.

According to Denscombe (2007), a case study is useful in providing the focus on one or few instances by allowing the researcher to deal with refinements of complex situations. In addition, this approach enables the usage of different research methods in order to capture reality. Another benefit of utilizing a case study is when the researcher has little control over the occurred events. Hence, different phenomena naturally occur in this setting, without the imposed pressure by the researcher. A disadvantage of a case study can be related to its boundary and gained access to relevant data. Moreover, another drawback attributed to case studies is that in settings where the researcher is deeply involved in the study over a longer period of time, the research subjects might feel that they are being observed, which can be denoted as the observer effect.

Lincoln and Guba (1985) describe an approach to case studies (which also can be referred to ethnographic, hermeneutic and subjective studies) that take place in a natural setting. Such studies are claimed to require a human instrument that can respond and adjust to a context which cannot be ascertained. The human instrument in this context can use unspecified knowledge in order to expand on hypotheses and gain insight into the study. Data should in this setting be collected by suitable means and may consist of observations and interviews. Lincoln and Guba (1985) further describe the procedure to be an iteration consisting of purposive sampling, inductive data analysis, elaboration of a grounded theory based on the analysis, and planning of the subsequent steps. This process remains open until satisfactory results are obtained.

Yin (1994) on the other hand, mentions five components as constituents to a case study. These pertain to the question of the study, the proposition of the study, the units of analysis, the logic which links the data to the proposition, and criteria used for interpretation of the findings. The most common data sources according to Yin are archival records, direct observations, documentation, interviews, participant observations, and physical artifacts. These sources should preferably be combined in order to account for the disadvantages that they possess. The purpose of a case study is according to Eisenhardt and Martin (2000) to provide a description, test and generate a theory, or to focus a research strategy.

The case study was suitable for Article II, as it emphasized on the process rather than the outcomes as described by (Denscombe, 2007). In Article III, case studies in each country provided national results, while multiple research methods provided an insight to the complex nature of the problem at hand. In Article IV, access was granted to confidential data about real applications submitted to SGBC for environmental certification of buildings in Sweden. Hence, one of the drawbacks of case studies which may comprise of restricted access to data was refuted, while the research efforts were carried out in natural conditions, as the collected data was provided once applications had been filed with SGBC. In Article VI, natural data was collected in a case study related to a church building, in which the benefits of a hydronic ground source heat pump system in comparison to an electric coil heating system was demonstrated. Article VII featured detailed case studies, which compared the use of VIPs with mineral wool.

The deliberate choice of four areas of interest for the research, namely technical, economic, energy, and workers' health issues, was due to the fact that these different disciplines were considered to be of great significance in order to obtain a greater understanding about the requirements for approaching sustainability in the built environment. The purpose has thus been to establish a framework for future studies of similar nature. In order to realize this framework, certain procedures were established that would address the different needs of each aforementioned discipline. In this approach, a combination of quantitative (inferential, experimental, simulation), and qualitative (subjective assessment of attitudes, opinion, behavior) research was utilized in order to meet the purpose of the undertaken research. The adopted methodology has hence been chosen in order to systematically address these questions. In addition, research strategies based on five different methods outlined by Yin (2009) of 'how' and 'why' nature were used in this study. The methods comprised of: *Experiment*, *Survey*, *Archival analyses*, *History*, and *Case study*.

In order to establish the trustworthiness of the data and avoid insufficient basis for generalisation, the suggested approach by Lincoln and Guba (1985) is undertaken which takes credibility, transferability and conformability into account. In order to obtain credibility, multiple data sources, in conjunction with a mixed method approach including triangulation, interviews, and surveys, were used in this thesis.

The transferability aspect of the conducted study has been communicated by means of visualization, such as flowcharts for procedures, so that comparative cases can be carried out by other researchers. Some generalizations have also been made in order to provide a means of comparison to other research studies. The aspect of conformability has in part been actualized by a set of established procedures pertaining to decision making processes in tenant owners' cooperatives, which will pave the way for novel studies.

The conducted research in this thesis was initiated by means of a review article in which approximately 50 different literature sources were reviewed, in order to identify the available tools associated with building refurbishment and decision making (Article I). The research methods utilized in this article were of qualitative/quantitative nature and *History* according to the classification of Yin (2009).

Article II, investigated methods to promote energy saving measures in conjunction with planned major renovations in residential buildings, owned by tenant owners' cooperatives, resulting in a proposal for a developed strategy; the operational decision support process. The questionnaires were aimed at decision makers and stakeholders involved in the case study. The research methods utilized in this article were quantitative (inferential)/qualitative (subjective assessment of attitudes), and *Case Study/Survey*.

Article III, outlined the decision making process related to sustainable renovation in buildings with emphasis of the attitude of stakeholders in Sweden, Denmark and Cyprus based on three separate case studies. The findings of the Swedish case study were in part based on the responses from stakeholders involved in a refurbishment project, where a collective of 14 apartments and two rooms were refurbished to 18 apartments, but also supported by responses of a questionnaire survey with 50 respondents. In Denmark, the analysis was carried out through 10 qualitative semi-structured interviews based on an interview guide with open questions. These were aimed at different stakeholders in order to determine their point of view and needs in relation to sustainable retrofitting of buildings in Denmark. The study from Cyprus utilized a structured questionnaire with one out of two possible closed answers for each of the 10 questions. The research methods utilized in this article were quantitative (inferential)/qualitative (subjective assessment of attitudes/opinions), and *Case Study/Survey*.

In Article IV, an insight was provided into two of the most commonly used programs for environmental certification of buildings in Sweden, by presenting an assessment framework with regards to building-related energy and indoor environment, in particular. A total of 60 applications submitted to SGBC were evaluated, 30 for Environmental Building (EB) and 30 for GreenBuilding (GB). The research methods utilized in this article were quantitative (inferential) and *Case Study*.

In ARTICLE V, a survey was designed and conducted with aims to identify a number of safety hazards that potentially endanger the health and safety of Swedish construction workers. The survey consisted of 20 questions and had 119 respondents who were active at 10 different construction sites or offices in Sweden. The majority of the respondents who participated in the survey were between the ages of $31 - 45$. The largest group of these respondents had between $3 - 5$ years of working experience in the construction sector. The research methods utilized in this article were quantitative (inferential) and *Survey*.

In ARTICLE VI, the energy performance of a church building subsequent to an exchange of an existing electric coil heating system to a hydronic ground source heat pump system, was assessed and discussed. Furthermore, the energy demand and energy signature were analyzed and presented prior to and after installation of the ground source heat pump system. The hourly energy usage of the church building was determined by means of an energy signature method. The research methods utilized in this article were quantitative (experimental) and *Experiment/Case study*.

In ARTICLE VII, the aim of the study was to perform a comparative analysis of VIPs and conventional thermal insulation materials. Further, other means of retrofitting in terms of life cycle energy and costs were evaluated. Particular attention was given to the comparison of exterior and interior applications of VIPs in buildings and the effects of thermal bridges at connections between the external wall and the adjacent floor slabs and balconies. The research methods utilized in this article were quantitative (simulation) and *Case study*.

In ARTICLE VIII, a case study on a multistory building was carried out with emphasis on sustainability and environmental impacts upon refurbishment, in comparison to the existing building performance. The simulation scheme adopted in this study was initiated upon a baseline simulation approach, based on conventional thermal insulation materials. By employing the enhanced insulation implementation, VIPs replaced the role of mineral wool in order to provide a higher thermal performance. The influence of geographic locations on the energy demand for heating was moreover investigated for four cities in Sweden and one in Spain. The research methods utilized in this article were quantitative (simulation) and *Case study*.

In ARTICLE IX, a simulation approach was undertaken in order to analyze a planned building design based on peak load heating and cooling analyses of a building. The employed approach established a foundation for comparison between the original building design and a modified one, with particular significance placed on sustainable building design and the overall building performance. The study focused on the influence of the modified building design on the heating and cooling performance when viewed against different geographical locations within the United States and Europe. The research methods utilized in this article were quantitative (simulation) and *Case study*.

In ARTICLE X, a simplified calculation tool, the Early Stage Primary Energy Estimation Tool (ESPEET), was presented by employing user input parameters for determining the primary energy usage within a net zero energy building. The simplified tool allowed for a first step energy analysis of a net zero energy building based on its energy demand and expected usage. The model was based on two different metrics for NZEBs; the primary energy and the renewable energy ratio. The research methods utilized in this article were quantitative (simulation) and *Case study*.

The intentional usage of different research methods enable for a more detailed understanding of the topics involved and motivates the choice of the employed multifaceted approach described in this thesis. In Figure 3.1, the distinct research tools; review, parametric studies, model development, computer simulations, in-situ measurements, and surveys clarify the reason why a combination of both quantitative and qualitative measures are required in order to address the specified research objectives/questions.

Upon revisiting Figure 1.1, many research studies are concerned with just a few of the shown aspects, for instance solely the technical aspect, which would most likely result in a narrow view of the sustainability topic as a whole, even if this specific aspect was to be thoroughly studied. The conducted research study has illustrated that the employed approach is significant in order to obtain a multidimensional view of the topic, where the influence of different aspects (technical, economic, energy, and workers' health issues) need to be considered. One challenge associated with obtaining efficient processes for sustainable building within the built environment is concerned with the vast interlinked topics involved. In this research study, a combination of methods have been used in order to enable enhanced efficiency in processes and approaches towards sustainability at early project stages.

3.1 Employed research methods

Tables 3.1 and 3.2, provide an overview of the research questions, the utilized research methods, research tools, and the corresponding outputs.

Research Question	Research methods	Research tool(s)	Output(s)
Q1. What approaches are taken towards sustainability in early project stages related to the built environment in this study and why are these of importance?	∘ Quantitative^{i} ∘ Qualitative^{s,o} ∘ History ∘ Case study ∘ Survey	∘ Review ∘ Model development ∘ Questionnaire	Article I Article II Article III
Q2. Can building owners/ stakeholders utilize the findings of this study in order to make sustainable decisions concerning renovation in early project stages?	∘ Quantitative^{i,sim} ∘ Qualitative^{s,o} ∘ History ∘ Case study ∘ Survey	∘ Review ∘ Model development ∘ Questionnaire ∘ Computer simulation	Article I Article II Article III Article V Article VII Article VIII
Q3. Do the findings of this research have applications within the realm of real-life situations?	∘ Quantitative^{i,e,sim} ∘ Qualitative^{s,o} ∘ History ∘ Case study ∘ Survey ∘ Experiment	∘ Review ∘ Parametric studies ∘ Computer simulation ∘ In-situ measurements ∘ Questionnaire ∘ Model development	Article I Article II Article IV Article V Article VI Article VIII Article IX Article X

Table 3.1. The utilized research methods, research tools and outputs for the posed research questions Q1−Q3. The superscripts are denoted by: *e* for experimental, *i* for inferential, *s* for subjective assessment of attitudes, *o* for opinions, and *sim* for simulation.

Research Question	Research methods	Research tool(s)	Output(s)
Q4. Which parameters constitute common inaccuracies in applications for environmental certification of buildings in Sweden?	∘ Quantitative^{e} ∘ Experiment	∘ In-situ measurements	Article IV
Q5. Can this study motivate building owners to renovate a building for improved performance concerning energy efficiency and indoor comfort?	∘ Quantitative^{i,sim} ∘ Qualitative^{s,o}	∘ Model development ∘ Questionnaire ∘ Computer simulation	Article II Article III Article VII Article VIII
Q6. What is the attitude of construction workers within the built environment in Sweden, concerning current health and safety related measures at their workplaces?	∘ Quantitative^{i} ∘ Survey	∘ Questionnaire	Article V

Table 3.2. The utilized research methods, research tools and outputs for the posed research questions Q4−Q6. The superscripts are denoted by: *e* for experimental, *i* for inferential, *s* for subjective assessment of attitudes, *o* for opinions, and *sim* for simulation.

This study has exhibited a depiction of opportunities associated with sustainable building, within the built environment. The author's own thought process in the context of this thesis has been based on the dissimilar research approaches undertaken herein and the combination of different research methods, which have contributed to an enhanced understanding of the topics of this study. For a more profound comprehension of the discussed topics in this study, further evaluation is needed based on the findings of this study, as described in Chapter 4.

Chapter 4

Results

4.1 Introduction

This chapter describes a brief summary of the obtained results, shown in Articles I–X. More in-depth details pertaining to the employed research methods and research background, are exhibited in the appended articles.

4.2 Review of Sustainable Refurbishment in Building Technology (Article I)

The objective of this study was to identify a number of key research efforts related to decision making tools in building refurbishment projects and selected energy efficiency efforts in the built environment by means of a literature review. Specifically, limited aspects of the regional disparities between Cyprus, Denmark and Sweden were considered. In a representative case, climatic factors such as the number of Heating Degree Days (HDD) per country and the population density served as measurements designed to reflect the demand for energy needed to heat a residential complex. These are shown in Table 4.1. In this context, HDD is a measure employed in energy analysis as an indicator of space heating energy requirements or usage over a time period in relation to a base temperature.

Country	**Population Density [inhabitants/km^2]**	**Average annual HDD**
Cyprus	119.2	782
Denmark	130.3	3,503
Sweden	21.8	5,444

Table 4.1. Comparison of population density and average annual heating degree days for Cyprus, Denmark and Sweden.

This article in addition identified that energy efficiency measures could indeed have a significant impact on energy consumption and the energy saving potential for electric lighting in office buildings in Northern Europe. A number of suggested strategies for reducing energy utilization of electric lighting included: ballast (a device intended to limit the amount of current in an electric circuit) and luminaire technology, improvements in lamps, utilization of task/ambient lighting, improvement in maintenance and utilization factor, reduction of maintained illuminance levels and total switch-on time, use of manual dimming and switch-off occupancy sensors. Energy saving aspects for a European country in a warmer climate zone could in certain cases possibly coincide with the chosen energy efficiency measures. The study delineated that countries in warmer climatic zones, such as Cyprus, undoubtedly have a different energy demand in comparison to for instance the Nordic countries. From a broader vantage point, however, both the aspect of insulation of external walls and electric lighting are captured by the hierarchical process in Figure 4.1

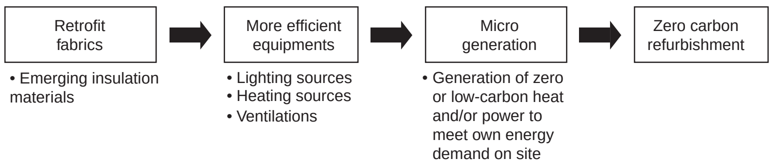


Figure 4.1. A hierarchical process towards zero carbon refurbishment (Gohardani and Björk, 2012; Xing et al., 2011).

Hence, one distinctive challenge in conducting a multilateral review study is to choose an appropriate research methodology, based on regional disparities and energy demand levels. This study further calls for a robust approach for assessment of retrofits, as shown in Figure 4.1, due to the existence of different assessment criteria provided by dissimilar tools. More detailed results from this study are presented in Article I.

4.3 The Operational Decision Support Process (Article II)

The purpose of this study was to develop and describe promotion of energy saving measures concurrent with planned major renovations in residential buildings. The method comprised of case studies, in which project team members at early project stages contributed to the overall decision making process related to building renovation. During these stages of a building project, while the building owner and other involved stakeholders still have not made definitive decisions, there are possibilities to influence the outlook regarding future renovation measures. This in turn, will facilitate the planning for renovation procedures resulting in an increased sustainability when operating the building. Despite the availability of various tools for decision making about renovation, there is currently a distinct ambiguity included in adopting a useful procedure that would influence stakeholders and decision makers to cogitate about a potential building renovation project. One specific project: the *Renovation Workshop of Riksbyggen* (RWR) illuminates several factors affecting the decision making process for a sustainable renovation within the built environment in Sweden. The findings of this study exhibit that this process consists of three different phases, as shown in Figures 4.2−4.4.

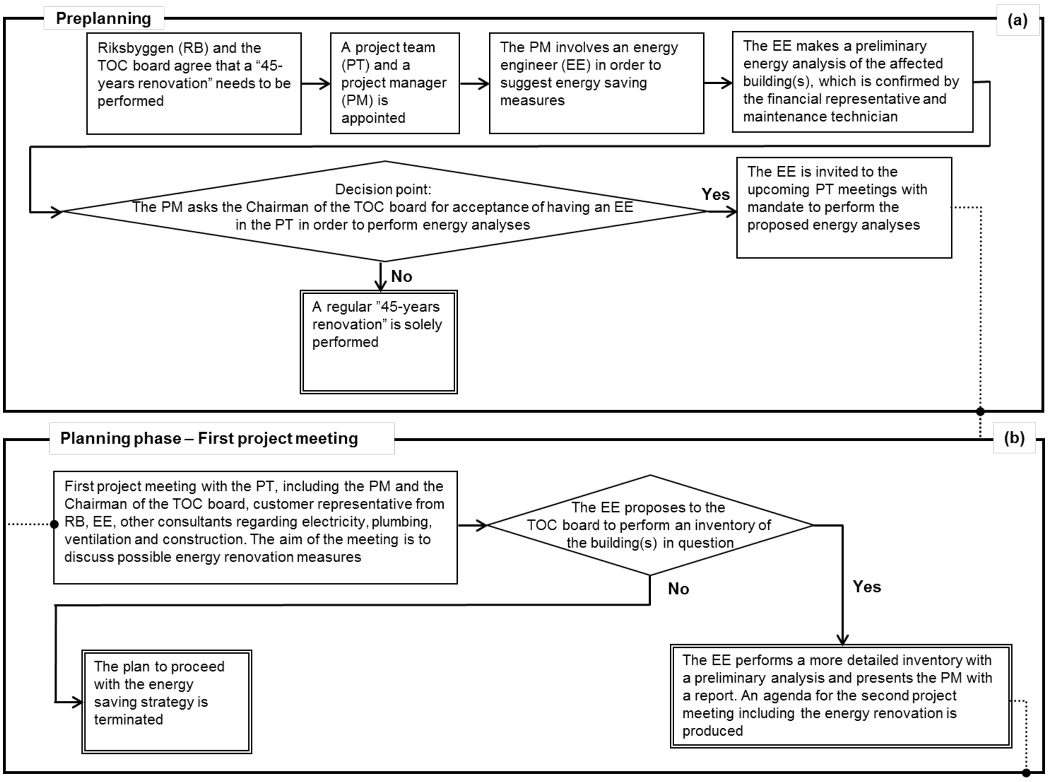


Figure 4.2. The initial preplanning and planning phases of the operational decision support process.

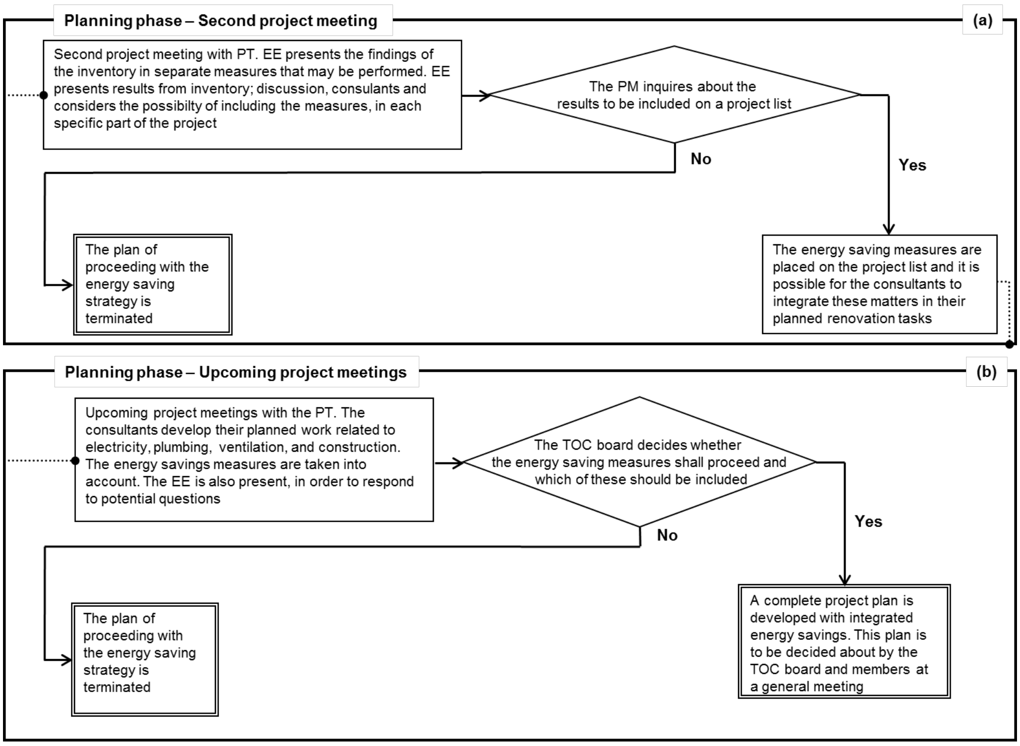


Figure 4.3. The succeeding planning phases of the operational decision support process.

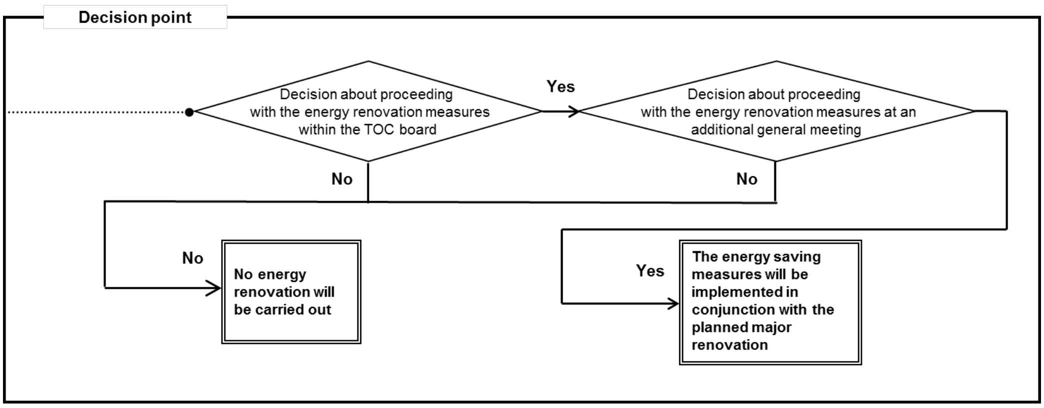


Figure 4.4. The decision point of the operational decision support process.

The performed case studies indicate that it is possible to motivate building owners to combine energy saving measures with major alterations to existing buildings, by means of the proposed operational decision support process. The objective of this process is to showcase and more importantly to implement energy saving measures, based on knowledge transfer between different parties involved in the renovation project. In addition, a number of key points can be identified to be integrated in a general renovation context, broadly identified in Figure 4.5.

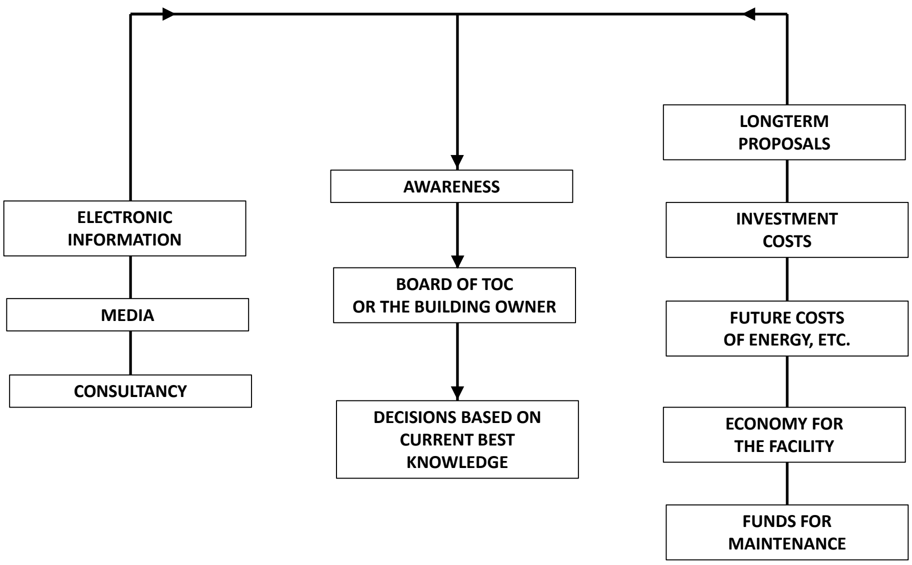


Figure 4.5. A proposed process for adequate decision making based on best knowledge.

Figure 4.5 describes the flow of information from electronic media, and consultancy as well as long-term proposals and investment costs in addition to other factors, as a baseline for awareness and for decisions based on current best knowledge. The most important issue in this context is awareness about the implications of renovation for both building owners and occupants. A high level of awareness is evident upon gathering of information from various sources, wherein particular electronic information sources, printed media and consultancy can be mentioned. The retrieved information may then be utilized both for common building owners and in tenant owners' cooperatives (TOC).

4.4 Sustainable Renovation and Refurbishment in Sweden, Denmark and Cyprus (Article III)

In this research study, the attitude of stakeholders in Sweden, Denmark and Cyprus to sustainable renovation of buildings was determined through three separate case studies. The objective was hence to establish an overview of the factors that influence the energy renovation process and act as the main drivers. The findings of this article is derived from the conducted research study within the ACES project, detailed in Section 2.1. The core emphasis of the ACES project addresses decisions about refurbishment to be considered at an early design stage, when usually no decisions are made about future building measures. Another purpose is to motivate building owners to renovate buildings for improved performance considering energy efficiency and indoor comfort, based on their geographic location and national requirements. The adopted methodology in this research study utilized a triangulated approach, consisting of a conducted literature study in conjunction with questionnaires and semi-structured interviews. Upon an initial literature review, an insight was obtained regarding the questions that were of interest for building owners in regards to renovation. Hence, this review served as the basis for designing the questionnaires in each country. The questionnaires summarized the most relevant parameters related to *durability/building physics*, *economy*, *environment*, *comfort*, and other important drivers that may be of great significance in energy renovation projects. Upon gathering of the data in each distinct country, the most important parameters were identified. A summary of these is shown in Table 4.2.

Parameter	**Sweden**	**Denmark**	**Cyprus**
Durability/building physics	Maintenance	Deterioration	Moisture
Economy	Cost	Payback time	Cost, income
Environment	Energy savings	Energy savings Local energy production	Energy savings Eco-friendly products
Comfort	Indoor climate	Indoor climate	Indoor air quality
Others	N/A	Branding, CSR	Building aesthetics

Table 4.2. The identified drivers for energy renovation for the considered countries.

The main parameters in Table 4.2 denote their importance, resulting in *durability/building physics* being considered as the most important factors for sustainable renovation, in this study. The *economic* drivers are on a second place, followed by the *environmental* drivers, *comfort* issues, and other relevant topics. Explicitly, the importance of different factors pertaining to energy renovations was assessed based on the questionnaire Appendix III in the article. Based on these findings, it is evident that factors such as *improvement of indoor air quality* and *elimination of moisture*, *improvement of heating* and *cooling performance*, as well as *reduction of electricity and heating*, are dominating factors for both Cyprus and Sweden that in turn will instigate energy renovation measures. The fact that there is a synergy between the findings of this study among two distinctly different countries in terms of climate i.e., Cyprus and Sweden, is indicative that these factors are indeed important when considering energy renovations. Due to lack of adequate number of responses, the aforementioned questionnaire could not be used in Denmark. The Danish study included 10 qualitative semi-structured interviews based on an interview guide with open questions. The reasoning behind utilizing different research methods originated from the challenge of obtaining a large enough sample size for all three studies.

4.5 Environmental Certification of Buildings in Sweden (Article IV)

This study examined the nature of common inaccuracies in applications towards environmental certification of buildings hosted by the Sweden Green Building Council (SGBC). In particular, a number of received applications related to the Swedish Environmental Building (EB) program (Miljöbyggnad) and the European Union's GreenBuilding (GB) program, were examined and the relevant errors made in the applications sent to SGBC were identified and accounted for. The objective of this case study was to instigate further understanding about the level of aptitude among building consultants and to find ways for enhancing their ability to produce high quality calculations concerning building-related energy usage and finally, comprehension of the certification process. The motivation behind this study originated from an identified need by SGBC, to raise awareness in relation to received applications for environmental certification of buildings, as a great deal of these currently exhibit lack of knowledge considering the attributes of buildings related to details expressing the energy consumption. The examined data derived from indicator analyses for this case study was collected and evaluated by reviewing 60 applications submitted to SGBC.

Factors in the analysis included the heated area of the building A_{temp}, the year in which the application was filed, the software utilized for energy calculations, the number of revisions during the evaluation process, and specific indicators for the first, second, and third revisions. The parameter A_{temp}, refers to the area enclosed by the inside of the building envelope of all floors including cellars and attics for temperature-controlled spaces, intended to be heated to more than 10 °C. In addition it refers to the area occupied by interior walls, openings for stairs, shafts, etc. In this context, the area for garages, within residential buildings or other building premises other than garages, are not included (Building Regulations, BBR, 2011). The evaluated EB applications were filed between 2009 and 2012, with the median year of the data being 2010. This time period was chosen as a consequence of disclosed application data from SGBC. The received applications differed considerably in terms of building size, with A_{temp} between 130 m^2 and 56,600 m^2, with an approximate median value of 5900 m^2. Figure 4.6 depicts the number of remarks per indicator for the first, second, and third revisions made by SGBC.

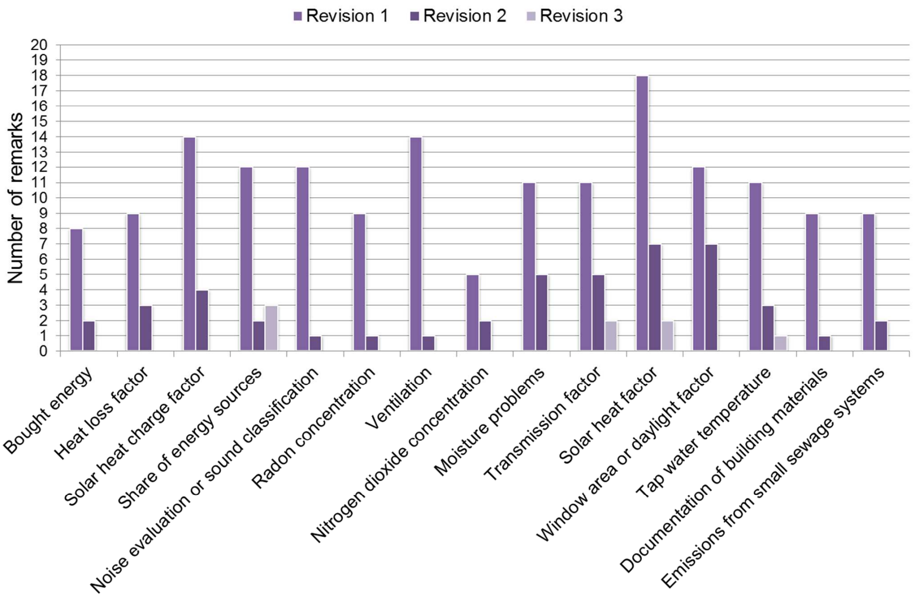


Figure 4.6. Indicators for EB with corresponding remarks from the certification council. The columns from left to right represent the corresponding revision. Hence, the maximum number of revisions received per applicant is three.

According to Figure 4.6, *solar heat factor* is subject to the most remarks, followed by the *solar heat charge factor*, *share of energy sources*, *noise evaluation or sound classification*, and *window area or daylight factor*. The indicator with least remarks in this context is *Nitrogen dioxide concentration*. In addition, there is a fairly well established spread in terms of the number of remarks for the different indicators. Furthermore, each indicator has obtained at least one remark. For the second revision, *solar heat factor* and *window area or daylight factor* are responsible for most of the remarks, followed by *transmission factor* and *moisture problems*. The indicators receiving the fewest remarks were *noise evaluation or sound classification*, *radon concentration*, *ventilation*, and *documentation of building materials and included chemical content*. For the third revision solely four of the indicators received remarks; since during the first and second revisions, the applicants revise their applications to address the received remarks satisfactorily. The number of indicators receiving remarks are thus greatly reduced. The energy simulation software used in the applications for EB are shown in Figure 4.7.

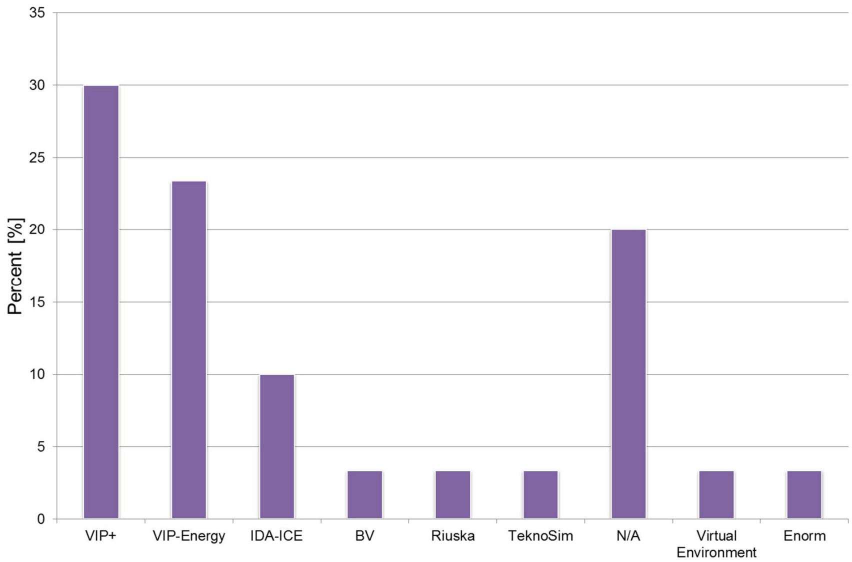


Figure 4.7. Energy simulation software used in applications for EB.

According to Figure 4.7, *VIP+* is mostly utilized in the evaluated applications for EB, followed by *VIP-energy*. These are essentially two different generations of the same software, indicating the importance of this simulation tool on the market. For the GB applications, the sample size consisted of 30 applications submitted to SGBC between 2009 and 2013, with 2012 serving as the median year. The heated area of the considered buildings, A_{temp} was between 300 m^2 and $39,000$ m^2 with an approximate median value of 6,000 m^2. In this study, the energy saving measures employed in order to fulfill the requirements for GB certification were identified as shown in ARTICLE IV. The findings of the article indicate that *air treatment system* is the most utilized measure for reduction of energy, followed by *heating and hot water systems* and *control of temperature and air-flow*. In accordance with the article, the level of reduction attained following the energy saving measures corresponds to $12\% \leq r \leq 69\%$, with an average value of 33%.

Upon comparison between applications submitted to SGBC for EB and GB, the main difference was that those sent for GB certification had been analyzed based on the energy measures that contributed to their approval. For EB applications however, the indicators that contributed to revisions had been considered. Furthermore, there were virtually no revisions for GB, as the building only had to fulfill the set threshold of energy reduction prior to the application being filed. This could be achieved by numerous energy saving measures. A larger number of revisions for the EB applications were identified, as these essentially covered a wider range of indicators, making the EB certification process slightly more intricate. A common denominator between both programs was the software utilized for the energy simulations. In the case of EB and GB applications, *VIP+* and *IDA-ICE* dominated, respectively.

4.6 Swedish Construction Industry and Applications of the Construction Sector Chain Disaster Theory (Article V)

In this study the Construction Sector Chain Disaster Theory (CSCDT) (Gohardani and Björk, 2013c) was employed in order to obtain an insight into preventive measures against injuries or death within the Swedish construction sector. The data collection in this study was actualized by means of a developed survey, based on the following categories:

- Category I: Metrics to identify trends that distinguish between the Swedish construction workers and construction workers in other parts of the world.
- Category II: The conscious perception construction workers hold about the Swedish construction industry.
- Category III: An approach to statistically verify the occurrence of accidents within the Swedish construction sector.
- Category IV: A mapping technique of different working conditions and procedures.

In addition, the aforementioned categories were combined with a set of structured questions. Figures 4.8 and 4.9 depict the age distribution of participating respondents in the survey and the respondents' working experience in the construction sector, respectively.

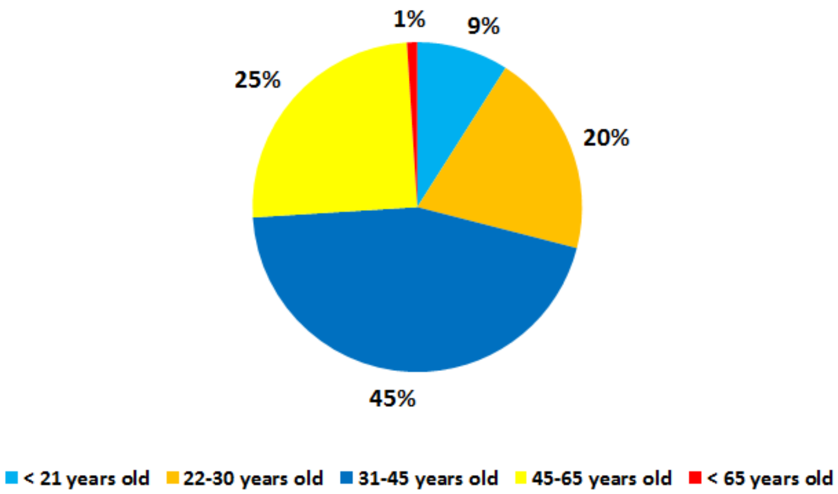


Figure 4.8. Age distribution of the survey respondents.

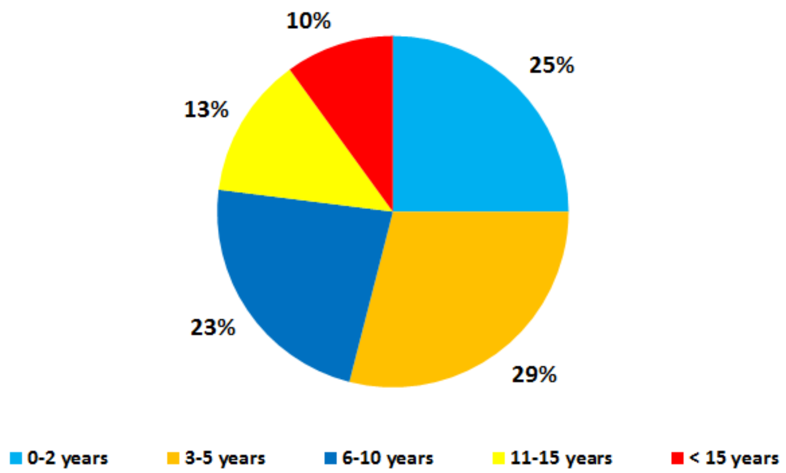


Figure 4.9. The years of experience among the responding construction workers.

Figure 4.8 indicates that the majority of the respondents are in the age range $31 - 45$ years. According to Figure 4.9, the largest groups of these respondents have between $3 - 5$ years of work experience in the construction sector. This study also provided an overview of the listed reasons for which the respondents reported themselves sick to work, as shown in Figure 4.10.

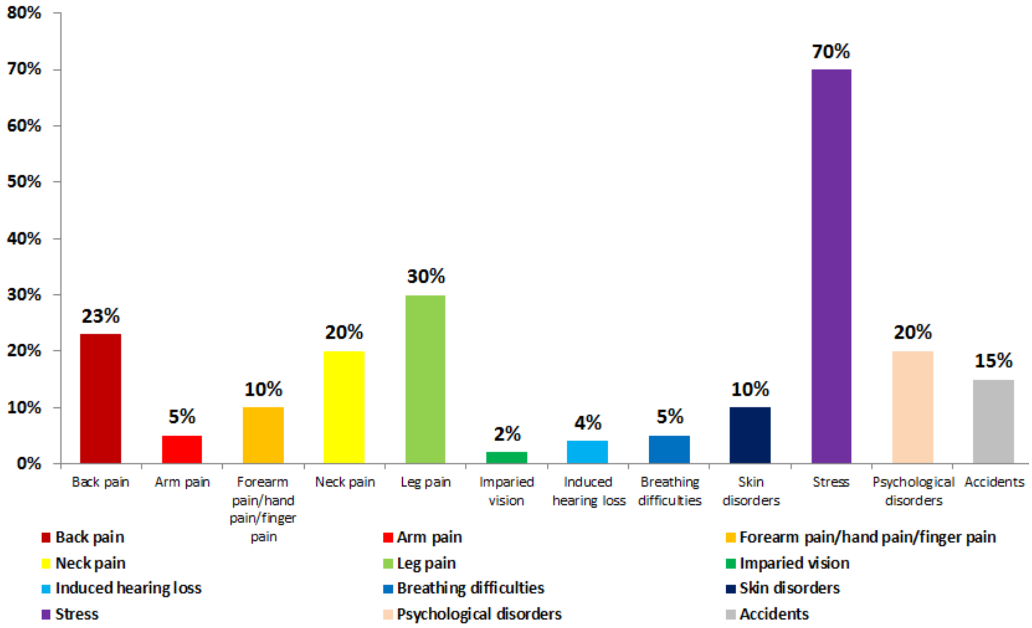


Figure 4.10. Listed reasons specified by the respondents for reporting themselves sick to work.

Figure 4.10 exhibits that *stress* is the main reason why the respondents have called in sick to work, followed by *leg pain* and *back pain*. The respondents' perception of means to enhance the health and safety level at construction sites in Sweden, are shown in Figure 4.11.

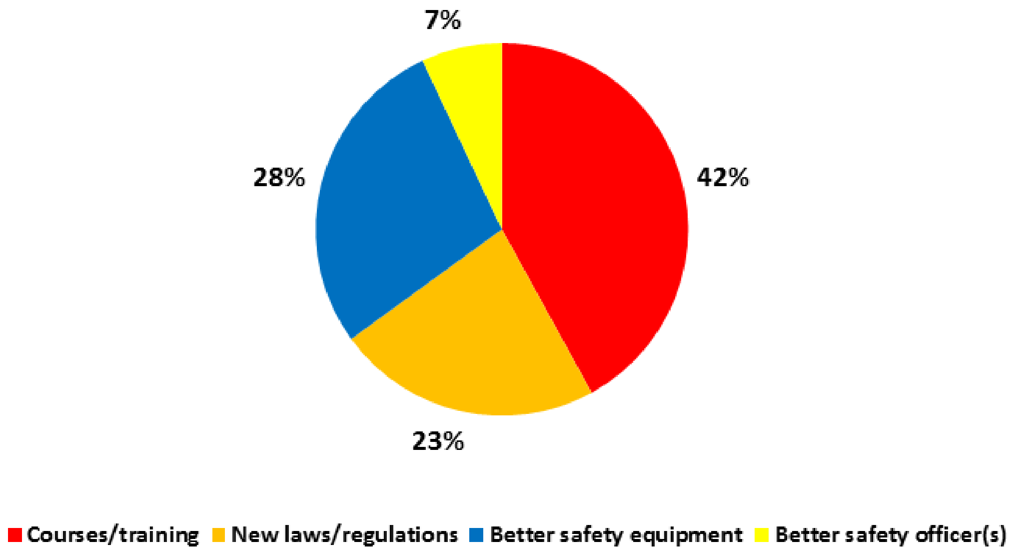


Figure 4.11. The respondents' perceptions about the most efficient methods to ensure enhanced health and safety approaches for Swedish construction workers.

Figure 4.12 further reveals that in cases when repetitive work procedures were tracked down in the study, a moderate repetitive intensity level represented the most frequent type of repetitiveness.

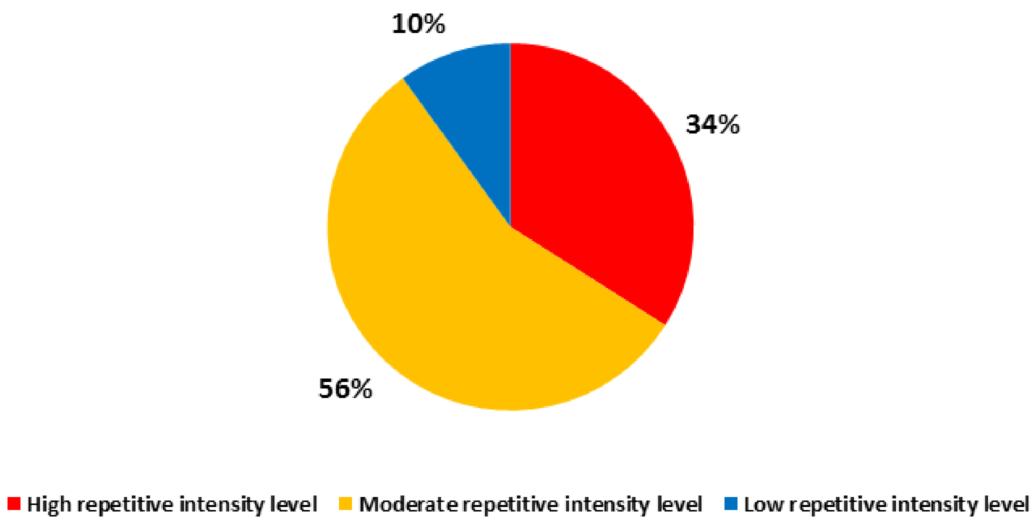


Figure 4.12. The distribution of intensity levels for monotonous movements.

The CSCDT denotes an alternative viewpoint by portraying the construction sector as an ongoing disaster zone. This perception institutes that disaster within the construction sector corresponds to the temporary or permanent ill health or death of a construction worker. The fundamental brick stones of CSCDT are thus related to elements such as vulnerability, disaster and hazard, more detailed by Gohardani and Björk (2013a). The findings of this article suggested that the Swedish construction work force still experience challenges, despite laws, regulations or additional factors that seek to ensure a safe and healthy environment. Based on the findings of the conducted survey, construction workers call for additional measures to ensure health and safety and it is evident that disorders and pain induced by their work duties result in absence from work.

4.7 Energy Performance Evaluation of A Church Building (Article VI)

For purposes of analyzing the energy savings resulting from the replacement of an existing electric coil heating system to a hydronic ground source heat pump (GSHP) system, a case study was conducted of a church building in Sweden. Estimation of energy performance indexes, such as the energy signature method was utilized, which calls for regression of the heating losses on the actual outdoor temperature.

The hourly energy usage of the church building was therefore plotted versus the outdoor temperature and the gathered data entailed that at least two regions could be identified in the plot. These regions were characterized by two distinct slopes of a linear curve, where the first portion was highly temperature dependent and the latter completely independent of the outside temperature, representing the building's base load. In this study, the calculated time periods prior and subsequent to the GSHP system installment, were divided into a *non-heating* and a *heating* season, as shown in Table 4.3.

Season No.	**Season**	**From date**	**To date**	$\overline{T}$ [°C]
I	Heating†	October 15, 2010	May 15, 2011	−2.87
II	Non-heating†	May 16, 2011	October 14, 2011	+12.26
III	Heating‡	October 15, 2012	May 15, 2013	−2.30
IV	Non-heating‡	May 16, 2013	August 25, 2013	+11.70

Table 4.3. The heating and non-heating seasons, prior (†) and subsequent to the GSHP system (‡) installment.

The energy signature for the church building, prior and post to the GSHP system installment is shown in Figures 4.13 and 4.14, respectively.

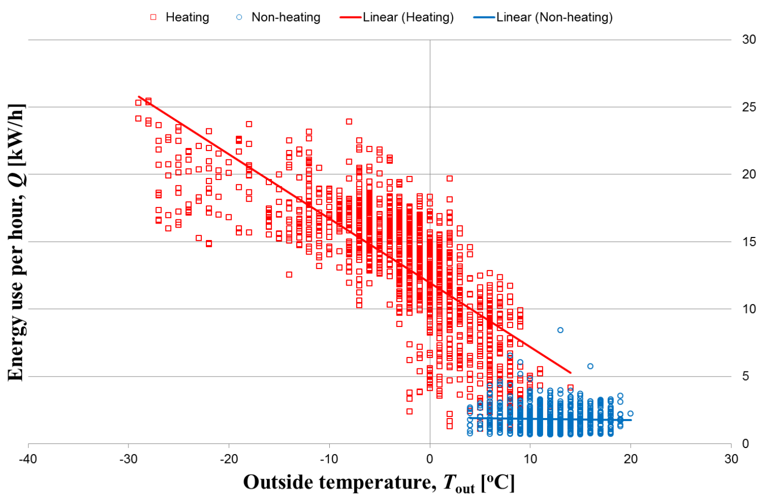


Figure 4.13. The hourly energy use versus outside temperature for the church building prior to the GSHP system installment.

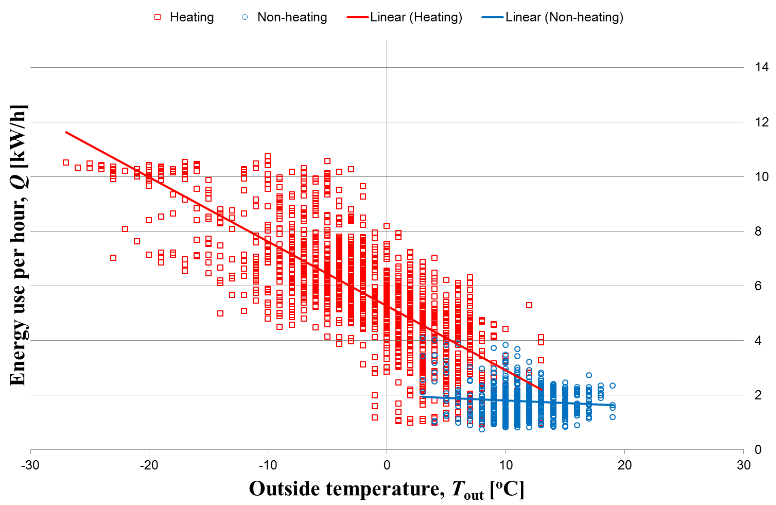


Figure 4.14. The hourly energy use versus outside temperature for the church building post to the GSHP system installment.

The average temperatures, prior and post to installment of the GSHP system are given by $\bar{T}_{\text{prior}}^{\text{I-II}} = \frac{1}{N}\Sigma_{m=1}^{N} T_{\text{out}}|_{\text{prior}}^{\text{I-II}} \approx 6.6\,°\text{C}$ and $\bar{T}_{\text{post}}^{\text{III-IV}} = \frac{1}{N}\Sigma_{m=1}^{N} T_{\text{out}}|_{\text{post}}^{\text{III-IV}} \approx 2.9\,°\text{C}$, respectively. A graphical comparison of the energy usage is provided in Figure 4.15.

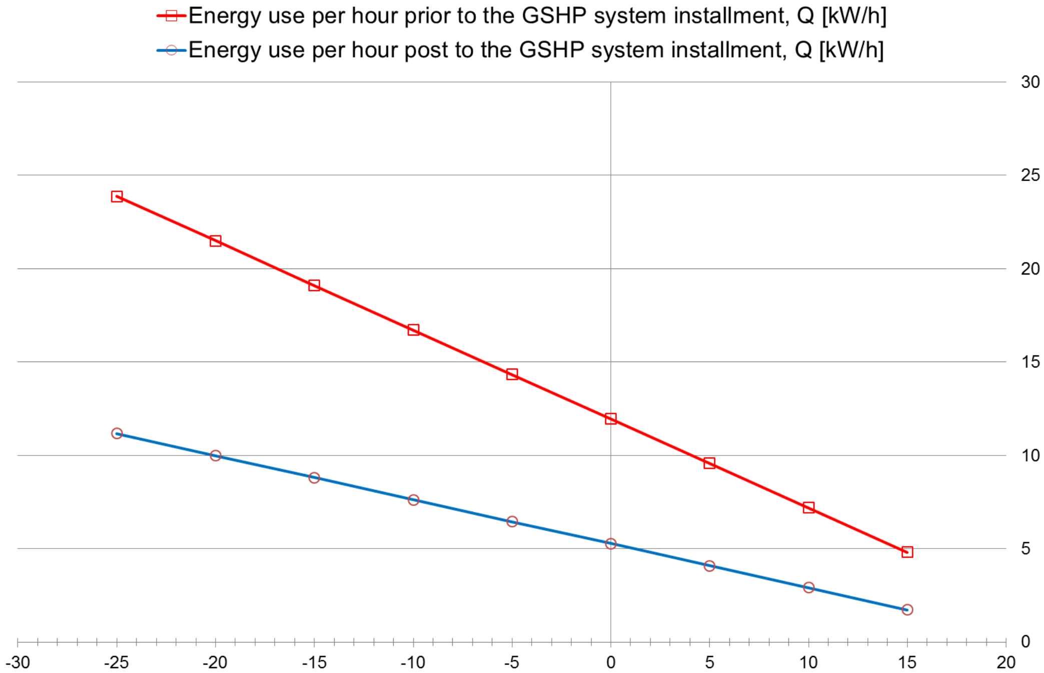


Figure 4.15. The hourly energy usage versus outside temperature for the church building represented by two different linear functions. These functions are given by $Q_{\text{Prior}}(T_{\text{out}}) = -0.4766 \cdot T_{\text{out}} + 11.951$ and $Q_{\text{Post}}(T_{\text{out}}) = -0.2358 \cdot T_{\text{out}} + 5.267$, respectively.

Table 4.4 demonstrates the coefficients for energy usage per hour when corrected for the base load of the non-heating season.

	Heating season		Non-heating season	
	f_B	f_T	f_B	f_T
Prior to GSHP installment†	11.951	-0.4766	1.9348	-0.0093
Prior to GSHP installment^{†,c}	9.9903	-0.4766	0.0259	-0.0093
Post to GSHP installment†	5.2670	-0.2358	1.9867	-0.0187
Post to GSHP installment^{†,c}	3.3063	-0.2358	0.0260	-0.0187

Table 4.4. A comparison between the non-heating and heating seasons starting from zero (†) and from the base load of the non-heating season (‡), prior and subsequent to the GSHP system installment. The superscript c denotes the coefficients for energy usage per hour, when corrected for the base load of the non-heating season. In addition, f_B and f_T represent the base load factor and the temperature dependent factor, respectively.

The mean temperature of the heating season post to the GSHP installment was −2.30 °C. At this temperature the ratio is given by

$$\Psi = \frac{Q_{\text{Post}}(T)}{Q_{\text{Prior}}(T)} \tag{4.1}$$

The corresponding energy saving can be estimated by

$$\chi = 1 - \Psi \tag{4.2}$$

The corresponding values are given by $\Psi = 0.45$ and $\chi = 55\%$ for the aforementioned temperature. Table 4.5 presents results for calculations at a few different temperatures.

T [°C]	Q_{Prior} [kW·h^{-1}]	Q_{Post} [kW·h^{-1}]	Ψ	χ [%]
−20	21.48	9.98	0.465	53.5
−15	19.10	8.80	0.461	53.9
−10	16.72	7.63	0.456	54.4
−5	14.33	6.45	0.450	55.0
−2.3	13.05	5.81	0.445	55.5
0	11.95	5.27	0.441	55.9
5	9.57	4.09	0.427	57.3

Table 4.5. A comparison between the energy usage per hour prior and post to the installment of the GSHP system. The ratio term Ψ denotes $Q_{\text{Post}}(T)/Q_{\text{Prior}}(T)$, and the term $\chi = 1 - \Psi$, the corresponding energy saving in percent.

From the data for the non-heating seasons, the base load of the building was $\sim$ 1.96 kW·h^{-1}. Hence, the power need could be adjusted by subtracting the base load values for the non-heating seasons pre and post to the GSHP system installment, from the power need as illustrated in Figure 4.16. The coefficients for the adjusted power need are given in Table 4.4 and results from these calculations at a few different temperatures shown in Table 4.6.

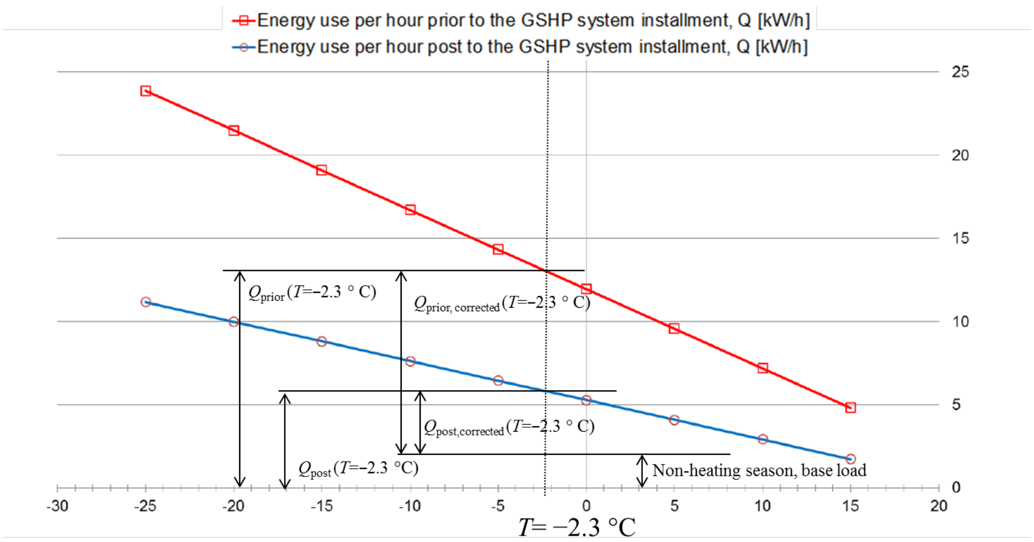


Figure 4.16. The hourly energy usage versus outside temperature for the church building post to the GSHP system installment. The base load of the non-heating season and the corresponding corrected factors for the heating seasons are shown in the figure.

T [°C]	Q_{Prior} [kW·h^{-1}]	Q_{Post} [kW·h^{-1}]	Ψ	χ [%]
−20	19.55	8.00	0.409	59.1
−15	17.17	6.82	0.397	60.3
−10	14.78	5.64	0.381	61.9
−5	12.40	4.46	0.360	64.0
−2.3	11.11	3.82	0.344	65.6
0	10.02	3.28	0.327	67.3
5	7.63	2.10	0.275	72.5

Table 4.6. A comparison between the energy use per hour prior and post to the installment of the GSHP system, for the corrected values. The ratio term Ψ denotes $Q_{\text{Post}}(T)/Q_{\text{Prior}}(T)$, and the term $\chi = 1 - \Psi$, the corresponding energy saving in percent.

The replacement of the original heating system with a ground source heat pump system for the church building constitutes a reduced energy consumption of approximately 66% at the average outside temperature of −2.30 °C.

4.8 Sustainable building renovation and refurbishment with applications of Vacuum Insulation Panels (Article VII)

In order to assess high-efficient insulation solutions, this study considered the usage of VIPs. Particular attention was given to the comparison of exterior and interior applications of VIPs in buildings and the effects of thermal bridges at connections between the external wall and the adjacent floor slabs and balconies. For renovation purposes of a building, an illustrative case was studied herein on VIPs with dimensions 1000×600 mm^2, a thickness of 30 mm and the thermal conductivity λ of 0.004 W/(mK) at the center section of the panels. Figure 4.17 exhibits results for three different interest rates (r_1, r_2, r_3) ranging between $3 - 7\%$ for a household income per square meter of surface and year, versus the net cost of the VIPs with the given cost of 1090 SEK (Swedish Kronor) per panel, as provided by the involved manufacturer of VIPs in the project. It is demonstrated that an investment in VIPs used in this study, waives the deposited amount after a distinct time period, depending on the cost of each panel and current interest rates.

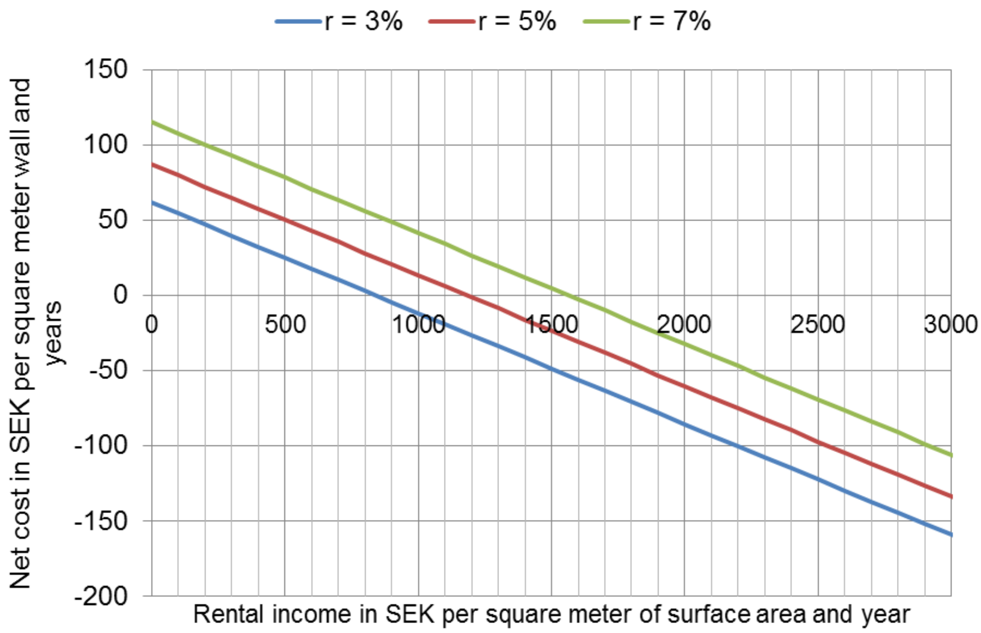
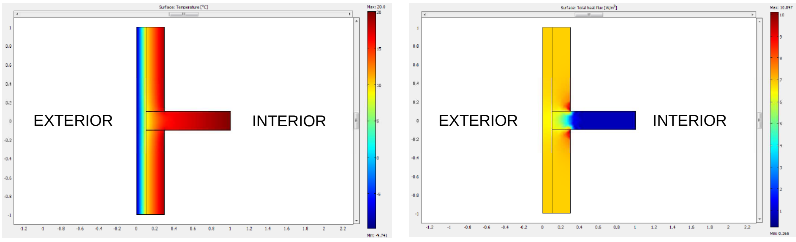


Figure 4.17. Rental income in SEK (Swedish Kronor) per square meter of surface area versus the net cost of VIP in SEK per square meter wall and years for different interest rates, r.

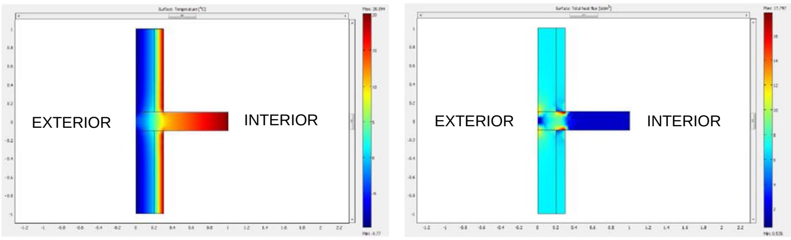
More detailed information related to Figure 4.17 can be found in Appendix C. This study also explored the influence of a thermal bridge on an exterior wall and floor slab connection. Set temperatures for the interior and exterior of the wall, $T_{\text{interior}} = 20$ °C and $T_{\text{exterior}} = -10$ °C were used in the simulations. These temperatures implied that the heat transfer coefficient for the interior and the exterior were given by $h_{\text{interior}} = R_{si}^{-1}$ and $h_{\text{exterior}} = R_{se}^{-1}$, with the thermal resistances for the interior $R_{si} = 0.13$ m^{2}K/W and exterior $R_{se} = 0.04$ m^{2}K/W. Four cases in particular were considered, with the placement of the materials seen from the exterior of the wall-section to the interior section, indoors.

- Configuration I: Mineral wool, light-weight concrete and vapor barrier
- Configuration II: Light-weight concrete, mineral wool and vapor barrier
- Configuration III: Envelope film, VIP, envelope film and Light-weight concrete
- Configuration IV: Light-weight concrete, envelope film, VIP and envelope film

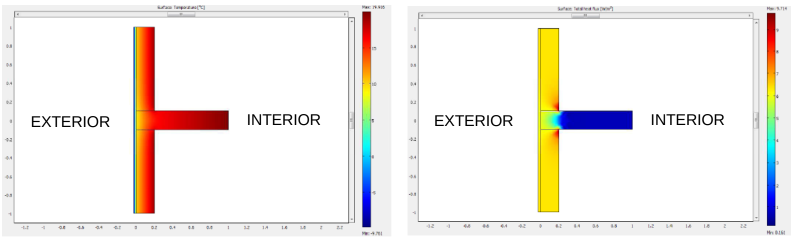
The simulation results, for the temperature distribution and the total heat transfer for the four configurations are shown in Figure 4.18.



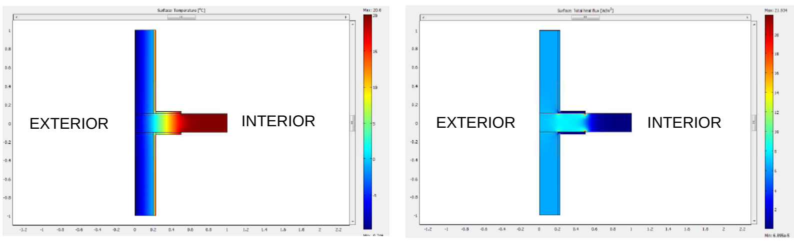
Temperature distribution (left) and total heat flux (right) for a thermal bridge under Configuration I, where floor and wall section consists of mineral wool and light-weight concrete



Temperature distribution (left) and total heat flux (right) for a thermal bridge under Configuration II, with mineral wool placed on the inside of the light-weight concrete layer



Temperature distribution (left) and total heat flux (right) for a thermal bridge under Configuration III, with VIP positioned as an external insulation and light-weight concrete as an internal layer



Temperature distribution (left) and total heat flux (right) for a thermal bridge under Configuration IV, with VIP placed as an internal insulation.

Figure 4.18. Temperature distribution (left) and total heat flux (right) for an exterior wall and floor slab connection according to configurations I-IV.

The simulation software was also used for calculation of the linear thermal transmittance, Ψ ranging between 0.037 $W \cdot m^{-1} \cdot K^{-1}$ and 0.050 $W \cdot m^{-1} \cdot K^{-1}$. It was identified that configurations II and IV with thermal insulation placed on the inner side, have the highest values of the linear thermal transmittance. In addition, this study explored the implementation of VIPs as supplementary insulation to a balcony slab originally insulated with mineral wool. The result of this simulation performed in COMSOL Multiphysics® is shown in Figure 4.19.

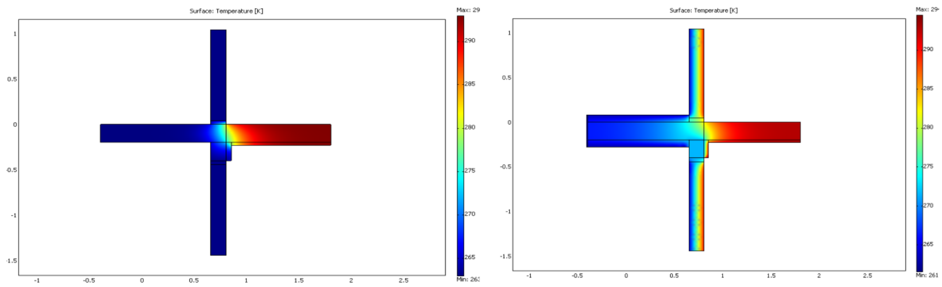


Figure 4.19. Finite Element Analysis of a balcony slab before and after supplementary thermal insulation with mineral wool and VIPs.

4.9 Economic and environmental benefits related to a sustainable building refurbishment (Article VIII)

A simulation study was undertaken with the purpose of exploring the estimated energy usage for heating, calculated in conformity with EN ISO 13790 (Energy performance of buildings - Calculation of energy use for space heating and cooling) and based on a dynamic method for buildings prior and subsequent to refurbishment with VIPs. The dynamic method provided details of the influence of the non-steady processes, thermal inertia and the dynamic properties of the building on the need for heating and cooling (Jóhannesson, 2005a). The simulation scheme was initiated upon a baseline simulation approach. The performance of VIPs in relation to mineral wool were studied and simulations were carried out simultaneously, with the same input parameters and building dimensions for both cases, using the software package Consolis Energy + (Jóhannesson, 2005a,b). This software calculates both according to EN ISO 13790 and a dynamic model. The simulations were performed on a number of considered geographic locations, specified in Table 4.7.

City	Country	Latitude
Kiruna	Sweden	67.82
Stockholm	Sweden	59.33
Göteborg	Sweden	57.72
Malmö	Sweden	55.37
Madrid	Spain	40.27

Table 4.7. Considered geographic locations, based on latitude.

An overview of the total energy consumption per annum with and without the usage of VIPs for different cases is shown in Figure 4.20 using EN ISO 13790 and the dynamic model approach.

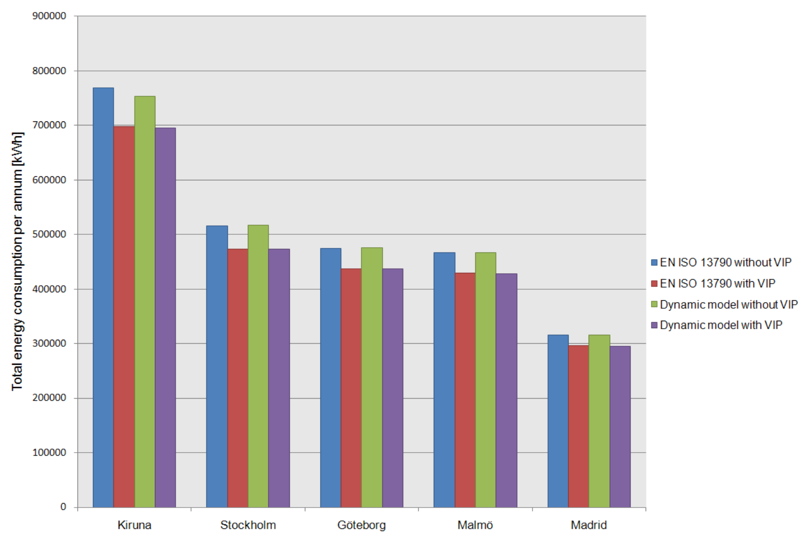


Figure 4.20. The total energy consumption per annum in kWh, with and without VIPs, using EN ISO 13790 and the dynamic model approach.

Based on the findings of Figure 4.20, it can be established that all cases with VIPs utilized as an alternative insulation material, result in energy savings for the building. The percentage in saved energy for the two employed methods with the amount saved in € (Euro), are shown in Table 4.8 and Figure 4.21, respectively. Simulations were performed for a typical multistory building with length, width and height dimensions of 61.3 m, 11.6 m and 15.6 m, respectively. The window percentage area for each façade was chosen as 15%. The software also employed the ground area and perimeter to calculate the ground heat losses. The supplementary insulation was in this study applied to the total wall and roof area of the building. The generic approach mimics a realistic building representation prescribed by set temperatures, building dimensions, horizontal solar angle, other building-related data points, and the occupancy percentage of windows.

This approach enabled a complete analysis to be conducted for a generic multistory building studied for different geographical locations. In accordance with Figure 4.21, the largest savings occur in Kiruna.

City	Method	Saved percentage
Kiruna	EN ISO 13790	9.3 %
	Dynamic model	7.6 %
Stockholm	EN ISO 13790	8.2 %
	Dynamic model	8.6 %
Göteborg	EN ISO 13790	7.9 %
	Dynamic model	8.3 %
Malmö	EN ISO 13790	7.9 %
	Dynamic model	8.3 %
Madrid	EN ISO 13790	6.1 %
	Dynamic model	6.5 %

Table 4.8. Energy savings due to VIP usage with the two different methods.

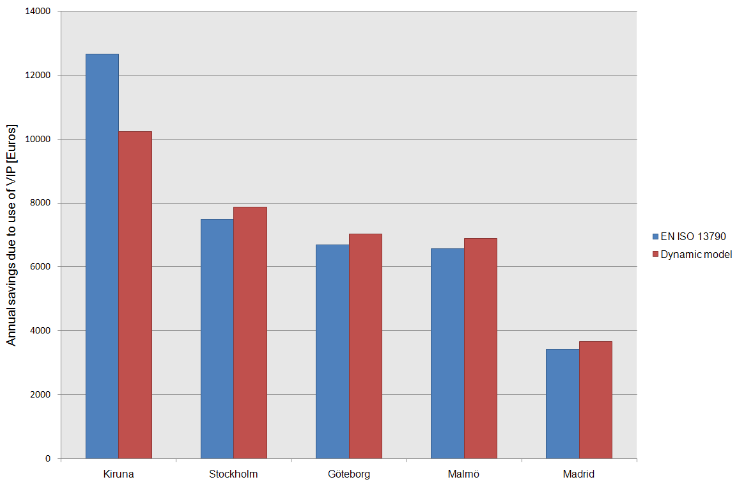


Figure 4.21. The annual energy savings due to VIP usage instead of mineral wool, in € (Euro).

4.10 A Simulation Approach Towards A Sustainable Building Design (Article IX)

The focus of this study was placed on the influence of building design on building cooling and heating performance when viewed against different geographical locations within the USA and in Europe. In particular, the simulation tool Autodesk Revit® MEP was employed in order to characterize the influence of building design on the resulting heating and cooling loads of a residential building. The software utilized *ASHRAE Handbook of Fundamentals* for computation of the loads and examined the influence of the geographical locations on the obtained results. Figure 4.22, depicts the difference between the two designs.

(a)

(b)

Figure 4.22. Design of the building, with (a) depicting the original design and (b) the curtain wall.

In addition to the different designs shown in Figure 4.22, six geographical locations were considered as outlined in Table 4.9.

City	Country	LAT	LON	SDB	SWB	WDB	MDR
Stockholm	Sweden	59.33	18.06	29 °C	20 °C	−17 °C	9 °C
Copenhagen	Denmark	55.68	12.57	27 °C	20 °C	10 °C	10 °C
Nicosia	Cyprus	35.17	33.37	35 °C	26 °C	4 °C	8 °C
Los Angeles	U.S.A.	34.05	118.24	38 °C	23 °C	4 °C	5 °C
New York	U.S.A.	40.71	74.01	35 °C	26 °C	11 °C	10 °C
Dallas	U.S.A.	32.80	69.77	39 °C	27 °C	6 °C	8 °C

Table 4.9. The same building used in different geographical locations. The following abbreviations are used: Latitude (LAT), longitude (LON), summer dry bulb (SDB), summer wet bulb (SWB), winter dry bulb (WDB), and mean daily range (MDR). The terms SDB and WDB refer to summer and winter ambient temperature without the influence of humidity, SWB to the summer temperature of adiabatic saturation, and MDR the mean temperature range.

Figure 4.23, exhibits that there is a significant difference between the cooling and heating loads, between the two designs for the kitchen zone. As the curtain wall allows more solar radiation to pass through the building envelope, it requires a larger peak cooling load value in comparison to the case without a curtain wall, as shown in Figure 4.23.

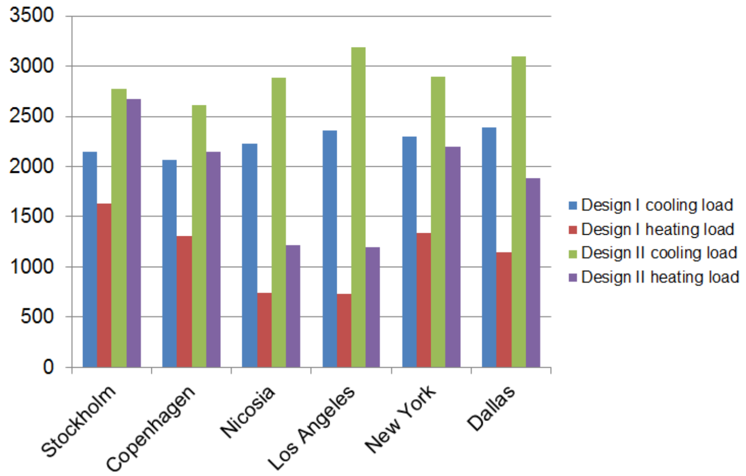


Figure 4.23. Peak cooling and heating loads for the original design (I) and the curtain wall (II).

4.11 The Early Stage Primary Energy Estimation Tool (ESPEET) (Article X)

The purpose of this study was to identify net zero energy buildings by means of a simplified calculation tool aimed at stakeholders, and decision makers.

The primary energy required for a building can efficiently be estimated using ESPEET. Based on four distinct factors (input parameters, data processing, calculation of parameters, and decision based on model findings), this tool makes use of required input parameters, as delineated in Table 4.10, in order to estimate the primary delivered energy and the renewable energy ratio, for a building. ESPEET can be used as a decision support tool at early project stages and also provides information about whether or not the building in question could be categorized as a NZEB, according to the definition. In order to quantify the capabilities of ESPEET, a study involving different countries at different geographical locations was conducted, with input parameters according to Table 4.11 for typical detached dwellings.

Parameter	**Parameter description**
A_{net}	Building area [m^2]
$E_{N,H}$	Net energy need for heating and ventilation [kWh]
$E_{N,C}$	Net energy need for cooling and ventilation [kWh]
E_A	Electricity for appliances [kWh]
E_L	Electricity for lighting [kWh]
$E_{S,T}$	Energy, solar thermal [kWh]
α_{SPF}	Ground source heat pump, seasonal performance factor
β_{SPF}	Free cooling, seasonal performance factor
γ_{SPF}	Seasonal energy performance factor (fans)
δ_{SPF}	Seasonal energy performance factor (ventilation)
χ_{SPF}	Gas boiler performance factor
$f_{Del,Exp,i}$	Primary energy factor for delivered or exported energy from energy carrier, i

Table 4.10. Example of ESPEET input parameters, where $i = 1$ (fuel) and $i = 2$ (electricity).

Country	A_{net} [m^2]	$E^*_{N,H}$ [kWh·m^{-2}]	$E^*_{N,C}$ [kWh·m^{-2}]	$E^*_{S,T}$ [kWh·m^{-2}]
Australia	206	58	13	18
Denmark	137	51	6.4	8.4
France	113	35	8.0	9.4
Ireland	88	24	5.5	4.0
Spain	97	9.8	4.2	3.6
Sweden	149	43	5.4	7.1
UK	76	24	4.2	3.9
USA	214	64	21	20

Table 4.11. Examples of ESPEET input parameters for typical detached dwellings placed in different countries. The following variables have been used: A_{net} denotes an average building area typical for the considered country, $E^*_{N,H}$ is the net energy need for heating and ventilation per square meter, $E^*_{N,C}$ represents the net energy need for cooling and ventilation per square meter, and $E^*_{S,T}$ is the solar thermal energy per square meter.

Based on the findings of this developed tool, Figure 4.24 exhibits the primary energy usage for a considered generic detached dwelling within the given countries.

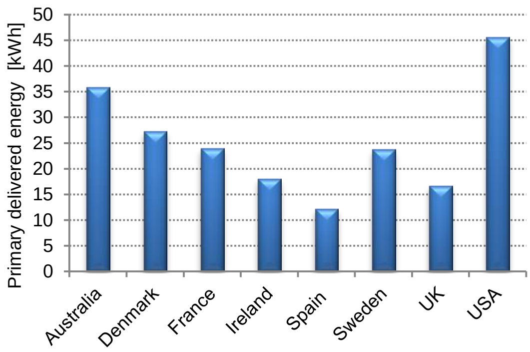


Figure 4.24. Primary energy usage for the considered detached dwellings in the given countries simulated by ESPEET.

The ESPEET model is moreover able to conduct a simplified sensitivity analysis, based on available data. One such example is demonstrated by Figure 4.25, where the influence of a larger building area on appliances, lighting, cooling, and heating is shown.

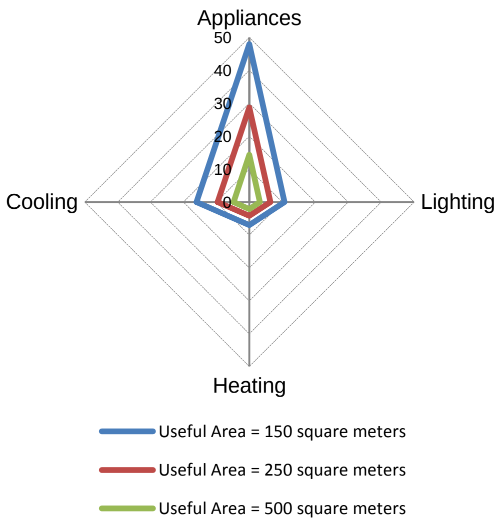


Figure 4.25. Sensitivity analysis conducted on the building area with all other input parameters remaining constant using ESPEET.

It should be noted that ESPEET is intended solely as a first approach analysis tool for estimating the required primary energy for a building for certain required input parameters and for determining whether or not the building can be categorized as a NZEB. Additionally, the tool can be utilized to provide simple analyses on both existing and new developed buildings, at an early project stage. More in-depth NZEB calculations are referred to commercial software as these will account for both the influence of climate, geographical location and other relevant factors for a more accurate analysis. Moreover, ESPEET is designated by its user-friendly interface aimed at stakeholders and in particular individuals not completely familiar with energy calculation software, as a means for decision support. Figure 4.26, depicts the Graphical User Interface (GUI) of ESPEET.

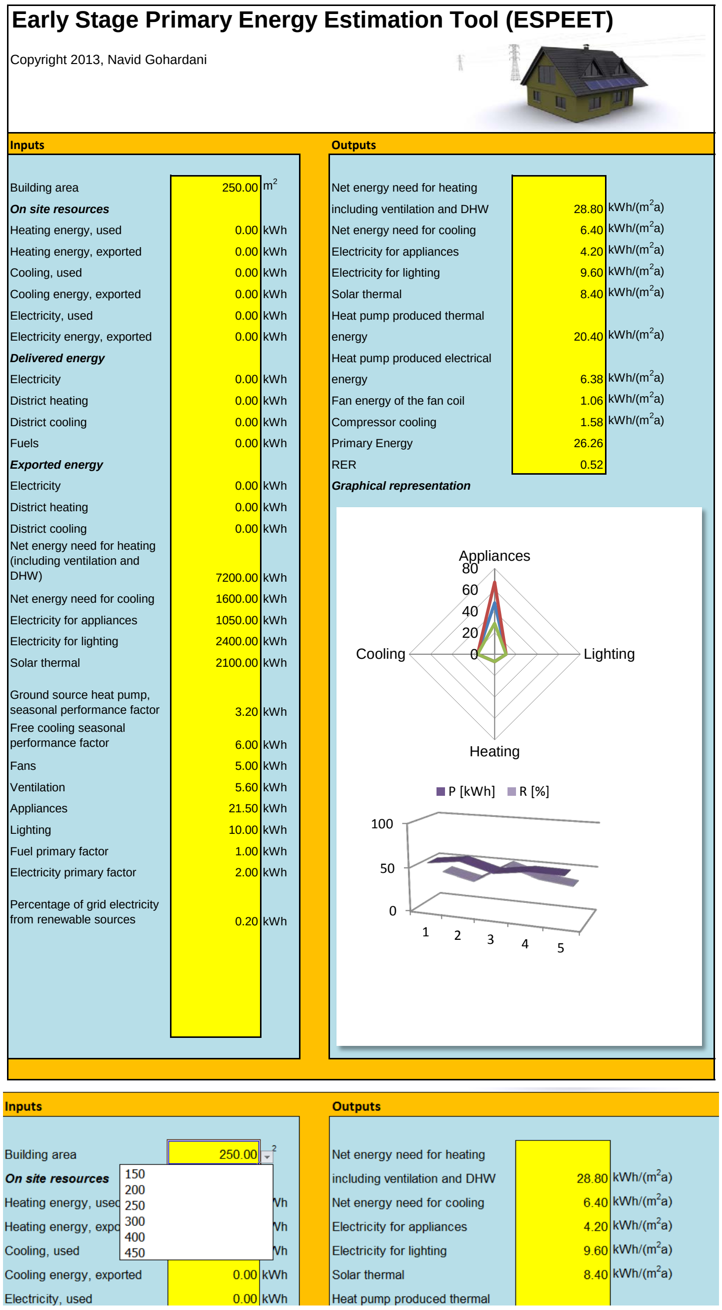


Figure 4.26. The Graphical User Interface (GUI) of ESPEET.

4.12 Key findings

The following conclusions are the key findings of the conducted study. These provide an insight into the multifaceted approach undertaken in this research.

- Given the fact that the majority of the available refurbishment systems and tools only address a limited number of refurbishment criteria, an alternative approach is needed.
- Regional disparities may carry great importance in multinational refurbishment research studies and should therefore not be neglected.
- The adopted research methodology in a multinational refurbishment study should be able to capture the major disparities between the nations with aims of a fair research comparison and assessment.
- High-efficient thermal insulation materials exhibit promising results in terms of significant energy consumption reductions in buildings.
- The operational decision support process exhibits that information about upcoming renovations is of great significance for both building owners and tenants.
- It is crucial to initiate the operational decision support process at early stages of the project, due to a mental ”open window” for energy efficiency measures. Equally, if these opportunities are not seized, such implementation will be intricate or even impossible after just a number of project meetings.
- The availability of a person with the competence and mission of serving as the Energy Engineer (EE) during the planning phase of the operational decision support process, is found to be of great importance. In particular, when decisions regarding energy saving measures in conjunction with scheduled renovations are planned.
- Economic and environmental aspects are the most significant factors for renovation measures within the built environment. Hence, generally it can be stated that issues related to these can motivate renovation.
- Within the framework of the conducted study, it is identified that durability/building physics, are the most important drivers, concerning energy refurbishment measures in Sweden, Denmark and Cyprus.
- In Sweden, Denmark and Cyprus, an identified characteristic is that energy renovations are mostly undertaken during more comprehensive refurbishments, where an upgrade of the buildings in a more general sense has become a necessity.
- It is noteworthy that energy refurbishment drivers are governed by the attitude of stakeholders and largely influenced by the national organizations in each country, in conjunction with the general view on environmental issues and energy savings.

- The largest number of studied applications with remarks from SGBC, intended for environmental certification of buildings in Sweden, were attributed to deficiencies in energy calculations.
- An improved understanding of the building renders more accurate energy calculations that conform with the building in question and could be helpful for future applicants considering environmental certification of buildings (EB/GB) in Sweden. A more detailed analysis of the EB indicators outline that encountered errors may be attributed to different types of simulation software used, varied levels of complexity, and the intricate nature of energy calculations for different building types.
- The findings of the conducted survey related to the Swedish construction industry, suggest that construction workers call for additional measures to ensure enhanced health and safety in their work environment, and that disorders/pain induced by their everyday duties result in absence from work.
- Accumulation of statistical data regarding construction workers, their working conditions, injuries or work related fatalities, provide researchers with significant information to ensure better health and safety environments and can alleviate these challenges by employment of efficient methods, such as the Construction Sector Chain Disaster Theory (CSCDT).
- The replacement of an existing electric coil heating system with a hydronic ground source heat pump (GSHP) system for a studied church building, results in $\sim 66\%$ reduction in energy demand for heating.
- When comparing energy consumption before and after renovation of a building, the energy signature method is a suitable option when the right kind of data is available, in terms of the hourly outdoor temperature and hourly energy consumption.
- Improved knowledge of economic performance and technical results of renovations can contribute to a snowball effect, with more property owners recognizing the value of energy aspects and thus provide an increased level of energy savings.

4.13 Hypothesis Review

Based on the findings of this study, it can be established that the importance of energy efficiency measures is highly dependent on an appropriate timing of their implementation. Preferably such implementation should be actualized at an early project stage in conjunction with other major refurbishment efforts. A motivating factor for this timing is based on avoidance of conceptual alterations during the preplanning phase and additional costs thereof. The results of this study also shed light onto the ambiguous nature of the term sustainability and has endeavored to explain the terminology that is commonly utilized within the built environment. Based on the fact that the operational decision support process (Article II) has been used by different stakeholders, it can be deduced that the findings of this study have been able to promote sustainable renovation. The attitudes of stakeholders/building owners have additionally been investigated in Article III. The "sound economy" aspect of the ACES project is partially investigated through Article VI and the importance of continuing education related to sustainability aspects such as building-related energy calculations, identified in Article IV.

The nature of the ACES project, presented herein had a number of benefits and also presented some challenges. In large, it can be stated that the benefits greatly outweighed the disadvantages, exemplified by specific research partners taking on tasks which would fall in their areas of expertise. In addition, a multifaceted approach with different cultural views and national differences provided a well-rounded insight and contributions towards the hypothesis of the project. Equally, these national differences presented dissimilar cultural views and some challenges in obtaining similar types of responses. Nonetheless, the differences in geographical locations have in this study served as beneficial factors and for instance been utilized in a triangulated approach for retrieving data as shown in Article III.

Chapter 5

Discussion

The research presented in this thesis has provided an overview of the aspects of sustainability within the realm of the built environment. Conclusively, to the research endeavors presented herein, the original research questions are revisited and addressed in further detail. The word sustainability has at least three definitions in the general sense, as follows:

- "*of or relating to a lifestyle involving the use of sustainable methods*" (Merriam-Webster's Dictionary)
- "*of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged*" (Merriam-Webster's Dictionary)
- "*Environmental Science. the quality of not being harmful to the environment or depleting natural resources, and thereby supporting long-term ecological balance*" (Dictionary.com)
- "*able to be maintained at a certain rate or level*" (Oxford Dictionary, 2013)

Within this research work, the definition of sustainability refers to a building in early project stages that is refurbished or designed based on a framework inclusive of workers' health, energy, economic and technical aspects. While most conducted studies consider sustainability from a single perspective where one of the aforementioned factors has been optimized, this study has been carried out with a collective mindset on the mentioned factors. The focus has hence been placed on providing an overall viewpoint of the topic of sustainability confined to early project stages within the built environment where all the aforementioned factors are significant for stakeholders and building owners. The objective of this study has partially been to raise awareness and promote sustainable building measures through a multifaceted viewpoint.

- **Q1**: What approaches are taken towards sustainability in early project stages related to the built environment and why are these of importance?

In addition to the aforementioned framework elements, this study has examined the topic of sustainability from an economic, energy-efficiency and building envelope perspective. In effect, from the economic perspective the usefulness of high-efficient insulation materials, actualized by a simulation approach of VIP usage, has been examined. It is demonstrated that an investment in VIPs used in building retrofits waives the deposited amount after a distinct time period, depending on the cost of each panel and current interest rates. In addition, the implementation of an operational decision support process has been realized in early project stages. This methodology is important due to the potential influence it has on decisions regarding energy efficiency in conjunction with planned renovation projects in buildings. Other approaches taken towards sustainability in this study have been realized by assessment of applications submitted to SGBC for environmental certification of buildings. Results from this study have identified indicators which received most remarks by SGBC, during the review process. This identification allows for a more efficient means to address these shortcomings.

- **Q2**: Can building owners/stakeholders utilize the findings of this study in order to make sustainable decisions concerning renovation in early project stages based on energy efficiency and a healthy indoor climate?

This study has provided a framework that can be used by both building owners and stakeholders in order to account for decision making with emphasis on sustainability. In particular, the early stages of a renovation project have been highlighted as a crucial phase as demonstrated by the operational decision support process. According to Article II, the key points that lead to decisions based on current best knowledge consist of information from electronic media and consultancy as well as long-term proposals and investment costs in addition to other factors, and form a baseline of awareness, which is essential in this matter. The findings of this study have further been placed in a larger context in comparison to other countries such as Denmark and Cyprus based on conducted case studies, where the drivers for energy renovations in Sweden were also identified. It is recognized that the drivers vary for dissimilar types of buildings in different countries. It is also established that durability and building physics are considered to be the most important factors for sustainable renovation. Other factors of importance are the economic drivers, followed by the environmental drivers, comfort issues and other relevant topics. It is a characteristic in Sweden, Denmark and Cyprus that energy renovation measures are mostly undertaken at more extensive refurbishments, where upgrading the building in a more general sense has become necessary. Pure energy renovations mostly concern limited measures with limited payback time. It is noteworthy that the considered parameters are largely influenced by the national organizations, the attitudes and the general views of the stakeholders within each country.

- **Q3**: Do the findings of this research have applications within the realm of real-life situations, such as those concerning energy calculations for sustainable buildings?

The findings of this study have highlighted the importance of energy calculations through a case study of a church building. The energy performance of the building subsequent to an exchange of an existing electric coil heating system to a hydronic ground source heat pump system, was assessed and discussed. Furthermore, the energy demand and the energy signature of the church building were analyzed and presented prior to and after installation of the ground source heat pump system. The data for energy consumption in this study was retrieved from the available electricity bills of the building. The data consisted of readings per hourly basis, for the consumption of the entire building. The employed method for weather normalization of energy consumption for the building was realized by an energy signature modeling, as it was considered to provide an adequate representation of the available data for the hourly outdoor temperature and energy consumption. The replacement of the original heating system with a ground source heat pump system for the church building resulted in a reduced energy consumption of approximately 66%. Additionally, an insight was provided to the process of choosing a suitable GSHP system provider/installer based on the provided quotations within the conducted case study.

- **Q4**: Which parameters constitute common inaccuracies in applications for environmental certification of buildings in Sweden?

According to Article IV, a comparison made between applications for EB and GB, designates the different nature of these programs in Sweden. The main difference between the two types of applications was that for GB applications, the analysis was based on energy measures that contributed to their approval. For EB applications however, indicators that contributed to revisions had been considered. Particularly, the indicators for EB with the most received remarks from SGBC were identified as the *solar heat factor*, followed by the *solar heat charge factor*, *share of energy sources*, *noise evaluation or sound classification*, and *window area* or *daylight factor*. For both programs however, the usage of similar simulation software was identified. Equally, a large portion of the applications had not specified a distinct simulation tool used for the performed energy analysis. Within the context of this research, the potential differences in employed simulation software in conjunction with the fact that different consultants perform the analysis for various types of buildings, may lead to calculation errors. Therefore, one step towards mitigation of this identified complexity might be to explicitly identify the employed simulation software for all filed applications and to propose continuing education for the consultants performing energy calculations.

- **Q5**: Is it possible to motivate building owners to renovate a building for improved performance concerning energy efficiency and indoor comfort?

Yes, indeed. One such scenario may unfold in conjunction with major planned renovations in residential buildings. Since a planned renovation is already expected, decision making in early stages of the building project, adds the advantage of changing the attitude of stakeholders towards future renovation measures, resulting in an overall increased sustainability in the building operation. An example of such methodology is shown herein as the operational decision support process (Article II). Additionally, in Article III, the most important drivers for energy savings in Sweden are identified as maintenance, cost, indoor climate, and energy savings. Hence, based on the conducted studies it is possible to motivate building owners to renovate buildings with emphasis placed on indoor comfort and energy efficiency.

- **Q6**: What is the attitude of construction workers within the built environment in Sweden, concerning current health and safety related measures at their workplaces?

Inspired by the safety measures of the Swedish Work Environment Authority, a survey was designed and conducted with aims to identify a number of safety hazards that potentially endanger the health and safety of Swedish construction workers. Following this identification process, certain elements of the Construction Sector Chain Disaster Theory (CSCDT) were highlighted as a proposed approach to minimizing injuries, health issues and fatalities among the Swedish construction workers. The findings of this survey suggested that despite current laws, regulations or additional factors that seek to ensure a safe and healthy environment for construction workers, the Swedish construction work force still experiences challenges. Findings from this survey indicate that construction workers call for additional measures to ensure health and safety in their work environment and that disorders and pain induced by their work duties result in absence from work. The CSCDT is suggested as an efficient method to prevent injuries or even death within the construction sector. Health and safety aspects related to construction workers are the primary concern of the construction industry which is designated as one of the most dangerous environments of the Swedish labor market. The findings of Article V, can thus be used as a contribution to sustainable development. By bridging the gap between the construction industry and current/future sustainable buildings through an in-depth understanding of workers' health issues, a safer working environment ensures that sustainability can also be achieved for the construction industry, leading to positive societal impacts.

In Appendix B, an overview of the practical applications of this research work is presented. In particular, attention has been devoted to service life of buildings, design of adequate indoor air quality, solutions to a healthier indoor climate, the building envelope, photovoltaic systems, energy demand for heating and cooling, and promotion of net zero energy buildings. In addition, a review of existing tools for building retrofits has been carried out in Article I, and new approaches for decision making at early project stages concerning sustainable building measures, in Article II. Articles III−X, moreover provide a multifaceted overview of the developed approaches towards sustainability.

The following indicators have been considered fully/partially in this study and presented pursuant to their core and subcategories, respectively:

- Technical: Heating, cooling, electric heating
- Environmental: Primary energy
- Economic: Payback time
- Process: Monitoring
- Social: Thermal comfort
- Safety and accessibility: Number of accidents/deaths
- Comfort: Visual simulation
- Cultural values: Cultural heritage

The hypothesis of the ACES project is based on the idea that there are rational reasons depending on ”sound economy” for carrying out renovation that will make a building operate in a sustainable manner. The renovation work will hence be a value-driven process, which contributes to sustainable development. This conclusion is valid, at least with regards to the following findings of the study:

- The facility owners have a willingness to certify their buildings according to EB and GB.
- The notation that when the correct information is offered to the TOC board, energy renovation measures will be included in the planned major technical renovation.
- In the three countries involved in the ACES project, it was possible to obtain an understanding from the stakeholders, related to the environmental profile to be prioritized during renovation measures.

Chapter 6

Conclusions and Recommendations

6.1 Conclusions

Knowledge about how sustainable buildings function raises awareness about sustainability and ensures a more efficient building operation. An overall sustainable building design approach should not only include to enhance understanding about sustainability in general and to educate the involved project team/client about sustainable design, but also to inform the occupants about how sustainable buildings operate. Sustainable buildings should also be monitored and their design strategy/building performance assessed. This in turn can facilitate promotion of sustainable design by improving general knowledge and understanding of how such buildings operate while avoiding the repetition of unsuccessful design strategies.

The future for sustainable building is not exclusive to a particular project or building type. There are however some areas with higher expected growth. In just a few years, the green/sustainable society has driven a shift in the manner of interaction between people and their buildings. Buildings today are expected to have the potential to improve the health and well-being of the people who use them as their home or workplace. Today, buildings need to be able to contribute to a better environment by operating in a sustainable manner with low operating costs.

The author's reflections concerning the challenges ahead for implementation of sustainable building measures can be linked to the often occurring problem associated with the presence of the many actors involved in the value chain of buildings. These actors may consist of legislative politicians, regional decision makers, building owners, contractors, and building occupants, to name a few.

Unless no alternative paths are presented for adapted incentives, it may not be uncommon with a scenario where one actor has to make an investment while another benefits from it. Thus, this can lead to cases where actors are deterred from investments due to lack of gained benefits.

The conducted research study has established that there is sufficient knowledge related to technological, economic and environmental aspects for actualizing sustainable building measures, where some existing barriers can result in inefficient processes. Moreover, no conflict of interest should exist between the mission of profitmaking among businesses and investments in sustainable building measures, as the investments will most likely be worthwhile once the building is in its operating state.

Sustainable building refurbishment is motivated by legislation and market. The recent shift of focus on energy and its impact have been incorporated on these drivers. In addition, the success of refurbishment is highly dependent on development of the most feasible strategy to serve the clients' objectives with their building and the deployment of these. There are a number of challenges associated with upgrading and refurbishment of the existing building stock, as outlined below (Shah, 2012):

- The structure of the building and its services need upgrading while conforming to new standards/legislation
- Becoming susceptible to potential effects of climate change while imposing minimal environmental impact
- Conserving cultural heritage buildings
- Providing more safe and secure internal environments
- Producing spaces that are adaptable for change of use
- Demonstrating best value through procurement and partnering
- Contributing to regenerating local communities

The benefits of sustainable refurbishment can contribute to preservation of the existing built environment and its protection for future generations. In addition, application of the concept sustainable building contributes to reduced environmental footprint and better adaptation to climate change, for instance by limiting the solar gain in summer and improved water efficiency contributing to lower operating costs (Shah, 2012). Moreover, sustainable buildings will be a mark of quality when accredited independently designating a healthy living environment. For building owners, the decision of refurbishment versus redevelopment is dependent on the commercially available options in conjunction with maximizing the building's economic performance for the building occupant as well as the owner. The refurbishment measure has to produce a working environment which makes a positive contribution to the performance of the occupants, while providing an adequate level of return to the investor, resulting in an economically sustainable option.

Some of the important aspects that often are considered as barriers to sustainable refurbishment comprise of financial considerations, disconnection between costs and benefits, lack of knowledge and of experienced workforce. These factors entail that, traditionally building owners often focus on initial capital costs, instead of considering the benefits of medium and longterm effects. Such short time investment aspects do not determine the overall rate of return. The lack of practical understanding about energy efficiency and sustainable buildings among building owners, is also a contributing barrier to sustainable building, which is inclusive of over estimation of the first cost premium. Conclusively, many small opportunities for sustainable improvements are often overlooked by building owners.

6.2 Recommendations and Future Work

As a result of the developed strategy in this research, additional funding has been sought for further development and implementation of the operational decision support process. The plan is to exercise this process among other building developers in Sweden, in accordance with their respective objectives for refurbishment.

The aspects of this study which have been explored by way of simulations, are recommended to be empirically verified and investigated in future research work. Additionally, the high-efficient thermal insulation materials should be used as a part of the energy retrofit measures of existing buildings, in order to assess their actual performance by empirical means. In-situ measurements in the actual building envelope, prior and post to modifications, would be beneficial, as a proof-of-concept of this specific assessment method.

The developed tool ESPEET should be verified by stakeholders in early project stages and its impact for decision making fully quantified, as such tools are in demand within the built environment.

Based on the findings related to the studied applications sent to SGBC for environmental certification of buildings, an effort for continuing education of consultants performing energy calculations would be beneficial.

A post occupancy evaluation of a building where sustainable building measures have been conducted would be useful, in order to identify the building performance according to the views of the occupants. Further, the occupants need to be informed and educated about the operation of sustainable buildings as a lack of such information will most probably lead to a poorer performance.

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Appendix A

List of Appended Articles

The following articles included in this thesis, have been communicated by the author:

A.1 International Peer-Reviewed Journal Publications

1. Navid Gohardani, Folke Björk. ”Sustainable refurbishment in building technology”, Smart and Sustainable Built Environment, Volume 1, Issue 3, pp. 241−252, Emerald, 2012.
2. Navid Gohardani, Tord Af Klintberg, Folke Björk. ”Turning Building Renovation Measures Into Energy Saving Opportunities”, Structural Survey. (Submitted for publication)
3. Navid Gohardani, Folke Björk, Per Anker Jensen, Esmir Maslesa, Stratis Kanarachos, and Paris A. Fokaides. ”Stakeholders and the Decision Making Process Concerning Sustainable Renovation and Refurbishment in Sweden, Denmark and Cyprus”, Architecture & Environment. Volume 1, Issue 2, pp. 21−28, Sciknow Publications, 2013.
4. Navid Gohardani, Ivo Martinac, Folke Björk. ”Common inaccuracies in environmental certification applications in Sweden”, Smart and Sustainable Built Environment. (Submitted for publication)
5. Amir S. Gohardani, Navid Gohardani, Folke Björk. ”One Facet of the Swedish Construction Industry and Applications of the Construction Sector Chain Disaster Theory”, Management & Marketing Journal. (Submitted for publication)
6. Navid Gohardani, Folke Björk. ”Improvement of the energy performance of a church building by the exchange of an electric coil heating system to a hydronic ground source heat pump system”, Energy and Buildings. (Submitted for publication)

A.2 International Peer-Reviewed Conference Publications

1. Navid Gohardani, Kjartan Gudmundsson. "Sustainable building renovation and refurbishment with applications of Vacuum Insulation Panels", SB11 World Sustainable Building Conference, Proceedings Vol. 2, Helsinki, Finland, 18 – 21 October, 2011.
2. Navid Gohardani, Folke Björk. "Economic and environmental benefits related to a sustainable building refurbishment", Proceedings of the 1st International Conference on Building Sustainability Assessment, Porto, Portugal, May 23 – 25, 2012.
3. Navid Gohardani, Folke Björk. "A Simulation Approach Towards A Sustainable Building Design Based on Energy Analysis", Proceedings of the 2012 International Conference on Sustainable Design, Engineering, and Construction, Fort Worth, Texas, U.S.A., November 7-9, 2012.
4. Navid Gohardani, Folke Björk. "A Simplified Approach Towards Net Zero Energy Buildings: The Early Stage Primary Energy Estimation Tool", BESS-SB13 CALIFORNIA: Advancing Towards Net Zero. Pomona, California, U.S.A., 24-25 June 2013.

Additionally, the following international journal articles, conference articles, internal, and national reports have been communicated by the author:

A.3 International Journal Publications

1. Navid Gohardani. "Architecture and Design Research: Reflections in relation to the design process", International Journal of Architectural Research, Vol. 5 - Issue 3, November 2011.
2. Navid Gohardani. "Architecture in Effect: A Glance at Critical Historiography", International Journal of Architectural Research, 2014. (Submitted for publication)

A.4 International Peer-Reviewed Conference Publications As Co-Author

1. Per Anker Jensen, Esmir Maslesa, Navid Gohardani, Folke Björk, Stratis Kanarachos, Paris A. Fokaides. "Sustainability evaluation of retrofitting and renovation of buildings in early stages", 7th Nordic Conference on Construction Economics and Organisation 2013. Trondheim, Norway, 12 – 14 June 2013.
2. Paris A. Fokaides, Andreas Kanarachos, Georgette Kanarachos, Stratis Kanarachos, Folke Björk, Navid Gohardani, Per Anker Jensen, Esmir Maslesa. "Promotion of sustainable renovation in Europe", 3rd International Exergy, Life Cycle Assessment, and Sustainability Workshop & Symposium (ELCAS3), Nisyros, Greece, 07 – 09 July 2013.

A.5 Internal Reports

1. Navid Gohardani. "Façade Renovation Systems for Energy Efficient Buildings", KTH Royal Institute of Technology, Department of Civil and Architectural Engineering, August 2011.
2. Navid Gohardani. "High-Efficient Insulation Materials in Building Applications", KTH Royal Institute of Technology, Department of Civil and Architectural Engineering, January 2012.

A.6 National Reports

1. Navid Gohardani. ”Vacuum Insulation Panels - Applications on Residential Buildings within the Swedish Million Homes Program”, Bygg & Teknik, May 2012.
2. Navid Gohardani. ”Concepts to Motivate Sustainable Refurbishment in Early Stages”, Bygg & Teknik, August 2013.

A.7 Seminars and Workshops

1. Navid Gohardani, Folke Björk. ”Introduction to ACES and Visions for Building Renovation”, DTU Technical University of Denmark, Centre for Facilities Management, March 2012.
2. Navid Gohardani. ”Retrofitting the Million Homes Program”, 2^{nd} Seminar on Robust and Durable Vacuum Insulation Technology for Buildings, KTH Royal Institute of Technology, Department of Civil and Architectural Engineering, April 2012.
3. Navid Gohardani, Folke Björk. ”ACES and Visions for Building Renovation”, DTU Technical University of Denmark, Centre for Facilities Management, April 2013.

Appendix B

Information Base for Practical Research Applications

The following section outlines some practical applications of the research findings, which can be utilized by stakeholders and decision makers when considering new-built and/or renovation measures within the built environment. This section intends to familiarize stakeholders/decision makers with some important functions as means for decision support, in early project stages. Hence, the featured list of research applications in this section is not exhaustive but solely indicative as a road map towards sustainable decision making related to building measures.

Service Life of Buildings

The service life of a building refers to the duration of the period in which the building will last. This term is based upon the available data regarding the service life of the components within the building. The service life is therefore a process in which an estimation of future events is established and predicted. This implies that complete accuracy in this regard cannot be expected. A building is influenced by many factors during its operation. Examples of such influences are the usage of energy and water, which over time will lead to impacts on its structural parts during the building operation. Nonetheless, the majority of the impacts are evident during the extraction, manufacturing and installation of the building, e.g. the initial stage of the building's life and at the end of its useful life, or during the disposal stage.

Therefore, it is evident that the environmental impact of building materials is reduced during the initial period in the service life of buildings. Hence, the longer these components last, the smaller impact is expected upon their disposal. Thus, the intended life of the building is important in this context, where different approaches have to be undertaken depending on its life expectancy. For instance, major changes to an existing commercial building or even its complete replacement are likely within a 20−year time frame (Yang et al., 2008). For such buildings, the materials should optimally have been designed and chosen based on their characteristics of recycling, reuse and removal. For buildings intended to last for centuries and withstand the challenges of time, it is important that finishing materials have been integrated into the structure of the building.

As discussed in the preceding paragraph, finite service lives are expected for building materials and components, due to chemical, mechanical and physical alterations, inhibiting their performance. Some important terms to be included in this context are durability, service life and performance over time. While the first of these is not easily measured and solely provides the likelihood of duration, the latter and third terms are easily quantified.

In light of this discussion it can be stated that degradation is an important parameter that needs to be considered in this context. There are numerous factors that can lead up to degradation in buildings, which are influenced by the geographical location of the building and the materials used. Hence, knowledge about these factors is essential in the development of test methods that are needed to predict the service life of the components involved. Figure B.1, shows a number of degradation agents related to building performance and Figure B.2, factors affecting service life and components.

Nature	Origin External to the building Atmosphere	Ground	Internal to the building Occupancy	Design consequences
1. Mechanical agents				
1.1 Gravitation	Snow loads, rainwater loads	Ground pressure, water pressure	Live loads	Dead loads
1.2 Forces and imposed or restrained deformations	Ice formation pressure, thermal and moisture expansion	Subsidence, slip	handling forces, indentation	Shrinkage, creep, forces and imposed deformations
1.3 Kinetic energy	Wind, hail, external impacts	—	Internal impacts, wear	Water hammer
1.4 Vibrations and noises	Wind, thunder, airplanes, explosions, traffic and machinery noises	Earthquakes, traffic and machinery vibrations	Noise and vibration from music, dancers, domestic appliances	Services noises and vibrations
2. Electromagnetic agents				
2.1 Radiation	Solar radiation, radioactive radiation	—	Lamps, radioactive radiation	Radiating surface
2.2 Electricity	Lighting	Stray currents	—	Static electricity,electrical supply
2.3 Magnetism	—	—	Magnetic fields	Magnetic fields
3. Thermal agents	Heat, frost, thermal shock	Ground heat, frost	User emitted heat, cigarette	Heating, fire
4. Chemical agents				
4.1 Water and solvents	Air humidity, condensation, precipitation	Surface water, ground water	Water sprays, condensation, detergents, alcohol	Water supply, water waste, seepage
4.2 Oxidizing agents	Oxygen, ozone, oxides of nitrogen	—	Disinfectant, hydrogen peroxide	Positive electrochemical potentials
4.3 Reducing agents	—	Sulphides	Agents of combustion, ammonia	Agents of combustion, negative electrochemical potentials
4.4 Acids	Carbonic acid, bird droppings, sulphuric acid	Carbonic acid, humic acids	Vinegar, citric acid, carbonic acid	Sulphuric acid, carbonic acid
4.5 Bases	—	Lime	Sodium hydroxide, potassium hydroxide, ammonium hydroxide	Sodium hydroxide, cement
4.6 Salts	Salty fog	Nitrates, phosphates, chlorides, sulphates	Sodium chloride	Calcium chloride, sulphates, plaster
4.7 Chemically neutral	Dust, soot	Limestone, silica	Fat, oil, ink, dust	Fat, oil, dust, soot
5. Biological agents				
5.1 Vegetable and microbial	Bacteria, seeds	Bacteria, moulds, fungi, roots	Bacteria, house plants	—
5.2 Animal	Insects, birds	Rodents, worms	Domestic animals	—

Figure B.1. Degradation agents related to building performance. Adapted from (Masters and Brandt, 1987).

A significant analysis often utilized in buildings is the Whole Life Cost analysis (WLC) (Caplehorn, 2012), which allows for full determination of the costs involved pertaining to design, operation, maintenance (facility management during the entire service life of the building, inclusive of its disposal cost). This method provides a comparison basis between different building designs for a given time period. Each distinct WLC alternative can be calculated by usage of Equation (B.1), as follows (El-Haram et al., 2002):

$$\text{WLC} = Cc + \Big(\sum_{i=1}^{n}\Big(\sum_{j=1}^{m} Oc_j\Big)\Big) = \sum_{i=1}^{n}\Big(\Big(\sum_{j=1}^{m} Mc_j\Big) + \sum_{i=1}^{k} Rc_i\Big) \pm Dc \qquad \text{(B.1)}$$

In Equation (B.1), Cc, represents the capital cost (design/build cost), Oc, the operating cost, Mc, the maintenance cost (reactive and preventive), Rc, the replacement cost (operating, maintenance and replacement cost, collectively known as the facility management cost), Dc, the disposal cost, n the number of years (expected life of project), m the number of cost elements, and k the number of replacements or refurbishments.

1. Weather factors	Radiation
	Solar
	Nuclear
	Thermal
	Temperature
	Elevated
	Depressed
	Cycles
	Water
	Solid (such as snow, ice)
	Liquid (such as rain, condensation, standing water)
	Vapor (such as high relative humidity)
	Normal air constituents
	Oxygen and ozone
	Carbon dioxide
	Air contaminants
	Gases (such as oxides of nitrogen and sulphur)
	Mists (such as aerosols, salt, acids and alkalies dissolved in water)
	Particulates (such as sand, dust, dirt)
	Freeze-thaw
	Wind
2. Biological factors	Microorganisms
	Fungi
	Bacteria
3. Stress factors	Stress, sustained
	Stress, periodic
	Stress, random
	Physical action of water, as rain, hail, sleet and snow
	Physical action of wind
	Combination of physical action of water and wind
	Movement due to other factors, such as settlement or vehicles
4. Incompatibility factors	Chemical
	Physical
5. Use factors	Design of system
	Installation and maintenance procedures
	Normal wear and tear
	Abuse by the user

Figure B.2. Factors affecting the service life and components. Adapted from (Masters and Brandt, 1987).

For procurement of new technologies and in the context of this thesis, it is often advantageous to be able to provide a quotation based on a product's Life Cycle Costing (LCC). This term essentially describes the total cost of a piece of equipment throughout its lifetime including the operation and maintenance costs (Jernkontoret, 2013). Equations (B.2) – (B.6), can be used for calculation of the total LCC, $(LCC)_{\text{Total}}$, for three different investments concerning replacement of windows, during a refurbishment project (Belok, 2012). As an exemplary case, LCC can be used in order to compare the costs for competing systems or equipment during their entire life. This method is hence appropriate for pre-investment decision support. The total life cycle cost of the window replacements can be determined by using:

$$(LLC)_{\text{Total}} = C_{\text{Investment}} + C_{\text{Maintenance}} + C_{\text{Energy}} + C_{\text{Residual}} \tag{B.2}$$

Equation (B.2), consists of the following parameters

$$C_{\text{Investment}} = \tilde{c}_{\text{investment}} \cdot A_{\text{window}} \tag{B.3}$$

$$C_{\text{Maintenance}} = C_{\text{Investment}} \cdot A_{\text{Maintenance}} \cdot \frac{1-(1+\tilde{i})^{-\tilde{n}}}{\tilde{i}} \tag{B.4}$$

$$C_{\text{Energy}} = \widetilde{U} \cdot \widetilde{A} \cdot \widetilde{D}_d \cdot \left(\frac{14}{100}\right) \cdot \tilde{e}_{\text{energy}} \cdot \frac{1 - \left(\frac{1+\tilde{q}}{1+\tilde{i}}\right)^{\tilde{n}}}{\frac{1+\tilde{i}}{1+\tilde{q}} - 1} \tag{B.5}$$

$$C_{\text{Residual}} = C_{\text{Investment}} \cdot \tilde{c}_{\text{investment}} \cdot (1+\tilde{i})^{-\tilde{n}} \tag{B.6}$$

As an exemplary case, the total life cycle cost, $(LCC)_{\text{Total}}$ can be calculated for three different window alternatives with the following input data.

Input parameters

Calculation period, $\tilde{n}$	12 years
Real annual energy cost increase, $\tilde{q}$	6 %
Daily energy cost, $\tilde{e}_{\text{energy}}$	0.6 SEK/kWh
Real calculation interest, $\tilde{i}$	4 %
Size of the window, $\widetilde{A}$	1.51 m^2
Number of degree days, $\widetilde{D}_d$	4149 (Stockholm)

Glass parameters

	Window 1	Window 2	Window 3
$g-$value (solar transmittance)	0.5	0.6	0.7
$U-$value [W $\cdot m^{-2} \cdot K^{-1}$]	1.5	1.4	1.3

Capital costs

	Window 1	Window 2	Window 3
Initial cost of the investment, $\tilde{c}_{\text{investment}}$ [SEK $\cdot$ m^{-2}]	1200	1400	1600
Rest value, $\tilde{c}_{\text{residue}}$ [%]	0	0	0

Misc. costs

	Window 1	Window 2	Window 3
Maintenance cost per year [%]	3	4	3

Results

	Window 1	Window 2	Window 3
$C_{\text{Maintenance}}$ [SEK]	456	709	608
C_{Energy} [SEK]	839	783	727
$(LCC)_{\text{Total}}$ [SEK]	**3107**	**3606**	**3751**

Design of adequate indoor quality

In order to establish an improved indoor quality design, usually at least four different principles have to be considered. These consist of control of source, ventilation and occupant activity, as well as maintenance of the building. The sources that potentially can contribute to air contamination and discomfort in a building are for instance construction materials, equipment, building contents, human activity, noise, light, HVAC systems, and furnishings. In order to carry out the source control, initially the materials that produce emissions should be identified. Other steps that can be taken in order to improve source control can consist of establishing an improved indoor air quality for building owners and occupants.

Besides the source control, the ventilation control plays a vital role on the influence of indoor air quality. The factors that affect the ventilation control are air intake/air exhaust location, air filtration, fibrous insulation, temperature, humidity, exhaust and control systems. Some of the challenges with maintaining a good indoor air quality originate from the airtightness of buildings with thick building envelopes and the possible insufficient ventilation of some sustainable buildings, where building occupants spend most of their time. Since poor air quality inside a building is not easily detected, often times the affected occupants are unaware of this. Steps towards more sustainable buildings should therefore account for a proper ventilation and air filtration which alleviate the exposure to potential hazardous materials (Matela, 2006; Yu et al., 2009; Kubba, 2012).

Biological contaminants emerge when the moisture level in a building cannot be controlled. Adhesives, paints, solvents, regular building materials, and household products are examples of chemical hazards in buildings. In addition to these, radon which is a common gas in nature, is the cause of lung cancer among many individuals. The awareness about airtight buildings originated in Europe where the airtight concept contributed to replacement of natural products with synthetic materials. Many building occupants around the world are currently in contact with numerous hazardous materials, but very little is known about some of these and their prospective health implications. Particularly for children, buildings are considered to be the originators of many health problems since young people spend a great deal of time in homes/schools.

In the United States, approximately 15% of the population exhibit a tendency to allergies which originate from their own homes (Johnston and Gibson, 2008). Biological contaminants or bio-aerosols, either originate from the interior of the building or from its exterior. These contaminants all consist of small living organisms that are suspended in air. Fungi, pet dander, mold, dust mites, pollen, and bacteria are examples of such contaminants.

Common reactions caused by bio-aerosols are rashes, asthma, coughing, and headaches. The most common biological contaminant encountered in residential buildings is mold (Crook and Burton, 2010), as its spores can be found almost everywhere. In order to initiate the growth process however, a high moisture content is needed without the possibility for the moisture to dry out. This entails that the growth of mold usually occurs in wet areas, inside wall cavities, and in rare occasions, in leaks in plumbing inside walls. A contributor to these leaks can be cavities that are not sealed. Formed mold colonies can either be entirely harmless, deadly or in certain instances beneficial. Their implications may range from allergy-like symptoms to asthma, which can be classified as a long-term disability. Children in particular, are usually more prone to become affected by mold.

Solutions To A Healthier Indoor Climate

In light of potential threats to the indoor air quality, a number of steps can be considered for its improvement. This can be achieved by taking the following steps into account (Johnston and Gibson, 2008):

- Control of moisture content
- Isolation of the garage from the building (where applicable)
- Mitigation of radon levels
- Utilization of safe building materials
- Air filtration

The first step towards a healthier indoor air climate is to control the moisture content inside the building. This in return will prevent mold growth and contribute to a healthier indoor environment. Secondly, isolation of the garage from the main residential building, contributes to isolation from unhealthy solvents, adhesives and fuels. Studies conducted in the nineties in Denver, Colorado, U.S.A., indicated that car exhaust from attached garages were the most common toxins in the indoor air. Hence, in order to avoid possible contamination of the indoor air from the garage, the wall between these two spaces has to be airtight. However, if the garage is well ventilated by for instance use of a fan, the exhaust gases escape and are removed from the building.

Radon, a radioactive gas, is an unhealthy element, which often gains access to a building by percolation through soil and rock. Approximately 630,000 dwellings in Sweden have high values of radon and are in need of radon mitigation (Boverket, 2010). Dwellings built between the years 1929 and 1975 often featured radioactive concrete (blue concrete), as this was a common building material at that time period. Following the use of this material, radon could be emitted into the indoor air. Sweden, in comparison with other European countries, has a high average radon concentration in the existing buildings stock (Boverket, 2010). All heated buildings are to a certain extent at risk to exposure by soil radon. Pressure suppression within the building, can cause radon to enter through leaks in the ground. Radon entering the building from the soil, can be removed by preventing it from entering the dwelling by (Boverket, 2000):

- Sealing the leaks that let in radon soil air
- Installation of a radon extractor
- Installation of a radon well
- Installation of a device employing the air cushion method

In addition, radon can be diluted by:

- Installation of a mechanical supply and exhaust ventilation system
- Increase of ventilation by installing several outdoor air intakes/ducts
- Providing air gaps along the floor

The implications of radon exposure may cause serious illnesses such as lung cancer. One mitigation system aimed for radon removal consists of a PVC pipe which is perforated and placed under the concrete slab in the basement. By connecting this pipe to another running up and out of the house, the gas can be exhausted by utilizing of a fan.

The potential problems associated with indoor air quality are difficult to recognize and detect, due to their non visible feature. It should be emphasized that the ventilation of new buildings essentially determines the level of comfort and exposure to toxins and the healthiness of the indoor air quality. In addition, sustainable buildings often encapsulate a more airtight feature, which in some cases could lead to a poorer indoor air quality, due to the lack of natural ventilation. An overview of the most common indoor air contaminants is provided in Table B.1.

Volatile organic compounds	Formaldehyde Paints and resins Solvents Printed materials Printer and photocopier emissions
Dust/fibers	Asbestos Man-made mineral fibers (fiberglass) Dirt, construction, and paper dust
Bioaerosols	Bacteria Fungi Molds Dust mites Viruses Animal danders and excreta Pollen
Entrapped outdoor sources	Bacteria Vehicle exhaust Industrial exhaust
Physical factors	Temperature Humidity Noise Lighting
Contaminants generated by human activity	Carbon dioxide Perfume
Other	Fuel combustion products Radon Tobacco smoke Cleaning agents Pesticides Some building materials

Table B.1. An overview of the most common indoor air contaminants (Redlich et al., 1997).

Building envelope

For building owners and architects, some of the most significant decisions are related to the building façade. It has a considerable impact on the total building performance harmonizing aesthetics and performance. A well-designed building envelope assists in reducing the dependence on mechanical systems, leading to energy savings due to reduced heating and cooling loads. The building envelope acts as a separation between the interior and the exterior environments of a building, reacting to heat, moisture and air transfer. It insulates against heat gains and losses, while allowing useful daylight, whereas excluding moisture. Furthermore, it influences building performance such as energy efficiency, thermal comfort, daylight, natural ventilation, and noise.

Building façades for energy-efficient buildings nowadays are designed in a way to connect creative considerations with the most advantageous frameworks for indoor comfort. Nevertheless, in view of the building's life cycle, additional considerations need to be accounted for by relevant decision makers concerning:

- The functional reliability of the building façades
- Rain and wind tightness
- A concept for maintenance and cleaning
- Fire protection strategy

A noteworthy issue in the design stages of building façades is associated with the choice of appropriate glazing design. More glass areas indicate additional solar heat gains, and vice versa. Windows are elements that account for the most transmission of energy in the building envelope. Even the highest performance glazing has an overall heat transfer coefficient ($U-$value) at least five times greater than typical insulated opaque elements (Baker, 2005). Consequently, placement and orientation of façade glazing should be planned in a manner to optimize views and daylighting while avoiding solar heat gains. Glass with a lower $U-$value and shading coefficient reduces solar heat gains and succeeding cooling loads. Low shading coefficient values are most effective at reducing heat gains. Façade glazing have a significant effect on building performance. Refurbishment measures provide decision makers with the opportunity to incorporate the latest technology for glazing materials and framing components as well as shading and reflecting elements.

Photovoltaic systems

Photovoltaic (PV) systems directly convert sunlight into electricity, with no greenhouse gases or CO_2 generated in the process. The PV modules generate direct current (DC) electricity when exposed to direct sunlight, instantaneously converting sunlight to electricity. An inverter converts the direct current to alternating current (AC) electricity coordinating it to the power grid. During the course of the day, PV systems are able to supply up to 100% electricity, depending on the intensity of the sunlight and the size of the systems in relation to the demand. In cases where a PV system generates more electricity than the demand of the building, the surplus electricity can be fed back to the power grid. Stakeholders and decision makers considering implementation of PV systems should contemplate a number of factors. Furthermore, the decision making process in regards to PV technology has to consider whether the made assumptions today will be valid for the next $10 - 20$ years from now.

Is the purpose of installing a PV system:

- to reduce energy consumption and savings in regards to electricity costs?
- the reduction of carbon footprint of the building?
- to provide enhanced novelty value to the building?

Further,

- How appropriate is the building in question for installation of a PV system?
- Is the building well exposed to direct sunlight, or shaded by taller buildings and/or trees?

The manufacturing process of PV modules requires energy and is associated with the emission of some greenhouse gases. This is referred to as the embodied energy of the product. The time it takes for a PV module to generate the equivalent of its embodied energy (the energy payback time) obviously varies with different climates. Market prices for PV systems in comparison with present electricity retail tariffs result in that even a large rooftop PV system has a payback time surpassing 20 years (Keung, 2010). Consequently, the return on investment (ROI) calculation necessitates the consideration of both real benefits such as a reduction in electricity costs, in addition to intangible benefits.

Energy demand for heating and cooling

The greatest proportion of heat energy in existing residential and non-residential buildings is utilized for indoor heating. Although heating energy requirements decline in newly constructed buildings, energy requirements for heating of drinking water remains unaffected for renovation projects, as a result of improved technologies related to thermal insulation and energy-efficient systems. For a building fulfilling thermal insulation requirements according to current standards, energy demand for heating of drinking water corresponds to no more than 20% of the total heating energy demand (Bauer et al., 2010).

The energy demand for existing buildings in moderate climates is presently dominated by heating energy attributable to low levels of insulation standards. In warm climates however, cooling dominates the total energy consumption. Nevertheless, as building standards continuously improve, there is a clear shift from the dominance of thermal energy to electrical energy consumption (Eicker, 2009). In warmer climates such as in Southern Europe, numerous buildings are not equipped with any kind of thermal installation. Hence, an acceptable indoor comfort level can only be achieved by improved thermal insulation.

Building Energy Management Systems (BEMS) are presently used in the greater part of all mechanically conditioned buildings and increasingly in naturally ventilated buildings. They have the ability to control energy use and record energy consumption, but also to regulate the internal environmental conditions. BEMS can be utilized in order to monitor virtually all aspects of the building including, heating, cooling, plant, internal temperatures and air quality, ventilation systems, night cooling, optimal start/stop, and solar control blinds (Baker, 2009). These systems further allow the operator to retrieve data about current building conditions and instigate certain modifications. In theory, BEMS are deemed to be very useful systems, but in practise factors such as poor system design, operator knowledge and system complexity result in less desired monitoring conditions.

Promotion of Net Zero Energy Buildings and Stakeholders

For implementation of net zero energy buildings, a set of different stakeholders need to discuss the optimal definition of such buildings as well as realization of policies and elimination of existing barriers in this path. The main concern of net zero energy buildings is energy efficiency. From an early design stage, the design team work actively towards reducing energy consumption of the final building (DeBaillie, 2013). Usually, the incorporated design team consists of the building owner, architects, engineers, and contractors. Using energy-saving features from an early design stage of construction is a considerably different approach in comparison to conventional building methods. Energy efficiency measures integrate passive solar techniques with advanced glazing and insulation, building integrated photovoltaics, use of intelligent sensors and controls, daylight harvesting, and natural ventilation. Net zero energy buildings accumulate available energy to meet their imposing electricity and heating or cooling needs. Some buildings are fully autonomous, while others are connected to the electrical grid in order to export electricity in case there is a surplus, or draw electricity when a sufficient amount is not being produced (Marszal and Heiselberg, 2009; Stahl et al., 1995; Voss et al., 1996; Kramer et al., 2007; Platell and Dudzik, 2007). Another significant aspect in the path towards achieving net zero energy consumption is to educate building occupants as well as employing building energy monitoring for feedback on the health of the building and its systems. Continuing energy audits and commissioning will furthermore aid in ensuring proper building performance and also provide the facility manager and the building occupants with required data and feedback to maintain the systems. Conclusively, the lack of independent information that is perceived as trustworthy, comparable and impartial, is a key barrier to the comprehension of energy-efficient, low and zero-carbon technologies.

Appendix C

Useful formulaes - Cost of VIPs

Input parameters:

• λ_{core}	[W/mK]	• λ_{min}	[W/mK]
• ψ	[W/mK]	• r_{int}	[%]
• b	[m]	• r_{inf}	[%]
• h	[m]	• p_e	[%]
• A	[m^2]	• r_{mod}	[%]
• p	[m]	• n	[year]
• d	[m]	• p_{VIP}	[SEK/m^3]
• p_{foam}	[SEK/m^3]	• R	[SEK/m^2]

Formulaes:

$$U_{\text{core}} = \frac{\lambda_{\text{core}}}{d} \quad [\text{W}/(\text{m}^2\text{K})]$$

$$E_{\text{loss}} = \frac{\psi \cdot p}{A} \quad [\text{W}/(\text{m}^2\text{K})]$$

$$U_{\text{net}} = U_{\text{core}} + E_{\text{loss}} \quad [\text{W}/(\text{m}^2\text{K})]$$

$$R = \frac{1}{U_{\text{net}}} \quad [(\text{m}^2\text{K})/\text{W}]$$

$$d_{\text{min}} = R \cdot \lambda_{\text{min}} \quad [\text{m}]$$

$$d_{\text{save}} = d_{\text{min}} - d \quad [\text{m}]$$

$$A_{\text{factor}} = \frac{r_{\text{mod}}}{1-(1+r_{\text{mod}})^{-n}} \quad [\text{W}/(\text{m}^2\text{K})]$$

$$p_{\text{VIP}-600-1000} = \frac{p_{\text{VIP}}}{33 \cdot 0.6} \quad [\text{SEK}/\text{m}^2]$$

$$U_{\text{net}} = U_{\text{core}} + E_{\text{loss}} \quad [\text{W}/(\text{m}^2\text{K})]$$

$$C_{\text{vac}} = p_{\text{VIP}} \cdot A_{\text{factor}} \cdot d \quad [\text{SEK}/\text{m}^2]$$

$$C_{\text{min}} = p_{\text{foam}} \cdot A_{\text{factor}} \cdot d_{\text{min}} \quad [\text{SEK}/\text{m}^2]$$

$$C_{\text{net}} = C_{\text{vac}} - C_{\text{min}} \quad [\text{SEK}/\text{m}^2]$$

$$RS = \frac{d_{\text{save}} \cdot R}{2.5} \quad [(\text{m}^2\text{K})/\text{W}]$$

$$CO_n = C_{\text{net}} - RS \quad [\text{SEK}/\text{m}^2]$$

In Figure 4.17, R (rental income in SEK per square meter of surface area and year) is plotted versus CO_n (net cost in SEK per square meter wall and years), i.e. $R = f(CO_n)$.