DOUBLE DEGREE PHD DISSERTATION

A multi-methodology and sustainability-supporting framework for implementation and assessment of a holistic building renovation

by Aliakbar Kamari

AARHUS UNIVERSITY

UNIVERSITÀ DEGLI STUDI DI PALERMO

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Abstract

Future building renovation concerns more holistic perspectives related to the sustainability seen in a wider range of objectives/criteria facilitated by the renovation scenarios. Renovation should be a means of improving and developing buildings to meet the needs and challenges of the future and of making homeowners and tenants less vulnerable due to rising energy costs in the future. There is a great potential for reducing energy consumption in existing buildings. However, that does not mean compromising on the quality and architectural values that make the buildings special. Therefore, existing buildings cannot simply be renovated, but must undergo a deep transformation to comply with wider range of objectives/criteria. That includes and addresses the "hard" objectives/criteria (quantitative/measurable criteria such as energy consumption or energy generation) and the "soft" objectives/criteria (qualitative/immeasurable criteria such as spatial quality) in parallel. These objectives both can be achieved, if holistic renovation scenarios are generated each time the buildings are renovated by focus on addressing both the mentioned objectives/criteria. In this framework, the major difference between a deep building renovation and an ordinary one is a commitment to a holistic approach in which objectives/criteria are targeted early in the design stages and subsequently are considered for their interdependence throughout sustainability perspectives.

A review of recent research has revealed that the present efforts on sustainable objectives fulfilment in renovation projects are not sufficient. It demonstrates compounding the typical challenges of a sustainable retrofitting from theory to implement stages is lack of an appropriate design methodology. It should take into account retrofitting projects initially in order to interact with the different stakeholders and then to embark on the sustainability objectives/criteria in its full sense. It should assist to identify, manage, and evaluate the holistic objectives among various alternative retrofitting solutions during the early design stages. In this perspective, the present thesis has been developed according to the following objectives:

a) It primarily considers building renovation as a complex messy/wicked problem. As such, it gives details on how combinations of methods that are parts of SSM (Soft Systems Methodologies) and MCDM (Multi Criteria Decision Making Methods) are able to cope with its complexity. It consequently develops a methodology, which is entitled *Holistic Multi-methodology for Building Renovation* – HMSR. The HMSR serve as a means to structure retrofitting problems in accordance with the sustainability in its full sense to support the decision-making and help to develop most appropriate retrofitting scenarios.
b) It addresses a new simplified holistic sustainability decision-making support framework, which applies to the structures of the built environment for building renovation projects. The developed framework can be applied during different project stages and to assist in the consideration of the sustainability issues through support of decision-making and communication with relevant stakeholders. It should be noted that, the framework can be considered not only as an abstract

model but a bound method of planning and design as well as evaluating and comparing retrofitting projects.

c) It investigates development of a Decision Support System - DSS for generating renovation scenarios with the aims to represent and navigate across existing dependencies. As such, the renovation sustainability objectives/criteria and the entire list of renovation approaches are discovered, explored and structured through development of a Domain Mapping Matrix - DMM. A major advantage of the DMM is in its compactness and ability to provide a systematic mapping among the items (represented in rows and columns) that is clear and easy to read regardless of size. It considers and demonstrates what the values are (sustainability objectives/criteria), how they can be created (application of renovation approaches), and where the value can be added by generation of the integrated renovation scenarios (use of the DMM) in renovation context.

d) It expands a conceptual framework under the topic of Tectonic Sustainable Building Design (TSBD). The TSBD seeks for interaction between architecture, sustainability objectives and an equipped design process. It is therefore attached to the *tectonics* (refers to architectural theory), the *sustainability* (refers to the holistic objectives) and a holistic multi-methodology - *HMSR* (refers to the integrated design methodology). By focusing on TSBD thinking in the field of building renovation, one forms a strategy of establishing a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building. Once this is established, the framework is intended to serve as a platform for refining and improving the contemporary building industry seen in the light of sustainability, by supporting the decision-making in the development of holistic renovation scenarios.

The research strategy employed in this thesis presents characteristics of two research types, namely the qualitative research approach, and the inter- or transdisciplinary research throughout mode 2. It therefore calls for an inductive research approach and involves an interpretive approach and comparative analysis to its subject matter. In order to enrich and validate the elements and principles of the above objectives, the thesis analyses 10 European renovation research projects, the Danish SIGMA database (by Molio[1]), as well as a case study linking to an ongoing renovation research project which is entitled RE-VALUE[2]. The case study is Section 3 of Skovgårdsparken[3] located in Brabrand, Denmark. It is a social housing complex (including nine blocks), and has been renovated by Brabrand Housing Association.

The future of the research in this thesis concerns expanding of the TSBD framework for Building Design in general. That means move from building renovation to design of new buildings.

Key words:

Building Renovation/Retrofitting; Sustainability; Sustainable Renovation, Methodology, Design Methodology; Multi-methodology; Problem Structuring; Soft Systems Methodology (SSM); Multi Criteria Decision Making (MCDM); Complexity; Holism; Decision Support Systems (DSS); System Architecture; Decisions Architecture; Domain Mapping Matrix (DMM); Dependency Structure Matrix; Tectonics; Tectonic Sustainable Building Design (TSBD).

[1] https://molio.dk/molio-prisdata/prisdata-footer/brug-molio-prisdata/

[2] http://www.revalue.dk

[3] https://www.bbbo.dk/projekter/skovgaardsparken/

Resumé [Abstract-Danish]

Fremtidige renoveringer af bygninger bør have en holistisk tilgang relateret til bæredygtigheden set i relation til en bredere vifte af kriterier og mulige renoveringsscenarierne. Renovering forbedrer og udvikle bygninger for at imødekomme fremtidens behov og udfordringer og gør husejere og lejere mindre sårbare i forhold til fremtidens energiomkostninger. Der er et stort potentiale for at reducere energiforbruget i eksisterende bygninger, men det betyder ikke, at man skal gå på kompromis med de kvalitetsmæssige og arkitektoniske værdier. Derfor kan eksisterende bygninger ikke blot renoveres, men skal gennemgå en transformation for at leve op til holistiske kriterier for renovering. Det omfatter "hårde" kriterier (kvantitative / målbare kriterier som energiforbrug eller energiproduktion) såvel "bløde" kriterier (kvalitative / umærkelige kriterier som rumlig kvalitet). Disse kriterier kan begge opfyldes, hvis der anvendes holistiske renoveringsscenarier hver gang bygningerne renoveres med fokus på at adressere opstillede kriterier.

En gennemgang af nyere forskning har vist, at den nuværende indsats for opfyldelse af bæredygtige kriterier i renoveringsprojekter ikke er tilstrækkelig bl.a. på grund af manglende designmetoder. I dette perspektiv er den aktuelle afhandling udviklet i overensstemmelse med følgende hovedpunkter:

a) Udgangspunktet er, at bygningsrenovering betragtes som et kompliceret uorganiseret problem. I afhandlingen redegøres for, hvordan kombinationer af metoder, der er dele af SSM (Soft Systems Methodologies) og MCDM (Multi Criteria Decision Making Methods), er i stand til at klare denne kompleksitet. Der udvikles derfor en metode, der har titlen Holistisk Multi-Metodologi (HMSR) til Bygningsrenovering. Metoden kan strukturere renoveringsløsninger i overensstemmelse med bæredygtighed efter opstillede kriterier.

b) Afhandlingen omhandler en ny forenklet holistisk bæredygtighedsbaseret beslutningsmetode. Den udviklede metode kan anvendes i forskellige projektfaser og medvirke til at overveje bæredygtighedsproblemet ved hjælp af beslutningstagning og kommunikation med relevante interessenter. Det skal bemærkes, at metoden ikke kun betragtes som en abstrakt model, men også en bunden metode til planlægning og design samt evaluering og sammenligning af renoveringsprojekter.

c) Afhandlingen undersøger udviklingen af et beslutningsstøttesystem - DSS (Decision Support System) til generering af renoveringsscenarier med det formål at repræsentere og navigere på tværs af eksisterende afhængigheder. Som sådan afdækkes, udforskes og struktureres renoveringsbæredygtighedskriterierne og hele listen over renoveringsmetoder gennem udvikling af en DMM (Domain Mapping Matrix). Den vurderer og demonstrerer, hvad værdierne er samt hvordan de kan skabes (anvendelse af renoveringsmetoder), og hvor værdien kan tilføjes ved generering af de integrerede renoveringsscenarier (brug af DMM) i renoveringskontekst.

d) Afhandlingen udvikler en konceptuel ramme under emnet: Tectonic Sustainable Building Design (TSBD). TSBD søger interaktion mellem arkitektur, bæredygtighedsmål og en designproces. Den er derfor knyttet til tektonikken (refererer til arkitektoniske teorier), bæredygtigheden (refererer til de holistiske mål) og en holistisk multimetodik - HMSR (refererer til den integrerede designmetode). Ved at fokusere på TSBD-tænkning på området for renovering af bygninger, har man en strategi for at etablere en sammenhæng mellem de intentioner, der er indlejret i den arkitektoniske omdannelse og den måde, de opfattes af brugeren / ejeren af bygningen. Når dette er oprettet, er rammen beregnet til at fungere som en platform for raffinering og forbedring af den moderne byggebranche set i lyset af bæredygtighed ved at understøtte beslutningstagningen i udviklingen af holistiske renoveringsscenarier.

Den forskningsstrategi, der anvendes i denne afhandling, præsenterer karakteristika for to forskningsmetoder, nemlig den kvalitative forskningsstrategi og den tværfaglige eller tværfaglige forskning i mode 2. Det opfordrer derfor til en induktiv forskningsstrategi og indebærer en fortolkende tilgang og sammenlignende analyse af dens emne. For at berige og validere de ovennævnte målsætninger og principper analyserer afhandlingen 10 europæiske renoveringsprojekter, den danske SIGMA-database (af Molio[1]) samt en casestudie i forbindelse med et igangværende forskningsprojekt, der har titlen RE-VALUE[2]. Casestudiet er afsnit 3 i Skovgårdsparken[3], der ligger i Brabrand, Danmark. Det er et socialt boligkompleks (herunder ni blokke), og er blevet renoveret af Brabrand Boligforening. Fremtiden for forskningen opstartet i denne afhandling vedrører udvidelse af TSBD-rammen for byggevirksomhed generelt.

[1] https://molio.dk/molio-prisdata/prisdata-footer/brug-molio-prisdata/
[2] http://www.revalue.dk
[3] https://www.bbbo.dk/projekter/skovgaardsparken/

Abstract [Italian]

La ristrutturazione degli edifici in futuro dovrà essere condotta secondo una prospettiva più olistica legata alla sostenibilità vista in una più ampia gamma di obiettivi/criteri e facilitata dagli scenari di ristrutturazione possibili. La ristrutturazione degli edifici dovrebbe servire a migliorarne le performance al fine di soddisfare le esigenze degli utenti, rendendo questi ultimi meno vulnerabili in relazione ai futuri costi energetici. Vi è un grande potenziale per ridurre il consumo di energia negli edifici esistenti. Tuttavia, ciò non deve comprometterè i valori architettonici e di qualità che rendono particolari. Pertanto, non possono essere semplicemente rinnovati, ma devono subire una profonda trasformazione per rispettare una vasta gamma di obiettivi/criteri. Ciò conduce a perseguire in parallelo obiettivi/criteri "hard" (criteri quantitativi/misurabili, come il consumo di energia o la generazione di energia) e obiettivi/criteri "soft" (criteri qualitativi/non misurabili, come la qualità spaziale). Questi obiettivi possono essere raggiunti se vengono generati scenari di ristrutturazione olistici ogni volta che gli edifici vengono rinnovati, concentrando l'attenzione su entrambi gli obiettivi/criteri menzionati (“hard” e “soft”). In questo contesto, la principale differenza tra una ristrutturazione profonda ed una “ordinaria” consiste nell’adozione di un approccio olistico in cui gli obiettivi/criteri sono individuati sin dall'inizio delle fasi di progettazione e successivamente sono considerati per la loro interdipendenza attraverso un aproccio sostenibile.

Recenti ricerche hanno rivelato che gli attuali sforzi non sono sufficienti per perseguire obiettivi sostenibili nei progetti di ristrutturazione edilizia. Ciò dimostra che la combinazione delle sfide tipiche di un retrofit sostenibile, dalla teoria alla fase di attuazione, manca di una metodologia di progettazione appropriata. Si dovrebbe prendere in considerazione inizialmente l'adeguamento dei progetti al fine di interagire con i diversi soggetti interessati e quindi perseguire pienamente gli obiettivi/criteri di sostenibilità. Si dovrebbe aiutare a identificare, gestire e valutare gli obiettivi olistici tra le varie alternative di retrofit durante le fasi iniziali di progettazione. In quest’ottica la presente tesi è stata sviluppata secondo i seguenti obiettivi:

a) Considerare la ristrutturazione edilizia come un problema complesso.. In quanto tale, fornire dettagli su come combinando metodi ”soft” (Soft Systems Methodologies) e MCDM (Multi Criteria Decision Making Methods) si può essere in grado di far fronte alla sua complessità. Di conseguenza, sviluppare una metodologia, denominata “Multi-metodologia olistica per il rinnovamento delle costruzioni” - HMSR. L'HMSR è uno strumento che consente di strutturare i problemi di retrofit in conformità ai criteri di sostenibilità ,sostenendo il processo decisionale e contribuiendo a sviluppare scenari di retrofit più adeguati.
b) Mettere a punto un nuovo quadro di supporto decisionale semplificato, sostenibile, olistico, che si applica alle strutture dell'ambiente costruito per progetti di ristrutturazione. Il quadro sviluppato può essere applicato in diverse fasi del progetto e contribuire alla considerazione delle questioni di sostenibilità attraverso il supporto del processo decisionale e della comunicazione con i soggetti interessati. Va notato che il quadro può essere considerato non solo come modello

astratto, ma anche come metodo di progettazione, nonché per valutare e confrontare progetti di ristrutturazione.

c) Esaminare lo sviluppo di un sistema di supporto decisionale - DSS per la generazione di scenari di ristrutturazione con l'obiettivo di rappresentare e identificare le dipendenze esistenti. Come tali, gli obiettivi/criteri di sostenibilità della ristrutturazione edilizia e l'intero elenco di approcci di ristrutturazione vengono esplorati e strutturati attraverso lo sviluppo di una “matrice di mappatura di dominio” - DMM. Il maggiore vantaggio del DMM consiste nella sua capacità di fornire una mappatura sistematizzata di voci (rappresentate da righe e colonne) chiare e facili da leggere, a meno della rispettiva dimensione. Essa considera e dimostra quali sono i valori (obiettivi/criteri di sostenibilità), come possono essere creati (applicazione di approcci di ristrutturazione) e dove il valore può essere aggiunto generando scenari di ristrutturazione integrati (utilizzo del DMM).
d) Espandere un quadro concettuale nell'ambito del progetto “Tectonic Sustainable Building Design” (TSBD). Il TSBD persegue l'interazione tra architettura, obiettivi di sostenibilità e un processo di progettazione “attrezzato”. È quindi legato alla Tettonica (riferendosi alla teoria architettonica), alla sostenibilità (riferendosi agli obiettivi olistici) ed alla multi-metodologia olistica - HMSR (riferendosi alla metodologia di progettazione integrata). Focalizzandosi sulla TSBD nel campo della ristrutturazione edilizia è possibile definire una strategia che collega le intenzioni della trasformazione architettonica ed il modo in cui queste vengono percepite dall'utente/proprietario dell'edificio. Una volta stabilita la strategia, questa è destinata a servire da base per raffinare e migliorare l'industria dell'edilizia contemporanea vista alla luce della sostenibilità, sostenendo il processo decisionale nello sviluppo di scenari di ristrutturazione olistici.

La strategia di ricerca impiegata in questa tesi presenta caratteristiche di due tipi: qualitativa e inter transdisciplinare. Richiede pertanto un approccio di ricerca induttivo e coinvolge un approccio interpretativo e un'analisi comparativa. Per arricchire e convalidare gli elementi e i principi degli obiettivi summenzionati, la tesi analizza 10 progetti europei di ricerca per la ristrutturazione, il database danese SIGMA (di Molio[1]), nonché un caso studio che collega un progetto di ricerca di ristrutturazione in corso, intitolato RE-VALUE[2]. Il caso studio si riferisce alla sezione 3 di Skovgårdsparken[3] situata a Brabrand, in Danimarca. È un complesso residenziale sociale (di nove blocchi) ed è stato ristrutturato da Brabrand Housing Association.

Il futuro della ricerca condotta per l’elaborazione di questa tesi riguarderà l'espansione del quadro TSBD per la progettazione degli edifici in generale. Ciò significherà spostare l’attenzione dalla ristrutturazione degli edifici alla progettazione del nuovo.

[1] https://molio.dk/molio-prisdata/prisdata-footer/brug-molio-prisdata/

[2] http://www.revalue.dk

[3] https://www.bbbo.dk/projekter/skovgaardsparken/

Dedication

In the memory of my inspiring and honor of most compassionate

… *my grandfather*

Reminding me that life is a fragile gift.

… *my mom*

Reminiscing me to bring love, courage, endurance and passion to all of life's challenges.

Acknowledgment

First, I would like to express my deep and sincere gratitude to almighty God for giving my energy, time and strength to meet this degree. I offer my sincere appreciation and gratitude to numerous individuals and organizations in the successful completion of my doctoral studies. I would like to thank my venerable supervisors Prof. Rossella Corrao and Prof. Poul Henning Kirkegaard for all their supports and endless guides and helps. I am most grateful for their probing questions and validation of the worthiness of my research. I should thank the members of Ph.D committee for their guidance and support. I would also like to offer my gratitude to Prof. Marco Rosario Nobile, Prof. Søren Wandahl, Prof. Giuseppe Pellitteri, Prof. Dr. Francesco Lo Piccolo, and Prof. Steffen Petersen who provided me with guidance and professional opportunities during my doctoral program. Thank you, Prof. Filippo Schilleci and Mrs. Mette Stig Hansen for the deadlines and attention to administrative concerns. I would like to show my gratitude to all the participants in Danish project "RE-VALUE", for kindly assisting me in my research, run the interviews, workshops and collection of the required data.

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Abbreviations Used

Acronym	Explanation
AEC	Architecture, Engineering & Construction
AHP	Analytical Hierarchy Process – a decision support method
AI	Artificial Intelligence
BEAT	Building Environmental Assessment Tool
BIM	Building Information Modelling
BPIE	Buildings Performance Institute Europe
BPS	Building Performance Simulation
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer Aided Drawing / Computer Aided Design
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
CATWOE	Customer, Actors, Transformation, Weltanschauung, Owner, Environment
CMF	Centre for Facility Management
CM	Change Management
DGNB	Deutsche Gesellschaft für Nachhaltiges Bauen
DGNB-DK	Deutsche Gesellschaft für Nachhaltiges Bauen - Denmark
DHW	Domestic Hot Water
DIY	Do It Yourself
DM	Decision Maker
DMM	Domain Mapping Matrix
DSM	Dependency Structure Matrix
DSS	Decision Support System
EC	European Commission
ECM	Energy Conservation Measures
ED	Eco-design Directive
EED	Energy Efficiency Directive
EEM	Energy Efficiency Measure
EEO	Energy Efficiency Obligation
EEW	Energy Efficiency Watch
EFQM	European Foundation for Quality Management
ELECTRE	Elimination at choice translating reality
ELD	Energy Labelling Directive
EPBD	Energy Performance of Buildings Directive
EPS	Expanded Polystyrene
ER	Evidential Reasoning
EU	European Union
GA	Genetic Algorithms
GDP	Gross Domestic Product
HS	Hard Systems
HSM	Hard Systems Methodology
HVAC	Heating, Ventilation, and Air Conditioning

HMSR	Holistic Multi-methodology for Sustainable Renovation
IEA	International Energy Agency
IM	Interdomain Matrix
IP	Interactive Planning
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
LMS	Least Mean Square
MADM	Multi Attribute Decision Making
MAUT	Multi Attribute Utility Theory
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
MEP	Mechanical Electrical and Plumbing
MODM	Multi Objective Decision Making
NGO	Non Governmental Organizations
NGT	Nominal Group Technique
NHS	National Health Services
NZEB	Nearly Zero-Energy Buildings
OR	Operation Research
POT	Personal, Organizational, Technical
PROMETHEE	Preference ranking organization method for enrichment evaluation
PV	Photovoltaic
R&D	Research & Development
ROI	Return On Investment
RQ	Research Question
RSL	Residual Service Life
SAST	Strategic Assumptions Surfacing and Testing
SBi	Ministry of Climate, Energy and Building - Danish government
SBTOOL	Sustainable Buildings Tool
SMART	Simple Multi-Attribute Rating technique
SS	Soft Systems
SSM	Soft Systems Methodology
SOD	Systems Oriented Design
S&T	Science & Technology
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSBD	Tectonic Sustainable Building Design
UN	United Nation
VFT	Value Focused Thinking
WBDG	World Building Design Guide
WPM	Weighted Product Method
ZEB	Zero Energy Building

** papers with similar topics have been published and/or submitted for publication(for the list of publications see Thesis Details section).*

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Thesis details

Thesis Title:	A multi-methodology and sustainability-supporting framework for implementation and assessment of a holistic building renovation
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The following papers have either been published or accepted for publications as part of the PhD program at the time of submission:

[1] Kamari, A., Corrao, R. and Kirkegaard, P.H., "Towards the development of a Decision Support System (DSS) for building renovation: Domain Mapping Matrix (DMM) for sustainability renovation criteria and renovation approaches", Seismic and Energy Renovation for Sustainable Cities Conference, SER4SC 2018, Catania, Italy, 2018. [status: published]

[2] Kamari, A., Corrao, R., Petersen, S. and Kirkegaard, P.H., "Tectonic Sustainable Building Design for the Development of Renovation Scenarios – Analysis of ten European renovation research projects", Seismic and Energy Renovation for Sustainable Cities Conference, SER4SC 2018, Catania, Italy, 2018. [status: published]

[3] Kamari, A., Jensen, S.R., Corrao, R. and Kirkegaard, P.H., "A Holistic Multi-methodology in Sustainable Retrofitting", International Journal of Strategic Property Management, 2017. [status: accepted ahead of publication]

[4] Kamari, A., "Rise of complexity in the new age movement and its effects on updating the process of designing the buildings", Infolio, 2017. [status: accepted ahead of publication]

[5] Kamari, A., Corrao, R., Petersen, S. and Kirkegaard, P.H., "Sustainable Retrofitting Framework: Introducing 3 levels of Integrated Design Process Implementation and Evaluation", Passive Low Energy Architecture Conference, PLEA 2017, Edinburgh, UK (ISBN:978-0-9928957-5-4), vol. 1, 2017. [status: published]

[6] Kamari, A., Corrao, R. and Kirkegaard, P.H., "Sustainability focused Decision-making in Building Renovation", International Journal of Sustainable Built Environment (ISSN:2212-6090), 2017. [status: published]

[7] Jensen, S.R., Kamari, A., Strange, A. and Kirkegaard, P.H., "Towards a holistic approach to retrofitting: A critical review of state-of-the-art evaluation methodologies for architectural transformation", Transforming Our Built Environment through Innovation and Integration: Putting Ideas into Action Conference, WSBE 2017, Hong Kong, China (ISBN:978-988-77943-0-1), 2017. [status: published]

[8] Kamari, A., Jensen, S.R., Corrao, R. and Kirkegaard, P.H., "Towards a holistic methodology in sustainable retrofitting: Theory, Implementation and Applications", Transforming Our Built Environment through Innovation and Integration: Putting Ideas into Action Conference, WSBE 2017, Hong Kong, China (ISBN:978-988-77943-0-1), 2017. [status: published]

[9] Kamari, A., "Report paper: CIB W78 - 32nd international conference in 'Information Technology for Construction', Eindhoven, Netherlands, October 2015", Infolio (ISSN:1828-2482), vol. 33, 2016. [status: published]

The thesis includes 7 chapters consisting of 10 sections. Parts of the papers listed above have directly or indirectly been included in the chapters of the thesis.

CHAPTER I

RESEARCH POSITION AND THE STATE OF ART

CHAPTER'S SYNOPSIS

"This chapter provides the overall information about the thesis. In section 1, it gives detail about the major components of the thesis including research topic, state of the art, research objectives and questions, and the research methodology that has been employed for carrying it out. In addition in section 2, it will introduce readers into a theme of building renovation/retrofitting and to position its components such as benefits and barriers in the broader perspectives."

1. Introduction

The regeneration and transformation of cities from the industrial age to the knowledge age is essentially a 'whole lifecycle' process, consists of study, planning and research about historical, architectural, archaeological, environmental, social, economic, and various other perspectives. The world today is characterized as the time of transition with unprecedented changes, which are both fundamental, rapid and multidimensional. The pervasive paradigm that is often used to deal with these changes is a transition from an industrial age to a post-industrial information age. The new generation of humans inherited a world of technologies and systems of organization (regimes) which was born out of the industrial revolution. In addition, the newly found knowledge of modern science was supplied from the field of engineering and developing these technologies required to support the new form of mass society. Mass society unlike the previous period, needed to concentrate upon people and thus required the development of engineered systems to an unprecedented extent (Rhodes et al., 2009). Hence, the systems were designed and developed by a minority of professionals who created finished products that were pushed out to the end-user. The focus was upon provision of tangible objects. These goods were designed as finished products that operate in relative isolation from each other and follow a linear life cycle from production to consumption and disposal.

The post-industrial knowledge world inherited massive inherent industrial systems that were surrounded by challenges. The making of more products that are faster, stronger and bigger were being become increasingly commoditized. The new world of value was opening up in the design of complex systems that connect pre-existing resources to provide users with solutions to real world problems. As such, humans were presented with new challenges that requires to go beyond their logic along with existing differences between two antithetical ideologies called "*Reductionism*" and "*Holism*". A key factor to finding out about the concept of *Holism* in this regard is that it represents an alternative to our modern scientific way of thinking which is known as *Reductionism*. The *Reductionist* approach is primarily focused upon breaking things down into their constituent parts in order to analyze them and then try to understand the whole system as the sum of those individual elements (Weinberg, 2001). This approach results in a vision of the world that is made of isolated components, which interact in a pre-determined linear fashion; what is sometimes called the clockwork universe (Davis, 1991). The overall functioning of the system is then achieved by defining an overarching bottom-up plan based on "how these components give feedback to each other". In order to achieve this overall functionality of the system, it is important that the elements can be constrained, that is to say that they are relatively static and their behavior can be pre-determined and thus be controlled (Cheung, 2008). This approach works well when there are sets of things that do not have emergent attributes (Bertalanffy, 1968); but because some systems (in fact many systems) have emergent properties as a whole, this method does not always work best. In such cases, it sounds essential to apply other approaches which are known as *systems thinking* (Mingers, 2014; Weinberg, 2001). *Systems thinking* places a greater emphasis upon understanding systems in their entirety and within the environment, which gives them context. Comparing to the previous approach which is based on components *analysis*, the second one is based on the *synthesis* of elements and can be referred to as *Holism* (or Whole), which is a term known from modern philosophy (Weinberg, 2001). Society needs answers to analytical questions, but also to the bigger questions i.e., the need to design smart and sustainable buildings and cities that provide people with better quality of life or the need to design larger information systems. Looking into these facts question us with challenge of developing complex systems and it requires employment of the new methodologies and approaches.

As the world transited further into the 21st century, society became more complex and a number of factors revealed the inherent limitations to the industrial model. The possible key drivers for the rising complexity, within which we have to design systems for 21st century (Hallissy et al., 2013) were emerged into the following eras including *rise of the sustainable development paradigm*, *the rapid and pervasive information technology*, *the huge growth in the services economy*, and *the expansion of economic globalization* (see Figure 1.1). Developing the next generation of sustainable technology is not about making things that are faster, bigger and better. To some extent, it requires us to design systems that provide synergistic connections between things, that overcomes the death and effect of linear models and, as such, there is a need to develop systems that are more integrated, flexible and capable of adaptation within a more holistic vision. Today, specifically in the building industry, architects and engineers are exposed to well-known environmental issues, including resource depletion, pollution and global warming. To some extent, the overall goal can be defined as finding the right balance between *environmental*, *economic* and *social* concerns (Williamson, 2003) which are three traditional pillars of the sustainability development paradigm (see the Brundtland Commission, 1987). Similarly, this holistic concept has seeped into the various branches of building industry such as renovation/retrofitting[1] of existing buildings and therefore it calls for better equipped methodologies, processes, and approaches in order to deal with the existing complexity during the implementation of the design process, and address the required relevance to its *society* and *technology* comprehensively.

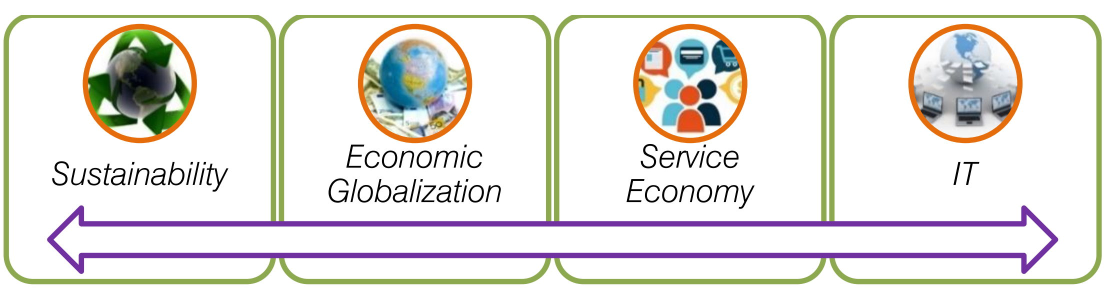


Figure 1.1. Key drivers taking us into a more complex environments concerning 21st century

[1] In this thesis, the term "building renovation" is used as the equivalent of "building retrofitting" in accordance with the "sustainable development paradigm". My intent is to fill the gap, which exists between these two terms in existing literature.

1.1. Towards holistic renovation[2] of the existing buildings

Let's start by asking ourselves a question: How does one eat an elephant? One bite at a time – a lot of teaspoons.

This is one way of drawing a picture of the enormous task associated with realizing the immense potential for energy-savings that exist in the existing buildings context. Recent investigations into the retrofitting and so energy improvements of existing buildings have revealed that it oftentimes can be more cost-effective than recently built projects. Today buildings are responsible for 40% of energy consumption and 36% of CO2 emissions in the EU (EC [European Commission], 2014). New buildings generally need less than 3 to 5 litters of heating oil per square meter per year while older buildings consume about 25 litters on average (EC, 2014). Some buildings even require up to 60 litters. Renovation of buildings is currently achieving increased attention in many European countries (BPIE [Buildings Performance Institute Europe], 2011); the primary reason is that about 35% of the EU's buildings are over 50 years old (JRC [Joint Research Centre], 2015), and thus they grow less attractive, if not maintained thoroughly during life time (for the reasons such as insufficient indoor air quality and thermal comfort). In retrofitting context via enhancing the energy efficiency (EEW [Energy Efficiency Watch], 2015), the total EU energy consumption can be decreased by 5% to 6% as well as CO2 emissions by about 5% (EC, 2014). However improving energy efficiency and carbon emission parameters are not the only goals in building renovation context. Energy and resource-conscious architecture are known as environmental friendly issues. Considering just them for a project is not sustainable if it is non-functional, much costly and malformed. Historical value, identity, aesthetic, integrity, innovation etc. are all rich unmeasured values why people still emphasize and keep living in their existing buildings over time that needs to be included and addressed by use of various renovation approaches.

Developing major retrofitting approaches for existing buildings to include sustainability initiatives can decrease operation and maintain costs, reduce environmental impacts, and can increase building adaptability, durability, and resiliency within other views. Due to this, the building may be less costly to operate, may growth in value, last longer, and contribute to a preferable, healthier, more convenient environment to the occupants who lives and works in there. Enhancing indoor comfort quality, reducing moisture, and improving efficiency all can result in enhancing user's health and productivity (Bluyssen et al., 2002). All of these impact our existing building stock, therefore, points into the conclusion that the decision regarding retrofitting of existing buildings is a multi-objective problem subjected to various building characteristics, criteria, constraints and conditions (NIBS [National Institute of Building Sciences], 2014) evidently. Over the last few decades different methods have been developed to implement and evaluate the renovation of existing buildings from technical and not-technical perspectives (Ma et al., 2012). Jensen et al. (2015) discussed that these methods have a narrow environmental or energy focus. Therefore, it leads to insufficiently understand and examine the sustainability objectives fulfilment and their greater chain of effects in

[2] This thesis concerns renovation of ordinary and contemporary built buildings. The outcome is particularly useful for renovation of residential buildings (social housings / dwellings) with no specific historical background and values which cause to exclude them to go under a deep renovation. In other words, the term building renovation in this paper should be distinguished with preservation or conservation fields that are related to the buildings with historical values or monuments.

aforementioned context (SBi [Danish Building Research Institute], 2014). Considering the intersections of the building design industry and the practices of sustainability allows us to foresee greater demand for systematic approaches to upgrade existing building stock close at hand.

1.2. Sustainability development paradigm

Sustainability development refers to a dynamic process from one state towards another which means there is no exact definition about it, in fact every societies and cities are evolving by passing the time in order to become more superior or inferior (UN [United Nation], 2013). Hence, our goals including visions, ambitions and technical feasibilities are all subjects to change (Brophy, 2014). The sustainability (Williamson et al., 2003) can be described as incontestable development of society and economy on a long-term basis within the framework of the carrying inclusion of the earth's ecosystems (UN, 2013). Figure 1.2 represents the framework for sustainable development (Boruge, 2012).

Figure 1.2: The framework sustainable development (source: Boruge, 2012)

Similarly, developing major retrofitting approaches for existing buildings to include sustainability initiatives can decrease operation and maintain costs; reduce environmental impacts; and can increase building adaptability, durability, and resiliency. Due to this, the buildings may be less costly to operate, may growth in value, last longer, and contribute to a preferable, healthier, and more convenient environment to the occupants.

From sustainability perspective, there are factors that must be taken into the consideration all together in order to gain ultimate goal which is known as "sustained prosperity" relevance to different stakeholders and so their various priorities. Hence, an optimal renovation solution is able to address the trade-off among a range of energy related and non-energy related factors that must be taken in account (Boeri et al., 2014). With sustainability moving up agendas across industry and government as well as enhancing sustainability awareness in public, being able to assess the sustainability impacts and opportunities of a project sounds crucial. Considering of where building design industry meets the sustainability solutions enables building designers to anticipate a larger demand for systematic strategies to upgrade existing building stock nearby. Furthermore, the sustainability paradigm is based on the modern information and communication systems (Afgan et al., 2002). As such, it is of special interest to verify the need for the deep understanding of sustainability as the pattern with the agglomerated set of indicators defined by the respective criteria (Afgan, 2010). If human settlements are to carry out sustainability as a target, it is necessary to develop methods to set criteria, plan, design, and evaluation. It is also necessary having such methods as a scientific basis in terms of comparison between various projects (Nguyen et al., 2011), and for considering how they should be developed over time.

From sustainability perspective through building renovation field, there are factors which must be taken into consideration in order to deal with different stakeholders and their various priorities or interests. It hence calls for a major consideration of this field and its related issues so as to create a high-performance building (to be in consistence with sustainability in its full sense) via application of a holistic and integrated design process (where different stakeholders are involved), which make sure all design goals are met.

1.3. A brief description of the current barriers in a building renovation context

Experience from projects and research carried out over recent decades has identified numerous barriers that hinder the uptake of a comprehensive building renovation. BPIE (2011) reported the existing barriers in this context including headlines such as '*financial*', '*institutional & administrative*', '*awareness, advice & skills*' and '*separation of expenditure and benefit*' (these have been elaborated further in section 2.6). Further, a list of five main constraints that building renovation projects face from pre-retrofit to post-retrofit stages were explored by Cattano et al. (2013), including:

- Pre-existing hidden conditions are identified late in the design process,
- Typical renovations do not account for interactions between building systems,
- Energy retrofits are not coordinated with other building system renovations,
- Many industry professionals lack experience with the methods and materials required to deliver successful sustainable renovations,
- Poor measurements of the benefits achieved in sustainable renovations.

Galiotto et al. (2015) discussed the retrofitting barriers that occurred due to *politico-economic* barriers (which need to be addressed by policy makers and market developers), *technical* barriers (which need to be addressed by architects and engineers), and *behavioral* barriers (which are the direct impact of building owners and occupants). Moreover, the authors (Galiotto et al., 2015) emphasized the role of occupants' behavior in building energy consumption and the reasons for *behavioral* barriers were reported as:

- Limited knowledge about the building renovation process and its benefits among stakeholders,
- Lack of interest among the building-owners,
- Lack of guidance from the government and responsible institutions,
- Lack of confidence due to essence of uncertainties over how the renovation is processed related to the rebound effect,

- Lack of social and emotional understanding of renovation benefits beyond building scale (block/district/local scales).

The building occupants indirectly influence the pattern of energy demands due to the changes over time in occupancy schedules and usage patterns (Masoso et al., 2010). In connection to this, Booth et al. (2013) categorized the most common barriers in building renovation context as the *pre-bound effect* which is known as the divergence between modelled and actual energy consumption for the pre-retrofit, and *rebound effect* in which the post-retrofit energy consumption is higher than predicted, due to changes in occupant behavior. The essence of the pre-bound and rebound effects lead to a massive disparity between the predicted and actual energy savings. The authors (Booth et al., 2013) considered that the removal of these barriers can reduce renovation costs and yield buildings that consume less energy and resources. Nevertheless, Yu et al. (2013) stated that understanding of building occupants' behavior in a renovation context is not addressed adequately through the renovation process since the general focus in this area is still on objectives, which can be obtained by concentrating on technical aspects i.e., energy efficiency. It seems essential that the design approach should integrate the effects of a building's technical aspects together with the users' behavior representation, giving them the same importance (Degan et al., 2015). From another perspective, Acre et al. (2015) discussed that post-occupancy evaluation of renovated buildings, which are often used to assess the impact of energy renovation, fails to examine the social context correctly due to the fact that many of the energy efficiency measures and technical issues in energy renovation remain abstract to the occupants. The authors (Acre et al., 2015) indicated that due to the abstract nature of technical issues and in order to improve the interface between technical dimensions and occupants, the non-technical issues that are more intuitive to human perception, needs to be unfolded.

1.4. The concept of *Holism* in building renovation

In order to find a common pattern for the identified barriers, let's begin by posing the question "what is the reason for renovating existing buildings"? Buildings are renovated to make changes. The motivation for making these changes can be different from project to project. From one perspective we can discuss how objectives/criteria are met by applying technical/physical or technological renovation solutions through changes to the building itself. As an example, we see how re-insulation of the external wall can be a possible renovation solution when the objective is to improve the energy efficiency of a building. From another perspective (as discussed in the previous section), many of the barriers in contemporary building renovations are related to use of the building. As such, another way of improving the objectives/criteria can be to update the building occupant's knowledge about renovation and sustainability objectives. Such objectives are usually demanded by governments, or bodies of the governments such as municipalities, to meet some specific goals i.e., promotion of consumption patterns for reduction of the energy.

Based on the above, the authors suggest that the origin of changes in renovation context can be divided into two categories including 1) the changes which need to be applied to the building itself (physical changes and potential application of renovation technologies) and 2) the changes which relate to the building's occupants (to respond to the behavioral barriers). For this discussion

I borrow the concept of *Transformational* and *Incremental* changes from the "organizational change management" domain (McNamara, 2006). The term *Incremental* change might include continuous operational improvement or implementation of a new technical system to increase efficiencies while *Transformational* (or radical, fundamental) change targets changing an organization's culture (the people or society). Similarly for the building renovation context, we can refer to option 1 above as the *Incremental* changes and option 2 as the *Transformational* changes.

However, in renovation context, culture refers to a bigger community than only the occupant of the building. In other words, various stakeholders are involved in this area and act as decision makers in the renovation design process. They all have influence in the process and therefore need to be included and considered as culture for this context. For more clarification, Figure 1.3 illustrate the different stakeholders who are involved in a building renovation process.

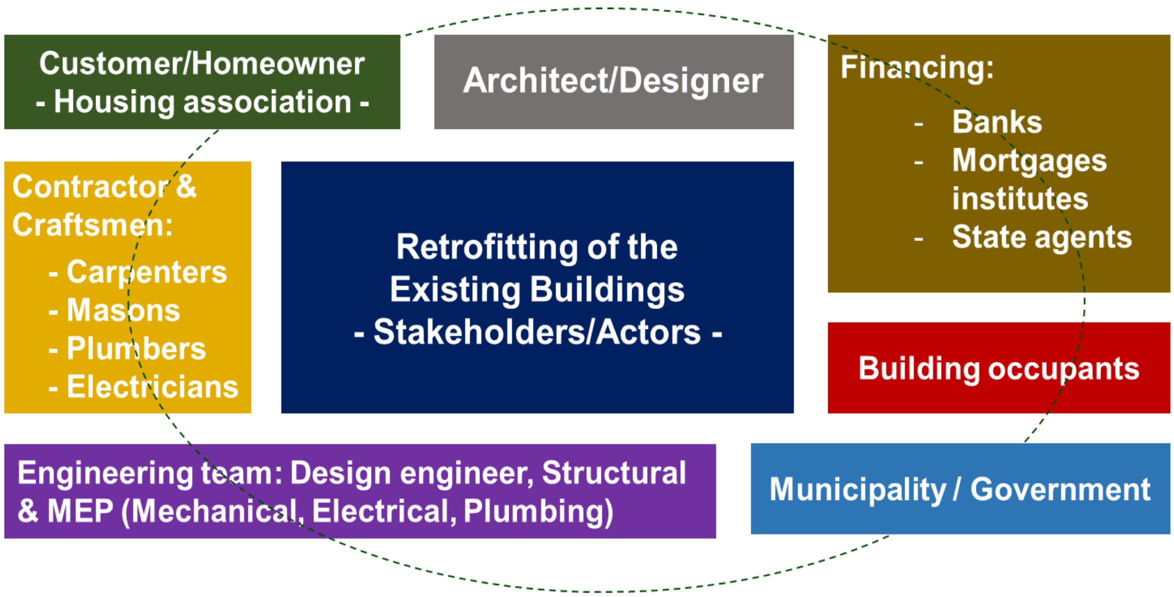


Figure 1.3. The different stakeholders involved in the process of a typical renovation project

Accordingly, in order to achieve a successful building renovation, the requirements are:

> *Cultural (or Transformational)* changes, [which targets society and here refers to enhancement of the awareness, education and inspiration among the 'society' or the community of different stakeholders who are involved in a retrofitting process],
>
> and
>
> *Technological/Physical (or Incremental)* changes, [which targets the physical changes of the building and potential application of new technologies (i.e., insulation of the external walls is a renovation technology/action) which will be applied as part of renovation strategy for the enhancement of the various objectives (i.e. energy efficiency, aesthetic, water efficiency, safety etc.)]. It seems important to be underlined that changes in building technology cannot be Transformation.

Hereafter, the word "*Holism*" has been assigned to this concept that targets the combination of *Transformational (cultural)* and *Incremental (technological/physical)* changes for building renovation. A renovation problem, hence, is considered as a complex system because it cannot be fully addressed, evaluated and enhanced without comprehension of the relationships between its *culture* and *technological/physical* changes. For further clarification about the problem, we lean on the notion of *messy/wicked* problems from the field of social planning. The phrase *wicked problems* (Churchman, 1967) was originally used to demonstrate problems that are difficult to solve, because they address complex social interdependencies (Midgley, 2000). There are at least two attributes of a wicked problem; firstly, it is difficult to formulate solutions, because of the complexity of socio-cultural interactions and interdependencies; this leads to the inability to foretell long-term effects of decisions since the recognition of the source of the problem is highly complicated. Secondly, the definition of objectives due to various circumstances is provisional, and it entails different features, ideas and interests (Estkowski, 2013). Similarly, the characteristics of the problem within the retrofitting discipline involves various types of stakeholders, sustainability criteria (qualitative and quantitative) and selection of potential renovation approaches that vary from case to case. In addition, renovation solutions that work well in one project may be inapplicable in another due to changes in environmental circumstances or in the constellation of stakeholders.

The description above reflects that building renovations make up highly complex problems. As such, there is an identified need to investigate and develop an appropriate holistic methodology, which can deal with both *cultural* and *technological/physical* aspects simultaneously. The methodology should be able to address the wicked nature of renovation problems and improve the awareness and learning about sustainability, sustainable retrofitting and sustainable living among the stakeholders. In addition, it should be able to identify, manage and evaluate the building objectives concentrating on selection of the multiple criteria, which form the basis for generation of renovation scenarios[3]/packages. Nevertheless, a logical question arises: what type of design methodology is most suitable and how can it be developed to deal with the complexity of such problems (?).

1.5. Research Objectives and Aims

As existing buildings are typically only renovated every fifty years, the solutions must be exhaustively thought through, in order to secure future-proof solutions with a long lifetime. To comply with the demands concerning energy savings and to satisfy the need for non-energy objectives in renovation of existing buildings as well as to cope with sustainability in its full sense, it sounds essential to develop a comprehensive approach and a holistic methodology that together form the four main objectives of the present thesis, as following:

a) The thesis, primarily considers building renovation as a complex messy/wicked problem. Later, it gives detail on how combinations of methods that are parts of SSM (Soft Systems Methodologies) and MCDM (Multi Criteria Decision Making Methods) are able to cope with

[3] The term "renovation scenario" used in this study refers to the selection and combination of different renovation approaches (i.e. insulation of the external walls or replacement of the windows are each a renovation action) that together build alternative renovation scenarios/packages and subsequently is applied in a renovation project.

its complexity. It hence develops a methodology, which is entitled *Holistic Multi-methodology for Building Renovation* – HMSR. The HMSR serve as a means to structure retrofitting problems in accordance with the sustainability in its full sense to support the decision-making and help to develop most appropriate retrofitting scenarios. The goal is to promote a 'proactive' multi-methodology, which can help consultancy companies and housing associations, or even municipalities, to deal with the increased complexity and wicked nature of building renovation. Further, it is the aim that the HMSR can address issues related to both cultural changes (subjects to essence of various stakeholders, and above all, behavioral barriers to improve the building occupants' learning about the sustainability and the sustainable living) and technological/physical changes (subjects to physical and/or technological changes to the building to promote sustainability in a holistic sense) for building renovation, simultaneously.

b) It addresses a new simplified holistic sustainability decision-making support framework, which applies to the structures of the built environment for building renovation purpose. It represents the results of research aiming at addressing sustainability of the entire renovation effort including new categories, criteria, and indicators. The developed framework can be applied during different project stages and to assist in the consideration of the sustainability issues through support of decision-making and communication with relevant stakeholders. Early in a project, it can be used to identify key performance criteria, and later to evaluate/compare the pros and cons of retrofitting approaches either during the design stage or upon the project completion. It should be noted that, the framework can be considered not only as an abstract model but a bound method of planning and design as well as evaluation and comparison with retrofitting projects.

c) It investigates development of a Decision Support System - DSS for generation of renovation scenarios with the aims to represent and navigate across existing dependencies between its items. As such, the renovation sustainability objectives/criteria and the renovation approaches are discovered, explored and structured through development of a Domain Mapping Matrix - DMM. A major advantage of the DMM is in its compactness and ability to provide a systematic mapping among the items (represented in rows and columns) that is clear and easy to read regardless of size. It helps to cope with the existing complexity among its items due to the broad number of solutions beside the various objectives/criteria, which need to be met. Developing such a matrix for building renovation can (1) capture the dynamics between the renovation approaches and the sustainability objectives/criteria, (2) show traceability of constraints across objectives/criteria, (3) provide transparency between the mentioned elements, (4) synchronize decisions across the domains, (5) cross-verify domain models, (6) integrate a domain with the rest of the project, and (7) improve decision making among design team, engineers, and other key stakeholders who are involved in the renovation process by providing a basis for communication and learning across domains.

d) It expands a conceptual framework under the topic of TSBD - Tectonic Sustainable Building Design. TSBD seeks for interaction between architecture, sustainability objectives and an equipped design process. It is therefore attached to the *tectonics* (refers to architectural theory), the *sustainability* (refers to the holistic objectives) and a *holistic multi-methodology* -

HMSR (refers to the integrated design methodology). By focusing on TSBD thinking in the field of building renovation, one forms a strategy of establishing a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building. It hence influences the experience of the built environment in human scale. Furthermore, it can serve as a means to unify the platform for renovation strategies for refining and improving the contemporary building industry seen in the light of sustainability, and supporting the decision-making ahead of developing renovation scenarios as holistically as possible. Above all, it provides a clear focus in the design process and a common language among the stakeholders involved that leads to improve the current practice of renovation.

In this sprite, the aims of the research work in this thesis are elaborated as following:

- To explore current conflicts against retrofitting of existing buildings process and rise of complexity in connection with sustainability in its totality.
- To develop a holistic framework and method, which initially can both guide and facilitate architect's work via support of design decision making processes during the conceptual design stages indicating the features, constraints, and classification/leveling upon different criteria. Above all, it can be applied as an assessment and comparison method between different projects either after the design stage is done or after execution is processed.
- To demonstrate of how combinations of methods that are parts of SSM and MCDM may support multiple perspectives representations of complex managerial problems.
- To promote a 'proactive' approach to be synchronized specially upon the nature of retrofitting process in order to improve the communication and collaboration through leaning among stakeholders and carry out a real sustainable retrofitting doing a multi-optimization. It can help consultancy companies and housing associations, or even municipalities, to deal with the increased complexity and wicked nature of building renovation.
- To facilitate designers in their consideration of the benefits and risks concerning different retrofitting approaches during the decision-making processes.
- To provide a conceptual platform which can be develop further as a decision support tool and later be linked to BIM (Building Information Modeling) as an innovative technology today.

1.6. Research Questions

For performing the research objectives in this thesis, there are four research questions, which have been designed in order to structure and develop the research work, systematically. They are as following:

<u>*Research Question 1:*</u> How can a design methodology for sustainable building renovation be developed and equipped via mixing methods so as to deal with the increased complexity and wicked nature of the problem through addressing the issues related to both *cultural* changes and *technological/physical* changes in parallel? Consideration of this question will lead to initially investigate the mechanism of existing methods and methodologies in other domains, which are

capable of dealing with mentioned issues. As such, the research study in this thesis, includes an overview of Engineering Design and Decision-making realms which are used in other domains (i.e. the automotive, business administration and planning domains). [see Chapter 2, Chapter 3, and Chapter 4]

Research Question 2: What are the main holistic objectives/criteria and sub-criteria for a sustainable retrofitting in terms of their specific change requirements? [see Chapter 5]

Research Question 3: What are the major elements for development of a Decision Support System (DSS) to produce holistic renovation scenarios? To answer, this question develops a complete list of renovation approaches in three levels. Next, it expands a Domain Mapping Matrix (DMM) between sustainability renovation criteria and renovation approaches for development of an appropriate Decision Support System (DSS) for generation of renovation scenarios. [see Chapter 6]

Research Question 4: The final question seeks to explore, how can the interaction between architecture, sustainability objectives and an equipped design methodology be addressed through development of a conceptual framework? [see Chapter 7]

It is worth noting that, the thesis will structure the conclusion and the future research work sections, by providing the contribution about investigation of the each mentioned research question, individually.

1.7. Research Hypothesis

There are two main tentative hypotheses that have been formulated in this thesis including:

- The methodologies and method developed to study and manage engineering change complexity in another domains (i.e. Automotive domain, or Aerospace) may have efficient application in renovation/retrofitting context.
- Development of an engineering design methodology based on mix of SSM and MCDM methods can harness their potential to support learning about the problem and more effective decision support in the early design stage of retrofitting projects.

With respect to the above tentative hypotheses, this thesis looks at the mechanisms and patterns of methods and methodologies that operate in refurbishment projects with the aim of identifying commonalities with engineering design. Therefore, the research begins with consideration of Engineering Design Methodologies. In the following, the analysis and expansion of Engineering Design and Decision Making methods for managing and handling the design stage of renovation projects is considered as a key upon the interactions of design dependent variables to involve the different stakeholders (see Figure 1.3) and to embark on sustainability in its full sense for this context.

1.8. Research Strategies and Methods

Any study of architecture is limited to a range of problems and "even the sum of such studies is unlikely to reveal the totality of architecture as it is used, sensed and understood in the everyday environment" (Brawne, 1992). Nonetheless, there are attempts to systematize architectural research strategies and methods (Groat et al., 2013). Most commonly, research in the field of architecture is based on the strategies from the social sciences (Stake, 1995, 2006; Creswell, 2003; Yin, 1994). On the most general level, Creswell (2003) identifies two major groups of research strategies within the social sciences:

- Quantitative strategies (experiments, surveys, etc.)
- Qualitative strategies (case studies, narratives, grounded theory, ethnographies, etc.)

As Creswell (2003) emphasizes, qualitative research is essentially interpretive – the researcher analyses and interprets data, develops descriptions of the processes studied, draws conclusions about the meaning of the phenomena explored, and eventually states the lessons learnt and indicates the further questions to be addressed. In qualitative studies, the phenomena studied are approached holistically – such studies propose broad, panoramic views rather than micro-analyses (Creswell, 2003). According to Creswell, qualitative research may be characterized as 'emergent', in contrast to a strictly prefigured quantitative inquiry. This means that the research questions are often restated in the course of research, as the inquirer gets a better understanding of the research problem. This 'unfolding' character of qualitative research makes difficult a precise definition of methods at the initial stage. Typically, multiple methods and complex reasoning are employed. Especially, the reasoning process may be described as:

- Multifaceted (i.e., both inductive and deductive);
- Iterative (moving back and forth from data collection/analysis to the reformulation of a research problem);
- Simultaneous (consists of collecting, analyzing and discussing data) (Creswell, 2003).

The research strategy employed in this thesis presents characteristics of two research types, namely the qualitative research approach (Groat et al., 2013), and the inter- or transdisciplinary (Repko et al., 2016) research throughout mode 2 (Woyseth et al., 2004). The qualitative approach is characterized by a multi-method in focus, involving an interpretive, naturalistic approach to its subject matter. This means that qualitative researchers study things in their natural settings, attempting to make sense of, or interpret phenomena in terms of the meanings people bring to them (Denzin et al., 1998). The open-ended research questions are begun to form, being re-shaped after more exploration, and changed during the research work to reflect an increased understanding of the problem, which looks appropriate to deal with actual situation in retrofitting context.

Consequently, this study involves interdisciplinary (Repko et al., 2016) features, which emerges from the several challenges corresponding to the concept of *Holism* described in section 1.4. It seems also essential to provide brief description about an interdisciplinary study. Repko et al. (2016) Interdisciplinary studies refers to a diverse and growing academic field with its own literature, curricula, community of scholars, undergraduate majors, and graduate programs. Importantly, it uses a research process designed to produce new knowledge in the form of more comprehensive understandings of complex problems. Interdisciplinarity is able to integrate insight from relevant disciplines. It studies perspective taking involves analyzing the problem from the standpoint or perspective of each interested discipline and identifying their commonalities and differences. Repko et al. (2016) discuss that it is possible to identify key elements that practitioners agree should form the basis of an integrated definition of interdisciplinary studies:

- Interdisciplinary research has a particular substantive focus.
- The focus of interdisciplinary research extends beyond a single disciplinary perspective.
- A distinctive characteristic of interdisciplinary research is that it focuses on a problem or question that is complex.
- Interdisciplinary research is characterized by an identifiable process or mode of inquiry.
- Interdisciplinary research draws explicitly on the disciplines.
- The disciplines provide insights about the specific substantive focus of interdisciplinary research.
- Interdisciplinary research has integration as its goal.
- The objective of the interdisciplinary research process is pragmatic: to produce a cognitive advancement in the form of a new understanding, a new product, or a new meaning.

The authors (Repko et al., 2016) mention that from the above elements, it is possible to offer this integrated definition of interdisciplinary studies:

> “Interdisciplinary studies is a process of answering a question, solving a problem, or addressing a topic that is too broad or complex to be dealt with adequately by a single discipline, and draws on the disciplines with the goal of integrating their insights to construct a more comprehensive understanding.”

This definition includes four core concepts—process, disciplines, integration, and a more comprehensive understanding. Importantly, this definition has both a what and a how component. I found it also interesting to address and distinguish briefly between interdisciplinary studies and multidisciplinary studies. According to Repko et al., (2016):

> “some who are uninformed and outside the field mistakenly believe that interdisciplinarity and multidisciplinarity are synonymous. They are not. Multidisciplinarity refers to the placing side by side of insights from two or more disciplines. For example, this approach may be used in a course that invites instructors from different disciplines to present their perspectives on the course topic in serial fashion but makes no attempt to integrate the insights produced by these perspectives. "Here the relationship between the disciplines is merely one of proximity," explains Joe Moran (2010); "there is no real integration between them" (p. 14). Merely bringing insights from different disciplines together in some way but failing to engage in the additional work of integration is multidisciplinary studies, not interdisciplinary studies.

> Multidisciplinary research "involves more than a single discipline in which each discipline makes a separate contribution.”

Developing a holistic methodology and a new sustainability framework, which fully employs the possibilities of a state-of-the-art “Socio-Technical system for building renovation context”, requires interdisciplinary solutions between architecture and other different domains and thus application of new methods from “Engineering Design Methodologies” to “Operation Research Methods” in order to address different characteristics involve in this context. Building renovation is associated to a high degree with society including integrity and spatial qualities, where intuition, ingenuity and nonverbal imagination play a significant role. At the same time, it requires a very rational and tangible approach, because it creates not only objects of contemplation and reflection but also functional objects constrained by real life requirements (i.e. indoor comfort). Because of its distinctive nature, transdisciplinary research in building renovation should be referred to as mode 2 knowledge production (Woyseth et al., 2004). Although the traditional approach dominates in academic science (particularly in the natural science), mode 2 demonstrates in problem solving oriented research. Scott (1995) and Gibbons (1994) argue that a second fundamental transformation is occurring, leading to the emergence of a new mode of knowledge organization which is taking shape outside of existing academic disciplines and, in part, outside the insularity of the traditional university. This new knowledge has its origins in the synergy and cross-fertilization taking place in the interstices between established disciplines and in the interaction of academic scientists with other knowledge practitioners located in firms, parastatals and civil society, all of whom are participants in the quest for industrial innovation and social renewal. Scott (1995) argues that the key feature of this new form of knowledge production is trans-disciplinarity - which they term mode 2 knowledge. It arises in the interstices of existing disciplines, and therefore is 'generated in the context of application' instead of being developed first and then applied to the context later. As such, mode 2 knowledge has two additional qualities: it is organizationally diverse and heterogeneous. Organizational diversity arises because mode 2 is the outcome of teams of knowledge workers with diverse backgrounds, who in most cases are employed in pursuit of innovation by networking firms - they include academicians, R&D designers, production engineers, skilled craftsmen and social scientists. The networked enterprise, which is the centerpiece of the new global economy, has clearly assisted in the development of a 'networked' mode of knowledge production - mode 2. Table 1.1 represents the characteristics of mode 1 and mode 2 knowledge.

Table 1.1. The characteristics of Mode 1 and Mode 2 knowledge (source: Kraak, 2000)

Mode 1 Disciplinary Knowledge	Mode 2 Problem-Solving Knowledge
Disciplinarily Knowledge is formal and coded according to the canonical rules and procedures of academic disciplines	Trans-disciplinarily Knowledge is problem-oriented; it attempts to salve problems by drawing on multiple disciplines, which interact in the real-world contexts of use and application, yielding solutions and new knowledge, which are not easily reducible to any of the participating academic disciplines.

Homogeneous production sites	Heterogeneous, tanks-institutional production sites
The development of disciplinary knowledge has historically been associated with universities and other institutions of higher education. These institutions often exist in (ivory tower) isolation from real-world problems.	Knowledge is produced in multiple sites by problem-solving teams with members emanating from various institutions: from Higher Education Institutions, networking enterprise R&D laboratories, state S&T (Science & Technology) institutes, and NGO (Non-Governmental Organizations) think tanks. Formal partnerships and joint ventures forged between these actors to generate new knowledge and exploit its commercial potential are common.
Insular knowledge	**Socially useful knowledge**
The only reference points for disciplinary knowledge are academic peers and the canonical rules and procedures internal to the academic discipline.	Many of the problems addressed by trans-disciplinary and trans-institutional knowledge workers today are of great social importance or commercial value. This is socially accountable knowledge.

Further, the authors (Woyseth et al., 2004) characterize mode 2 knowledge production as follows:

> "Mode 2 knowledge is created in broader, transdisciplinary social and economic contexts; in nonhierarchical, heterogeneously organized forma, which are essentially flexible and transient. It involves close interaction of many actors throughout the process of knowledge production, which thereby also becomes more socially accountable and more reflexive."

The above quotation suggests that knowledge reliability in mode 2 is achieved through interaction of many actors and confrontation of many viewpoints. Their opinions contextualize the research content and verify it on different levels. In the field of developing a holistic methodology in retrofitting context (as the main objective of the present study), the validity of the system would be consistent with how useful it is in an organized process in aforesaid context. The proposal here is to address these principles and the role of the system in connection to other studies that have been done so far in order to develop the holistic methodology by using mix of methods (consists of SSM and MCDM *approaches*) and going along an ongoing renovation research project entitled RE-VALUE (see section 1.10). Eventually, the question remains: How knowledge from other disciplines may be fetched together and assembled under a common denominator while keeps the scientific validity and achieve expected relevance. In their discussion over transdisciplinary research Woyseth et al. (2004) underline the practical approach as problem solving oriented forcefully. Researcher's considerations should be concentrated on a problem area, and knowledge should be applied on a temporary basis. In this spirit, the primary challenge in present thesis was to recognize areas and disciplines that effect the formulated research questions fruitfully. The identified areas of knowledge with relevance for the present study are: *sustainability*, *change management*, *decision-making*, *complexity*, *wicked/messy problems*, *culture (attached to the society)*, *operation (attached to the renovation strategies in order to meet sustainability in it full sense)* and ultimately configuring the concept of *Holism* for the building renovation context. In order to deal with these identified areas and in order to develop an equipped design methodology, the research has found a common ground and roots in *Systems Theory and Thinking* (Bertalanffy, 1968; Midgley, 2003), *Operation Research* (Churchman et al., 1957; Hillier et al., 1967), *Critical Systems Thinking* (Flood et al., 1996) which aims to combine systems thinking and participatory methods to address the challenges of problems characterized by large scale, complexity, uncertainty, impermanence, and imperfection (Bammer, 2003: p 1), and *Critical Realism* (Bhaskar et al., 2008; Mingars, 2014) which combines a general philosophy of science (transcendental realism) with a philosophy of social science (critical naturalism) to describe an interface between the natural and social worlds. Ultimately the anticipated areas of knowledge in relevance with the aforementioned context, finds the focus on the basis of the research problems, as they become evident in the development process over the possible outcomes.

With respect to an overall study of process, data collection, analysis and interactions corresponding to the qualitative strategy, current research study tends to be inductive, which means it is more open-ended and exploratory, especially at the beginning. In inductive reasoning, we begin with specific observations and measures, begin to detect patterns and regularities, formulate some tentative hypotheses that we can explore, and finally end up developing some general conclusions or theories (Trochim et al., 2015). It consequently develops a theory or looked for a pattern of meaning on the basis of the data that it has collected [this characteristic will consequently lead to develop the conceptual framework entitled Tectonic Sustainable Building Design in the last chapter (or in section 9) of this thesis]. The theory in this context refers to a contemplative and rational type of abstract or generalizing thinking, or the results of such thinking. This involves a move from the specific to the general and is [informally] called a bottom-up approach. Following this framework, the research work in present thesis would, therefore, be structured and carried out by:

- Research from bibliographic sources,
- Application of SSMs (including rich pictures, CATWOE, PQR),
- Application of VFT (Value Focused Thinking),
- Interview,
- Use of Delphi method,
- Analysis of 10 European renovation research projects,
- Case study (consideration of a recently renovated building).

Following the inductive characteristics of a research study (as stated above), the exploratory part of this thesis has been mostly carried out in the sections 2, 3, and 4. It is also a response to the interdisciplinarity features of the thesis. In the mentioned sections, I have provided a summary of the data (an overview), which I explored for learning purposes corresponding to Renovation/Retrofitting context (as the main focus of the research), and Engineering Design and Decision Making realms (that were included as tentative hypotheses in this thesis). Nevertheless, studying these three developed sections (particularly sections 3 and 4) in this thesis is very useful and helpful for other researches in our domain (Architecture and Architectural Engineering) who wants to expand their knowledge about topics regarding to the “methodology” and “Design methodology” or doing an interdisciplinary research in future; the outcome of these considerations has helped me in development of the different parts of the thesis linking to building renovation, from getting familiar with research methods that I used (such as the applied SSM methods in chapter 5), to deal with the four objectives of the thesis that was mentioned in section 1.6. Particularly, exploring in the sections 2, 3, and 4:

- for objective 'a' of the thesis that mentioned in section 1.6,
  enabled me to deal with methodology, design methodology, design science, scientific design, renovation context etc. and hence development of the main body of HMSR and its introduced methods by mix of SSM and MCDM; and
- for objective 'b' of the thesis that mentioned in section 1.6,
  enabled me to deal with renovation context and get familiar with SSM methods and Delphi study which I applied for the development of the sustainability framework; and
- for objective 'c' of the thesis that mentioned in section 1.6,
  enabled me to deal with renovation context and renovation approaches as well as to get familiar with the computational design synthesis field principles and therefore development of the DMM, which in fact is an active field and area of research in Mechanical Design and thus Engineering Design realm;

It can be highlighted that, several features of the mentioned items distinguish my research work from the work of others, which could be considered both as novelty in our domain (Architecture and Architectural Engineering) and a roadmap for further research in future.

1.8.1. Analysis of 10 European renovation research projects

Part VI of the present thesis contains an analysis of 10 European renovation research projects. It aims to evaluate what and why the recent researches have been established and targeted. It leads to realize about possible gaps regarding their outcomes for the future of the renovation field in practice (see section 9.2). In addition, the part of the analysis focus on systematically development of a comprehensive list of renovation approaches in three levels, which is provided in section 8.4.3.1.

1.8.2. Case study

Part VI of the present thesis contains an analysis of a case study linking to an ongoing project named RE-VALUE. It is a social housing project (including nine building blocks), modernistic in terms of typology and built during 1968/72. It is Section 3 –Skovgårdsparken[4], renovated by Brabrand Housing Association, which is located in 8220 Brabrand, Denmark. The case is included as an example of how a real renovation project is carried toady and b) what people expect about a holistic renovation scenario in real practice of this context (see section 8.4.3.2).

1.9. Significance of the research

The proposed research study in this thesis supports renovation context via development of a method to illustrate, address and evaluate sustainability as well as an integrated equipped design

[4] https://www.bbbo.dk/projekter/skovgaardsparken/

methodology for development of holistic scenarios. Therefore, from one side, designers in early design stages of renovation context will be able to develop and evaluate retrofitting scenarios in terms of their benefits for existing buildings under various objectives/criteria from functionality, feasibility, and accountability or sustainability in its full sense. The use of integrated design methodology, in other side, is to improve the design process for development of renovation scenarios. This affects building occupants and their behavior to promote and improve their learning about the sustainability, the sustainable retrofitting and the sustainable DIY (do-it-yourself). Consultancy companies and housing associations, or even municipalities would then have a methodology and method to deal with the society/community of different stakeholders, and evaluate the implications of design decisions subjected to the different retrofitting approaches towards performing a sustainable retrofitting for existing building projects, holistically.

1.10. RE-VALUE[5] research project

The research study carried out in this thesis has been launched in University of Palermo-Italy and in order to provide broader framework of implementation has been connected to an ongoing research project named RE-VALUE in Aarhus University-Denmark. RE-VALUE (Value Creation by Energy Renovation, Refurbishment and Transformation of the Built Environment, Modelling and Validating of Utility and Architectural Value) is a research project founded by Danish Innovation Foundation. The aim is to make a full-scale demonstration of two renovation projects in areas with different residential compositions, and to study their effects as regards the reduction in energy consumption and the impact on health and well-being. The RE-VALUE project investigates building renovation within *micro* and *macro* scale. The present thesis by focus on *macro* scale has dealt to the overall objective of the RE-VALUE project, which is to establish a more holistic approach to the assessment of value creation in building renovation projects.

1.11. Summary

This section provided details about the major components of the thesis including research topic, state of the art, research objectives and questions, and the research methodology that has been used for carrying it out.

The research study in this thesis is called for an inductive approach. Therefore, the research is expanded through an exploratory approach ahead of investigation of its tentative hypotheses and objectives. To this end, it employs characteristics of two research types, namely the qualitative research approach, and the inter- or transdisciplinary research throughout mode 2, which enables it to move between various disciplines to deal with the multifaceted problem which it has identified in current practice of the renovation context.

The renovation problem in this regard was identified related to necessity of Cultural (or Transformational) changes, [which targets society], and Technological/Physical (or Incremental) changes, [which targets the physical changes of the building and potential application of renovation technologies. The word Holism was assigned for the combination of this spectrum of changes which

[5] Participated by Brabrand Housing Association – with energy renovation in the Aarhus suburb of Gellerup – as well as DEAS, an administration company on the private rental housing market (for more info: http://www.revalue.dk)

needs to be performed in renovation field. To deal with *Holism*, the main objectives and relevant questions that the research should perform have been developed.

There are four main research questions that the thesis has set up in order to follow its structured objectives including:

a) How can a design methodology for sustainable retrofitting be developed and equipped via mixing methods from Engineering Design and Decision-making realms?
b) What are the main holistic objectives/criteria and sub-criteria for a sustainable retrofitting in terms of their specific change requirements?
c) What are the major elements for development of a Decision Support System (DSS) and generate holistic renovation scenarios?
d) How can the interaction between architecture, sustainability objectives and an equipped design methodology be addressed through development of a conceptual framework?

With respect to consideration of the mentioned questions, the thesis develops a multi-methodology and sustainability-supporting framework for implementation and assessment of a holistic building renovation. It consequently provides a theory entitled Tectonic Sustainable Building Design (TSBD) by looking at the pattern of meaning on the basis of the data that it is collecting. This conceptual framework is structured to deal with the different perspectives of the multifaceted problem that was addressed as *Holism* in renovation context.

2. Retrofitting/Renovation of the Existing Buildings

The European Union (EU) has recognized the retrofit of existing building heritage as a priority since it represents one of the most cost-effective solutions to reduce the global warming (EuroACE, 2014). Nevertheless, the available procedural tools are still inadequate. According to Ma et al. (2012), although there is a wide range of retrofit technologies available in the market, it remains a challenge to identify the most appropriate and cost-effective solution for a specific building because of the great number of variables that can widely change from building to building, e.g., climate conditions, user's behavior, policy, financial limitations, services, maintenance, malfunctions. As a result, a discrepancy exists between the building's targeted energy performance and the real one.

Retrofitting of an existing building can oftentimes be more cost-effective than building a new facility (Abdullah, 2016). Since buildings consume a significant amount of energy and because existing buildings comprise the largest segment of the built environment, it is important to initiate energy conservation retrofits to reduce energy consumption and the cost of heating, cooling, and lighting buildings (NIBS [National Institute of Building Sciences], 2015). According to BPIE (2011), deep renovation of buildings could cut 36% of their energy consumption by 2030, while reducing EU energy import dependency, creating growth, innovation and employment, reducing fuel poverty and resulting in more comfortable and healthier buildings. Because the potential for cost-effective energy savings is so high, the buildings sector has become a priority area for the European Union trying to meet its ambitious climate and energy targets for 2020 and 2050 (BPIE, 2011). However, conserving energy is not the only reason for renovation/retrofitting existing buildings. The goal should be to create a high-performance building by applying the integrated, whole-building design process, to the project during the planning or charrette (NIBS, 2016) phase that ensures all key design objectives are embarked on. For example, the integrated project team may discover a single design strategy that will meet multiple design objectives. Doing so, leads building to be less costly to operate, to increase in value, last longer, and contribute to a better, healthier, more comfortable environment for people in which to live and work. Improving indoor environmental quality, decreasing moisture penetration, and reducing mold all will result in improved occupant health and productivity.

Further, when deciding on a retrofit, consider upgrading for accessibility, safety and security at the same time. The unique aspects for retrofit of historic buildings must be given special consideration. According to (NIBS, 2015), designing major renovations and retrofits for existing buildings to include sustainability initiatives will reduce operation costs and environmental impacts, and can increase building adaptability, durability, and resiliency. For this discussion, topics include: necessity for extensive renovation/retrofitting of existing buildings, designing service life of interventions, defining intervention strategies, developing the renovation/retrofitting strategy, discus about the benefits from renovation/retrofitting of the existing buildings, barriers and challenges in retrofitting/renovation context. A more extensive consideration and evaluation in renovation can be obtained from series reports made by BPIE (Buildings Performance Institute Europe), EPBD (Energy Performance of Buildings Directive) and IEA (International Energy Agency).

2.1. Need for extensive renovation/retrofitting of existing buildings

Around 40 % of the total energy consumption today is used in buildings for heating and operating equipment etc. Energy consumption for heating accounts for 35 % of final energy consumption (SBi, 2014). This energy consumption has to be significantly reduced over the next 30–40 years if we are to attain the goal of covering EU's energy supplies in 2050 from renewable energy in a cost-effective way (SBi, 2014). There also needs to be a shift in the energy supply to these buildings from fossil fuels to renewable energy (see Figure 2.1).

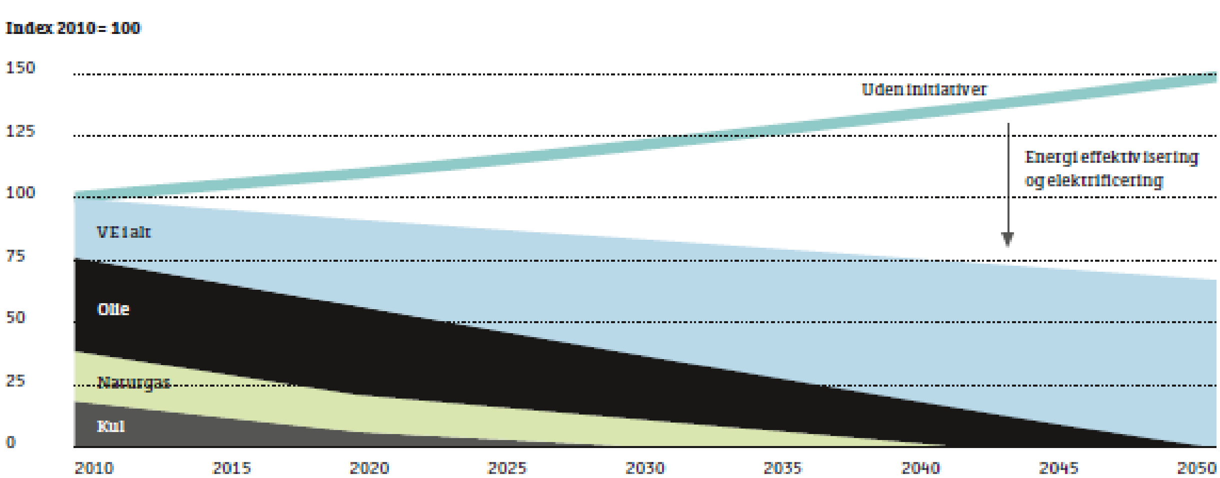


Figure 2.1. Development of energy consumption by 2050 (source: SBi, 2014)

The energy requirements for new buildings have been steadily tightened since the 1970s, and this has meant that new buildings now use much less energy than older ones. With the specified Building Class 2020, which is expected to be mandatory no later than 2020 (BPIE, 2013), European countries should meet the EU requirements for new buildings to have an energy consumption figure close to zero (see Figure 2.2). The potential for further requirements for new buildings is therefore limited.

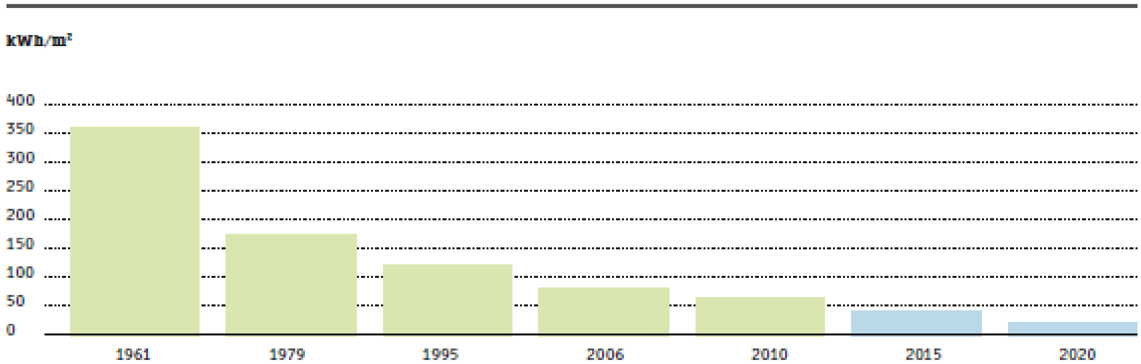


Figure 2.2. Energy consumption for building operations on new buildings (source: SBi, 2014)

A reduction of energy consumption in buildings can only be achieved by substantial energy savings in existing buildings (SBi, 2014). The energy savings can be achieved best and most cost-effectively when the work is done at the same time as the general building renovation. It may for example be combined with replacing the roof or windows or renovating outside walls or floors. The energy savings therefore have to be viewed in conjunction with the ongoing needs for retrofitting work to preserve the value of the buildings. SBi (2014) states that renovation/retrofitting also helps to increase the utility value and quality of buildings, as they can improve the indoor climate and daylight conditions, making the buildings healthier and better to live and work in. Energy renovations also need to take account of the architectural value of the buildings. In many cases, energy renovations will actually mean an architectural improvement to the buildings. Lastly, energy renovation plans need to take account of the environmental objectives for reuse and sustainability in the building industry (SBi, 2014).

2.2. Designing service life of interventions

2.2.1. Age of buildings and level of energy use

Boeri et al. (2015) based on the BPIE (2011), it is useful to group the European countries into three regions for analytic intentions in order to gain more homogeneous families based on climatic conditions, building typology and market similarities (see Table 2.1).

Table 2.1. Countries and Regions considered (source: BPIE, 2011)

North and West Europe	Austria (AT)	Belgium (BE)	Switzerland (CH)
	Germany (DE)	Denmark (DK)	Finland (FI)
	France (FR)	Ireland (IE)	Luxemburg (LU)
	Netherlands (NL)	Norway (NO)	Sweden (SE)
	United Kingdom (UK)		
Central and East Europe	Bulgaria (BG)	Czech Republic (CZ)	Estonia (EE)
	Hungary (HU)	Lithuania (LT)	Latvia (LV)
	Poland (PL)	Romania (RO)	Slovenia (SI)
	Slovakia (SK)		
South Europe	Cyprus (CY)	Greece (GR)	Spain (ES)
	Italy (IT)	Malta (MT)	Portugal (PT)

They mentioned that half of the total computed floor space is placed in the North and West zone, while the remaining 36% and 14% are included in the South and Central and East regions, respectively (Boeri et al., 2015). Building floor area is associated with two popular typologies: single family houses and apartments blocks. As shown in Figure 2.3, the contribution between these two main types alters significantly from country to country.

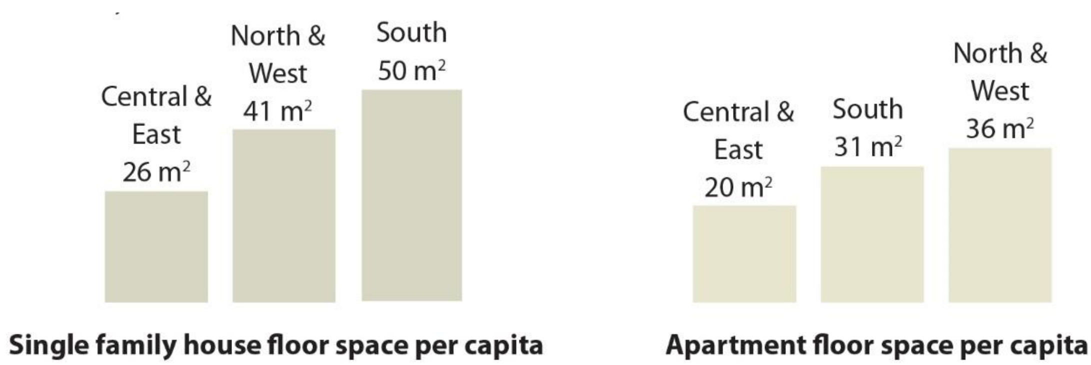


Figure 2.3. House floor space per capita (source: BPIE, 2011)

The present residential stock throughout Europe can be associated with different periods dating mostly from 1950s to 1990s, with some exceptions dating even before 1900s (Boeri et al., 2015).

The BPIE (2011) classify the above-mentioned buildings within different age bands (specific chronological periods) for each country according to:

- Old: typically representing buildings up to 1960
- Modern: typically representing buildings from 1961 to 1990
- Recent: typically representing buildings from 1991 to 2010

Figure 2.4 demonstrates the age categorization of housing stock in Europe. In addition, Figure 2.5 illustrates the energy mix in residential buildings by region.

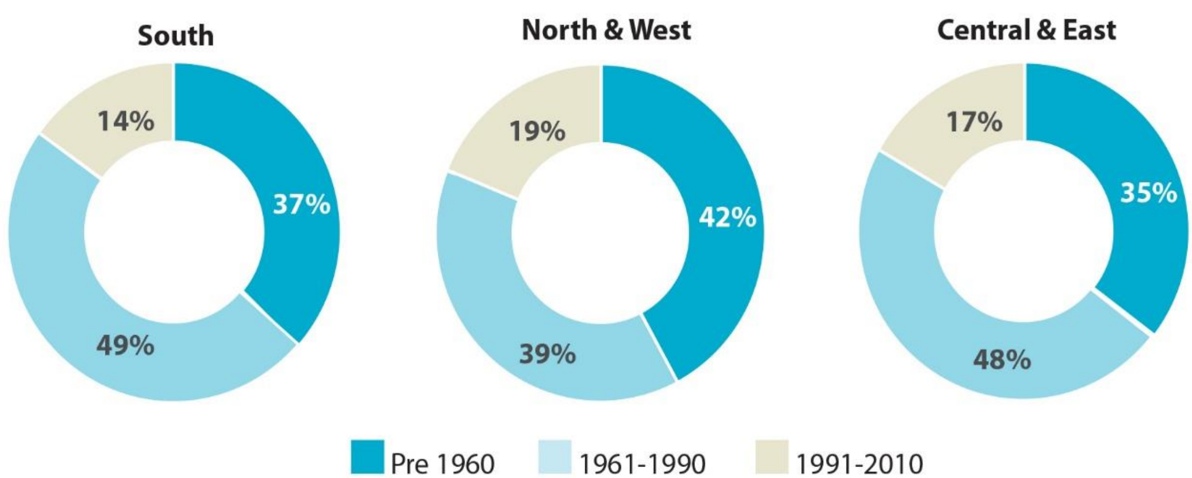


Figure 2.4. Age categorization of housing stock in Europe (source: BPIE, 2011)

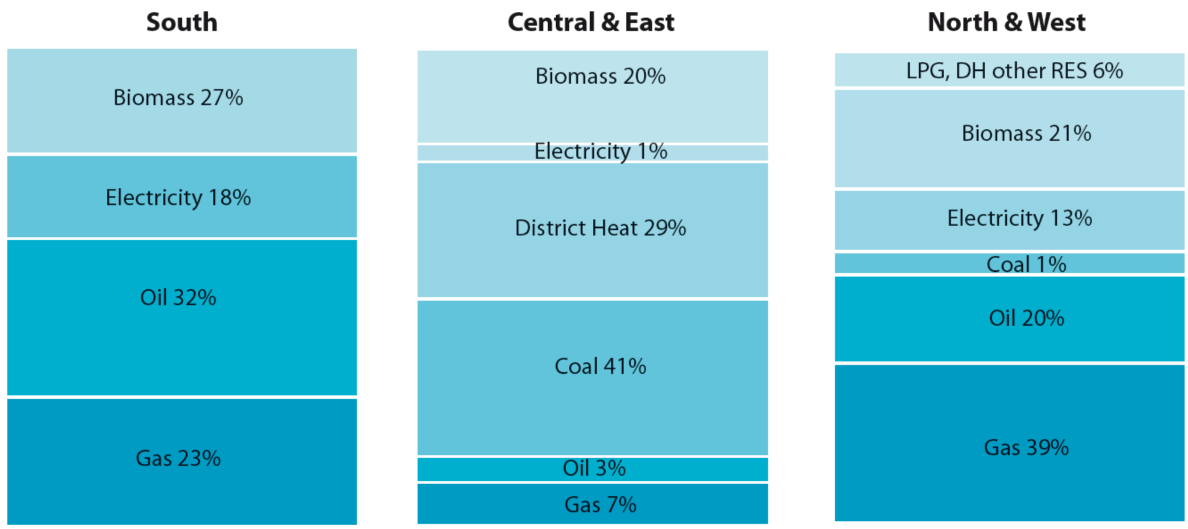


Figure 2.5. The energy mix in residential buildings by region (source: BPIE, 2011)

2.2.2. Obsolescence phenomena and influence of new requirements on expected performance level

Boeri et al. (2015) discuss that the ageing of a building is usually correlated with its physiological obsolescence that can be described as the natural loss of performance of a system or a part of it. Obsolescence phenomena produce a general decrease in the capability of the system (building) of meeting the initial requirements for which it was built.

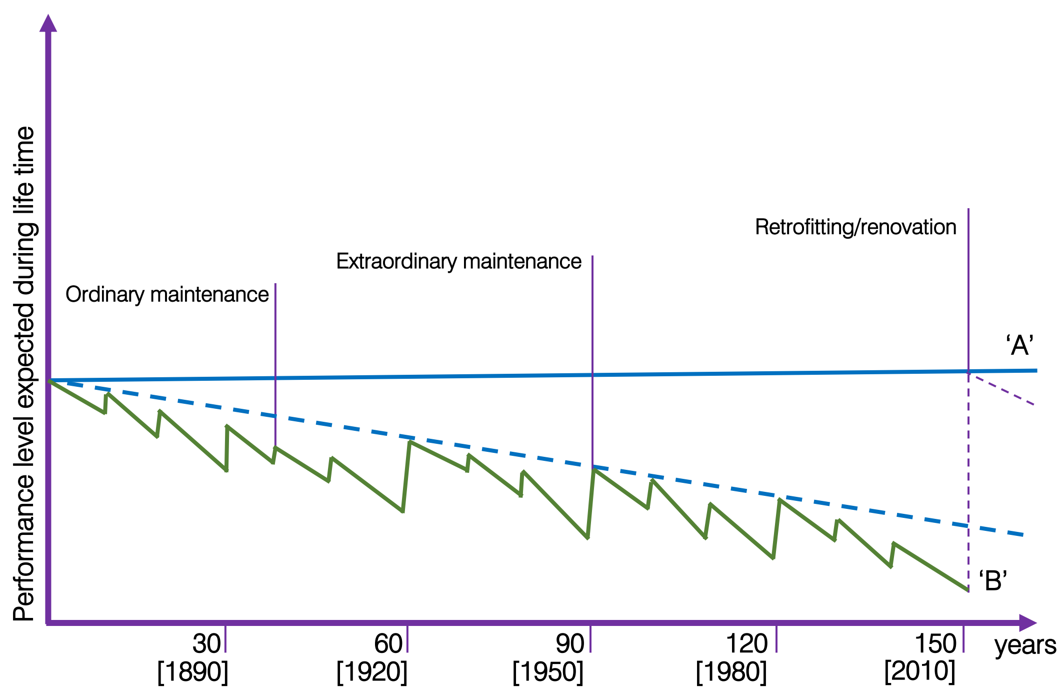


Figure 2.6. Obsolescence phenomena and influence on performance level in "old age band" (source: Boeri et al., 2015)

The authors (Boeri et al., 2015) state that if an "old age band" building is considered, it is feasible to estimate its lifespan in a range between 120 and 150 years, that is until 2010 if assuming a construction date from 1850s to 1900s (which is a very realistic circumstance in many European cities). This means that the building experienced multiple ordinary and extraordinary maintenance interventions involving, at least more than once, the replacement of windows and glazing, the refurbishment of the roof and/or the facade, the substitution of equipment and so on (Boeri et al., 2015). All these actions were targeted at covering the gap produced by its physiological obsolescence, as shown in Figure 2.6.

Straight line "A" in the graph demonstrates the theoretical performance level of the system (building) at construction date, while dotted line "B" describes the loss of performance and the corresponding ordinary and extraordinary maintenance actions (vertical segments) opposing it.

Boeri et al. (2015) argue that if a "modern age band" building is adjudged, no more than 50 years of lifespan are involved in this kind of process. However, a number of ordinary and extraordinary maintenance tasks are equally essential to deal with the deficits affecting the building.

Figure 2.7 shows that in this case the considered period of time of 50 years is one-third of the one considered for "old age band" buildings, and even if there is a general lower number of interventions, these last ones show an increase in proportion to the considered period of time (Boeri et al., 2015). This means that while in the first place interventions followed cycles of about 30 years, in the second instance they occurred more or less every 15 years.

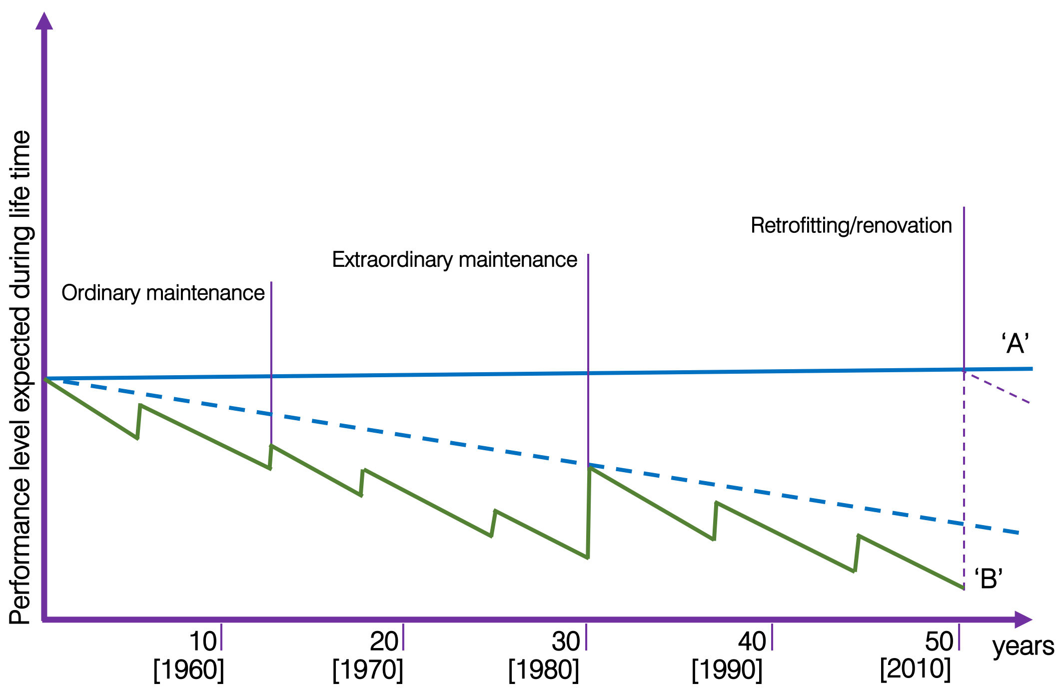


Figure 2.7. Obsolescence phenomena and influence on performance level in "modern age band" (source: Boeri et al., 2015)

Figure 2.8 demonstrates how the envisaged performance level moved from the potential original level represented by line "A" to a new curve called "C", indicating the trend of the requirements evolution (and, as a consequence, of the expected performance level) which cannot be demonstrated as a linear trend but rather as an exponential one(Boeri et al., 2015).

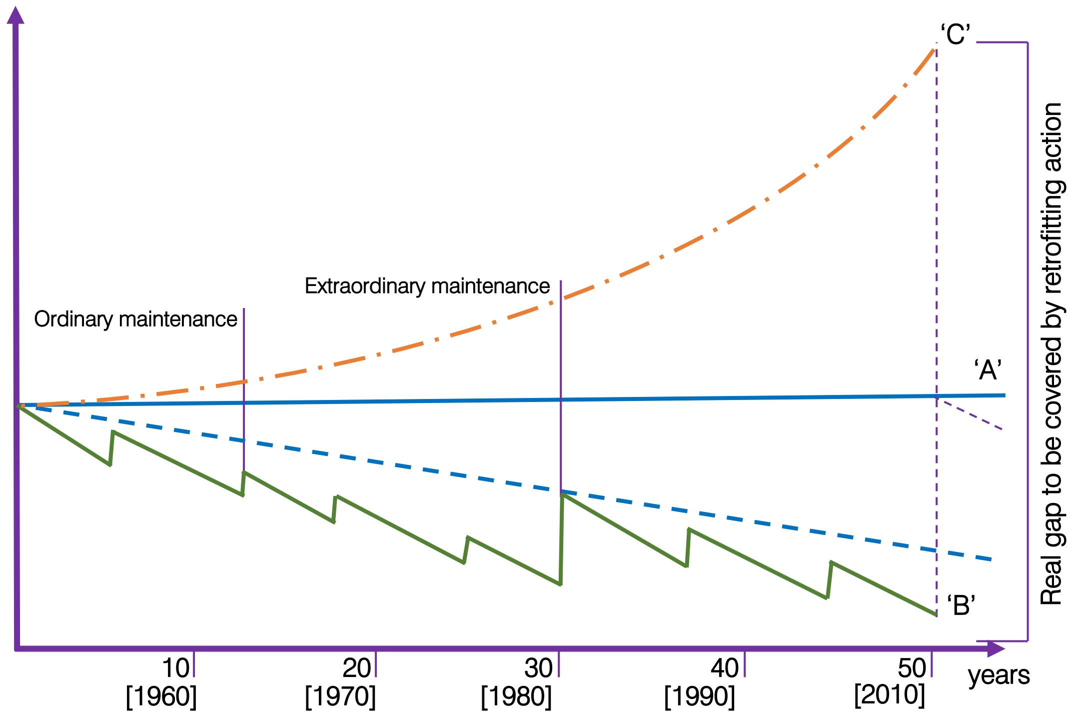


Figure 2.8. Trend of requirements and influence on expected performance level (source: Boeri et al., 2015)

Boeri et al. (2015) conclude that as an outcome, the renovation action has to provide a very high improvement in the level of performance and of course, this usually demands a much higher investment of resources, energy and a lot of endeavors. A balanced design approach is therefore essential in order to reach the expected outcomes combined to acceptable payback times. Hence, defining the expected lifespan of the renovated building is a key factor in the development of any renovation/retrofitting approach. To this end, the authors (Boeri et al., 2015), based upon following a long description, have suggested that the expected average lifespan constructed by renovation interventions seems logical to be set in 30 years.

2.3. Defining Intervention Strategies

2.3.1. Levels of Interventions

According to Boeri et al. (2015) the intervention strategies can be divided in three distinct scales:

1) The first one refers to the urban fabric and it deals with the effects the renovation process produces(methods) — involving one or more neighborhood/adjacency or sites — on the form of the city, the correlation between public and private regions and areas, on the quality of the built environment and so on (see Figure 2.9). The authors mention that a renovation process at urban scale is usually directed at increasing the quality of the built environment by operating on the buildings, on the voids between them, on interactions and connections to model the site or the neighborhood through an introduction of new volumes, the demolishment or extension of part of the existing buildings and obtain a more effective design of the space (see Figure 2.9) as well as increasing the general performance level of the involved buildings.

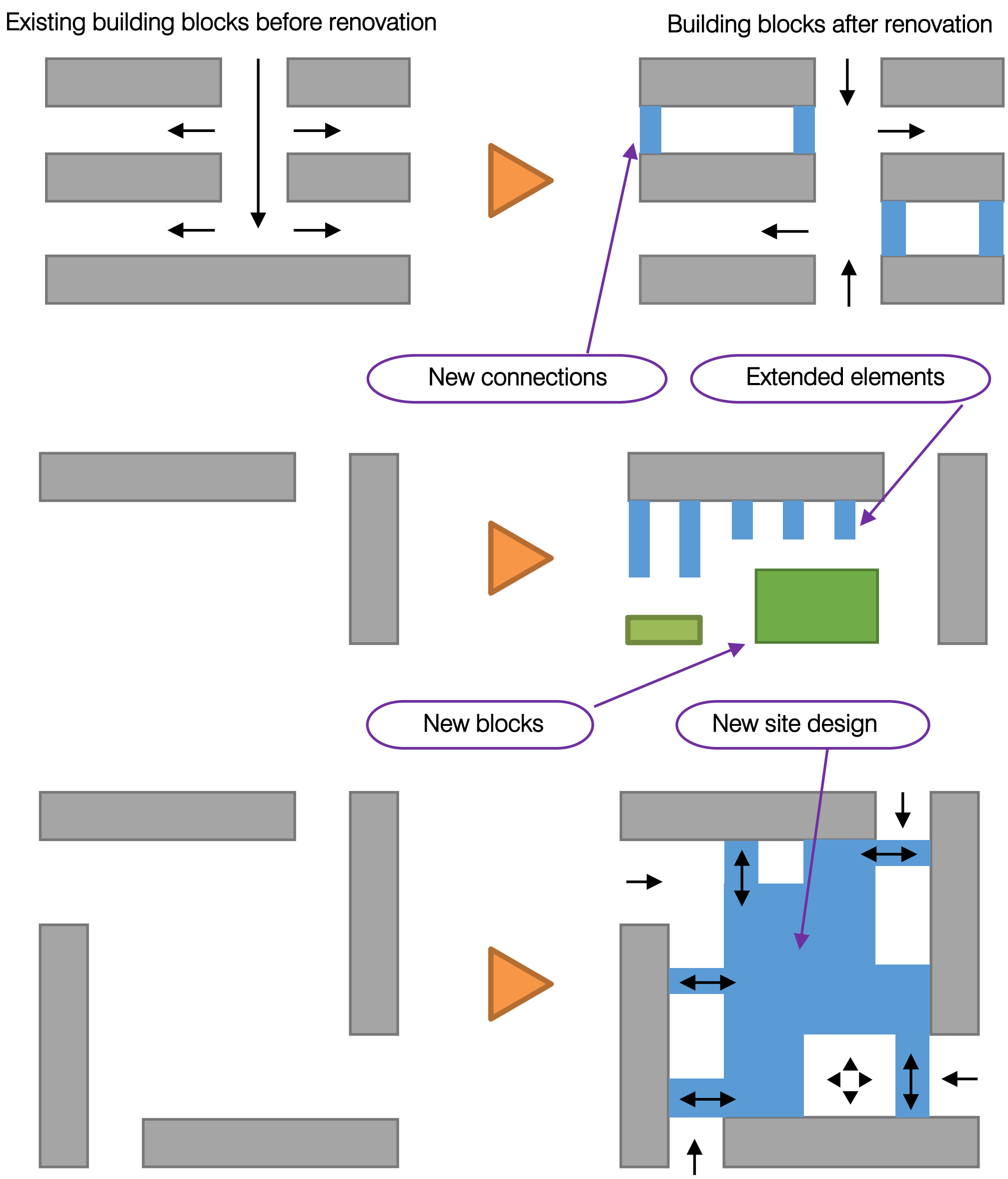


Figure 2.9. Effects of renovation actions as urban scale (according to Boeri et al., 2015)

2) The second one refers to the building itself and it deals with the renovation/retrofitting proceeding pursued according to very particular conditions which depend on the building's pathologies, the requirements to be faced, the level of performance to be accomplished and so on (see Figure 2.10). The authors mention that the design concept is generally based on the idea of reducing interventions inside the units dedicating most of the resources to the building envelope and to the technical core that can be placed inside the apartment or included in the volumetric extension, where foreseen. Following this approach, the size of the units can also be redefined as well as the vertical connections (see Figure 2.10) and the general view of the building. The introduction of new lodges or buffer zones or of additional floors allows to obtain a different cut and dimension of the units (simplex or duplex).

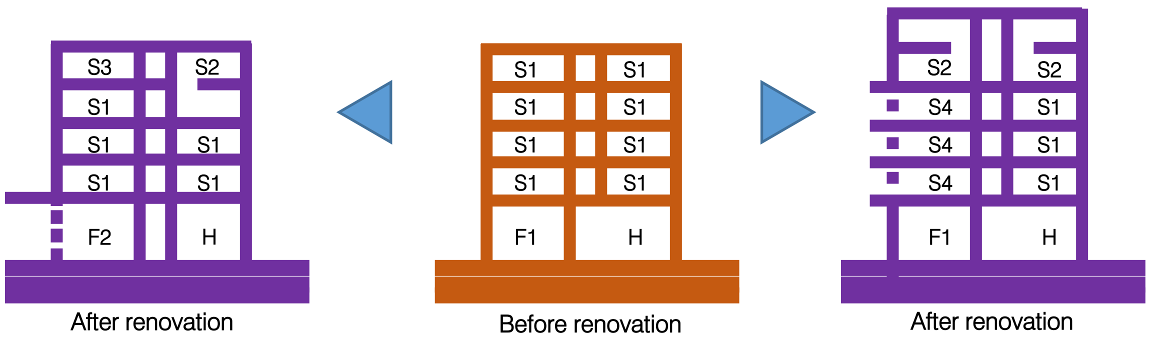


Figure 2.10. Effects of renovation actions at building scale (according to Boeri et al., 2015)

3) The third scale refers to the unit and it deals with the alternations entailed by the households in order to meet their preferences or their requirements. This multi-scale approach is typical for big buildings or multi-family housing complexes, while in the case of single-family houses the third scale level tends to be included in the second one (see Figure 2.11). The authors state that this leads to maximize the effectiveness of the new parts reducing the actions needed to rearrange the distribution of the unit itself providing a series of benefits regarding not only the thermal and energy behavior, but also the comfort conditions and the availability of new equipment and spaces like a second bathroom, a larger room or a new balcony or terrace (see Figure 2.10).

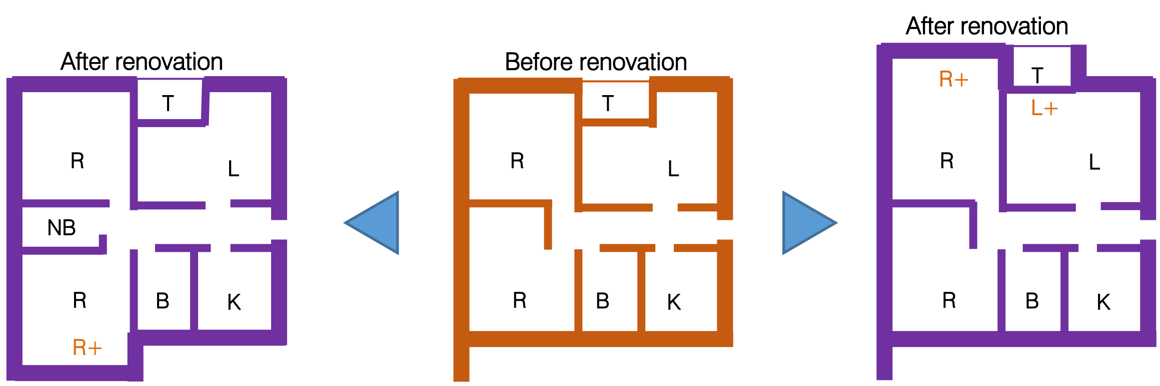


Figure 2.11. Effects of renovation actions as apartment scale
L – living room, K – kitchen, R – room, + extended room, B – bathroom, N – new and T - terrace
(according to Boeri et al., 2015)

2.3.2. Renovation/retrofitting approaches

Boeri et al. (2015) in their book address four main types of renovation approaches. The authors state that the primary and most recurring approach — typically pursued in minor renovations —is the one that contains a replacement of existing elements or their integration with new components aimed at modifying the existing conditions and ensuring a superior level of performances and functionalities. This replacement/integration approach can run on a finite number of elements, such as windows, or on extended surfaces, such as part of the facade or of the floor slab, depending on the pathologies discovered and on the main aims of the refurbishment action (see Figure 2.12).

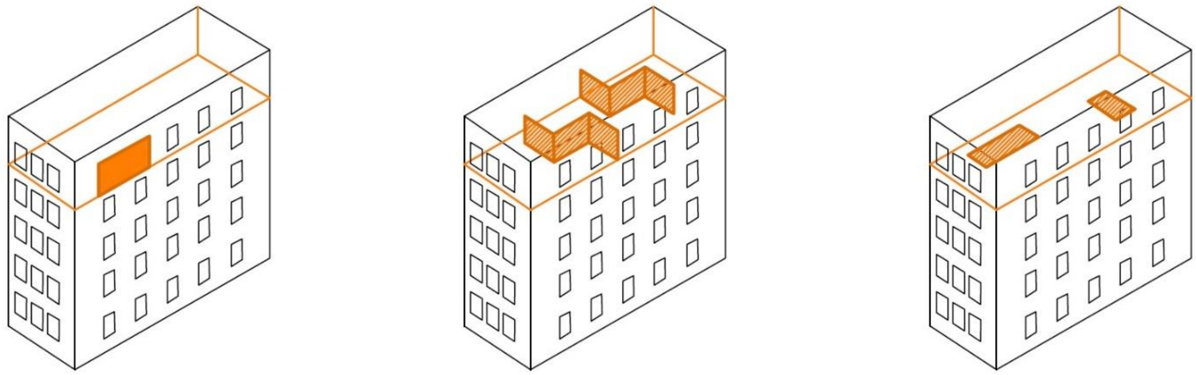


Figure 2.12. Models of minor interventions belonging to replacement/integration approach (according to Boeri et al., 2015)

The second approach introduced by Boeri et al. (2015) — called of the box in the box — was expanded to be usually adopted in historical buildings where the opportunity to operate on the existing elements is very limited. As its explanation suggests, this approach operates presenting one or more independent volumes inside an existing building that act as a box, as shown in Figure 2.13. This recent volume is usually a self-bearing structure with its own geometry, form, characteristics and features, allowing it to be distinguished from the original elements of the building.

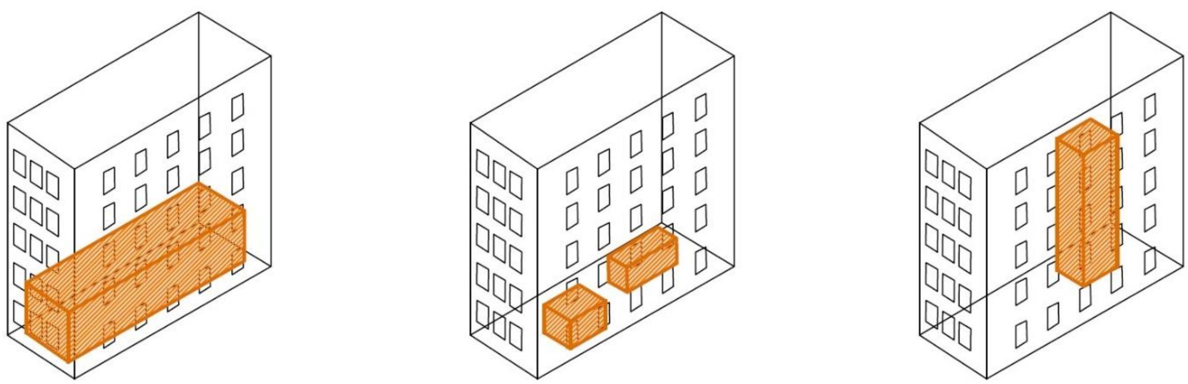


Figure 2.13. Models of box in the box approach (according to Boeri et al., 2015)

The authors from Boeri et al. (2015) addressed that the third approach is generally adopted in significant/deep renovation projects and it is mainly considered as a building envelope implementation. Basically, the concept is to wrap up the building in a new envelope, this can take the form of a cladding, of a double glazed façade or simply of a new insulation substrates. This approach tends to involve the largest part of the building as its target is mainly to improve the thermal situation of the system as a whole and accordingly to increase its energy efficiency. Inherently, this intervention can be reduced to a single facade or to a division of the building, however reducing its effectiveness (see Figure 2.14).

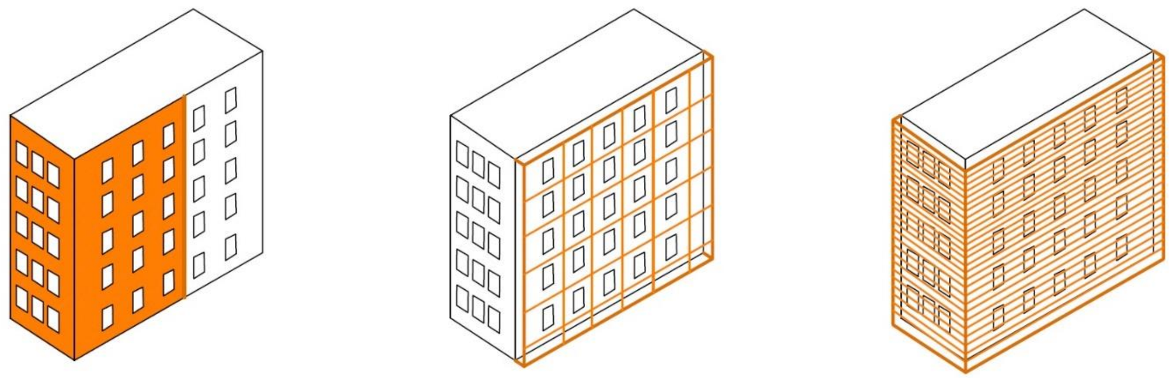


Figure 2.14. Models of building envelope implementation (according to Boeri et al., 2015)

The fourth and the last approach Boeri et al. (2015) concerns models of volumetric additions. It results depend on the additions dimensions and layout with respect to the original geometry and features of the existing building envelope and form. As Figure 2.15 shows, volumetric additions can be expanded to a façade of a building or can be limited to independent boxes, or they can involve the rooftop of the existing volume. These elements can function as lodges, balconies and greenhouses or they can be operate as housing new services and connections or simply for extending the existing rooms of the units. At the same time, they can also act as thermal buffers — especially to regulate the building envelope behavior according to climate conditions and winter/summer or night/day cycles — and they can be used for housing new instruments and devices for heating and cooling. This approach is usually applied in major renovations and needs several preliminary analyses in order to assess the ability of the existing building to support or interact with the new volumes.

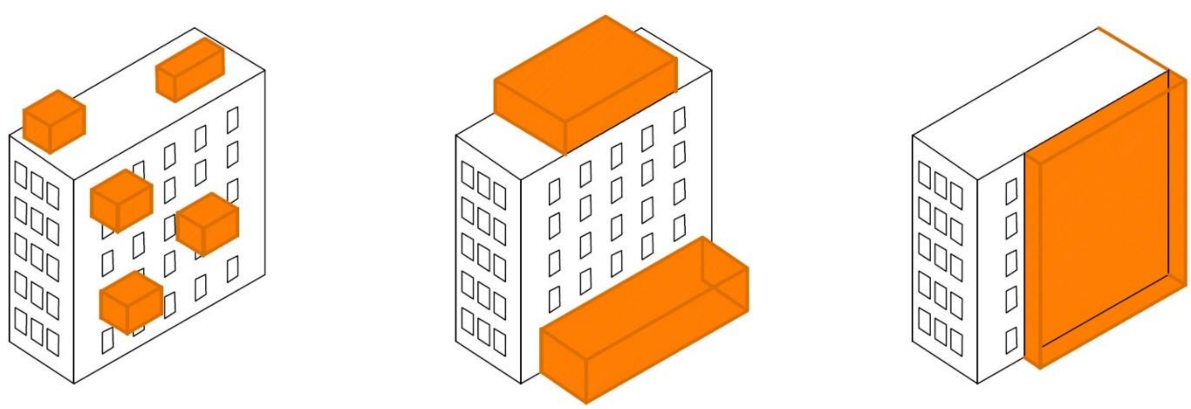


Figure 2.15. Models of volumetric additions (according to Boeri et al., 2015)

2.3.3. A step-by-step design approach

In order to analyze and compare the effects of the described approaches above (or by a mix of them), Boeri et al. (2015) have developed a methodological approach to renovation design in different steps. Each step provides a different degree of renovation depth (from lower to higher) and relevant impacts on the energy efficiency of the building as well as on its general level of quality (comfort conditions, distribution, functions, equipment, etc.). This methodology targets on obtaining a prognostication of the energy performance level reached after each stage in relation to the technological solution adopted — which are assumed as variable — based on a defined lifespan of 30 years. The authors (Boeri et al., 2015) state that this anticipated operational lifetime follows the projection of roadmap to 2050 and it is needed in order to evaluate the payback time of the renovation action and the required cost investment. When the general concept of the intervention is defined, the design phase is developed by following the steps summarized in Table 2.2.

Table 2.2. Structure of the step-by-step methodology (source: Boeri et al., 2015)

Step No.	Renovation approaches
S1	Replacement of existing windows
S1b (depending on starting conditions)	Integration or replacement of existing equipment, heating/cooling system
S1c (optional)	Integration of PV and solar collectors on the roof
S2	Building envelope implementation of roof and partially of facades to avoid thermal bridges.
S3	Total building envelope implementation
S4 (S1 + S2)	Replacement of existing windows, total building envelope implementation (optional integration or replacement of existing equipment, heating/cooling system)
S4b (optional)	Integration of PV and solar collectors on the roof/facades
S5	Volumetric additions, partial replacement of existing windows, partial building envelope implementation (optional integration or replacement of existing equipment, heating/cooling system)
S5b (optional)	Integration of PV and solar collectors on the roof/facades

The depth of renovation varies based on the different steps (S1 to S5 in the above) adopted, where the first ones focuses on limiting the deficits affecting the building and amending its performance as an outcome of reducing dispersions and avoiding thermal bridges, while the consecutive steps are aimed at enhancing the level of energy efficiency by modifying or implementing the building envelope (increasing U-value, providing insulation and/or an integration of active and passive solar systems).

2.4. Developing the renovation/retrofitting strategies

BPIE (2013) has addressed the key steps in the development of retrofitting strategies. They have been divided into 5 phases including: a) Identifying Key Stakeholders & Information Sources b) Technical & Economic Appraisal c) Policy Appraisal d) Drafting & Consulting on the Renovation Strategy e) Publication & Delivery. Figure 2.16 illustrates the main phases including the key steps within each phase.

Figure 2.16. Simplified process flow chart for strategy development (source: BPIE, 2011)

BPIE (2013) has also provided an indicative timescale concerning each phase. Clearly, circumstances will vary from country to country, and it is realistic to undertake certain phases simultaneously. BPIE believes it could take up to a year for Member States to develop their first renovation strategies, as indicated in Table 2.3.

Table 2.3. Indicative timeline for building renovation strategy development (source: BPIE, 2013)

Month	1	2	3	4	5	6	7	8	9	10	11	12	year2+
PHASE 1 - Identify key stakeholders & information sources	■	■											
PHASE 2 - Technical and economic appraisal		■	■	■	■	■	■						
PHASE 3 - Policy appraisal		■	■	■	■	■	■						
PHASE 4 - Drafting & consultation						■	■	■	■	■			
PHASE 5a - Finalisation & publication											■	■	
PHASE 5b - Delivery													Ongoing thereafter

2.5. Benefits from renovation/retrofitting of the existing buildings

Before outlining the renovation/retrofitting challenges, it is instructive to consider the wider impacts and benefits that can be achieved as a result of building stock renovation. When undertaking an economic appraisal of an energy saving investment for a building, the only benefit that is normally monetized by the potential investor is the energy cost saving, yet doing so undervalues the full impact (BPIE, 2013). However, many benefits accrue to society at large and hence are not valued by individual investors. Broadly speaking, the impacts of undertaking sustainable renovation of the existing buildings by BPIE (2013) summarized into a) Energy System Benefits, b) Environmental Benefits, c) Societal Benefits, and d) Economic Benefits.

2.5.1. Energy system benefits

Energy security

Reducing energy demand as a key component of energy security is acknowledged in "A Strategy for Competitive, Sustainable and Secure Energy" published by the European Commission, where top priority is ascribed to achieving the biggest energy saving potentials, namely in buildings and transport.

Avoided new generation capacity

According to Commission estimates, achieving the 20% energy efficiency target would avoid the construction of the equivalent of 1000 coal fired power stations [Assuming each power station has a 600 MW capacity, operating 7000 hours/a] or 500,000 wind turbine installations [Assuming each turbine has a 4MW capacity, operating 2300 hours/a].

Reduced peak loads

Energy demand reduction measures save a disproportionate amount at times of high demand (through reduced winter heating and summer cooling). By avoiding use of the most expensive generation capacity which is required to meet peak demands, and also lowering the load, and hence the losses, in the transmission and distribution systems, all electricity users benefit from reduced system operation costs.

2.5.2. Environmental benefits

Carbon saving

The importance of the building sector in achieving carbon savings is amply illustrated by the analysis of BPIE (2013) based on the Intergovernmental Panel on Climate Change (IPCC), as presented in Figure 2.17. In all world regions, and at all carbon prices up to at least US$100/tonne of CO2 equivalent, buildings hold the greatest potential for cost effective carbon emission reductions.

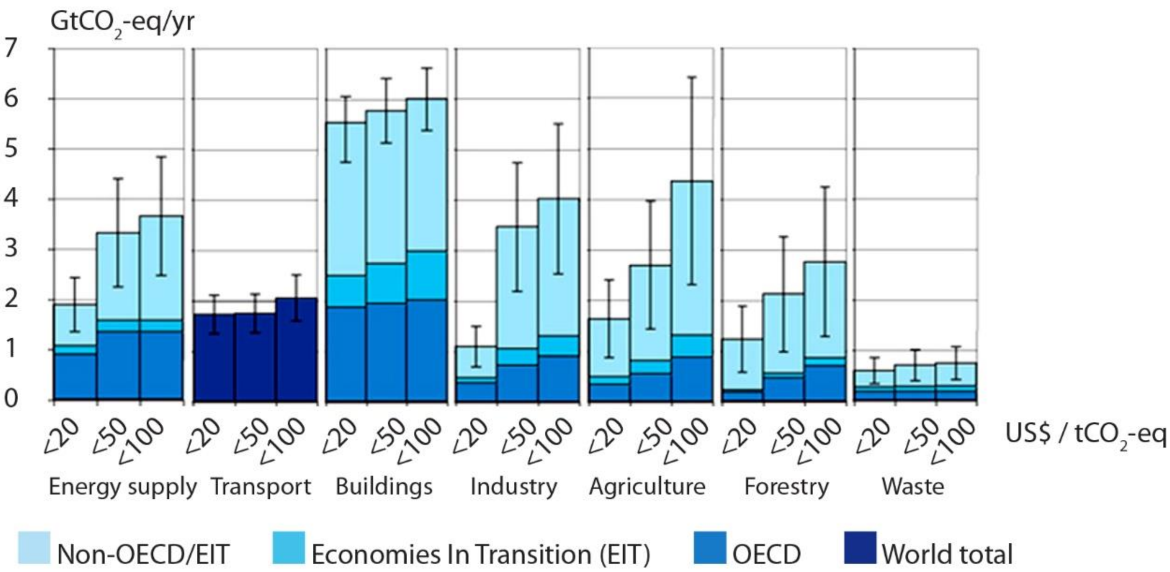


Figure 2.17. Comparison of cost effective CO2 reduction potential in 2030 by sector, at different carbon prices (source: BPIE, 2013)

Reduced air pollution

By reducing the need for energy production from fossil fuels, there is a reduction in the amount of pollutants such as SO2 , NOx and particulates that are damaging to health, to buildings and the environment.

2.5.3. Societal benefits

Reduced fuel poverty

Between 50 million and 125 million people in Europe (10- 25% of the total EU population) are estimated to be fuel poor, according to the European Fuel Poverty and Energy Efficiency study. Deep renovation can provide the means whereby homes are “fuel poverty proofed” as a result of the affordability of the very low energy bills that arise after such a renovation.

Health

Closely allied to reducing fuel poverty are the health benefits from warmer homes with fewer cold spots & draughts, less condensation/mould and improved indoor air quality. BPIE (2013) based on Copenhagen Economics estimate that the health benefits from energy retrofits could be worth more than the value of the saving in energy costs (see Figure 2.18). However, they acknowledge that the value of the health benefits is subject to considerable uncertainty.

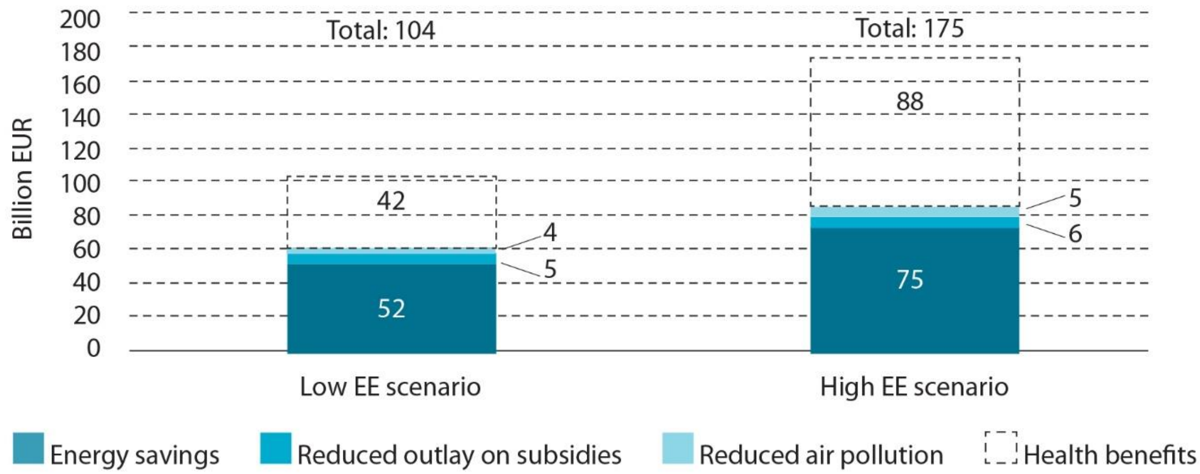


Figure 2.18. Annual gross benefits to society from energy efficient renovation of buildings (2020) (source: BPIE, 2013)

Increased comfort and productivity

Whilst those in fuel poverty are likely to witness the greatest improvement in terms of increased comfort, building occupants across the spectrum can benefit from homes and workplaces that are easier to maintain at comfortable temperatures, avoiding both overheating in summer as well as under heating in winter as a result of thermal renovation. It is well established that a better working environment leads to increased productivity (BPIE, 2013).

2.5.4. Economic benefits

Energy cost saving

For individual households, current energy bills typically range between €1000-1800 per annum, equivalent to around 1 month of median annual income, as represented in Figure 2.19. The increased disposable income that is generated through reduced expenditure on energy utilities leads to increased expenditure on other goods and services, producing economy-wide benefits.

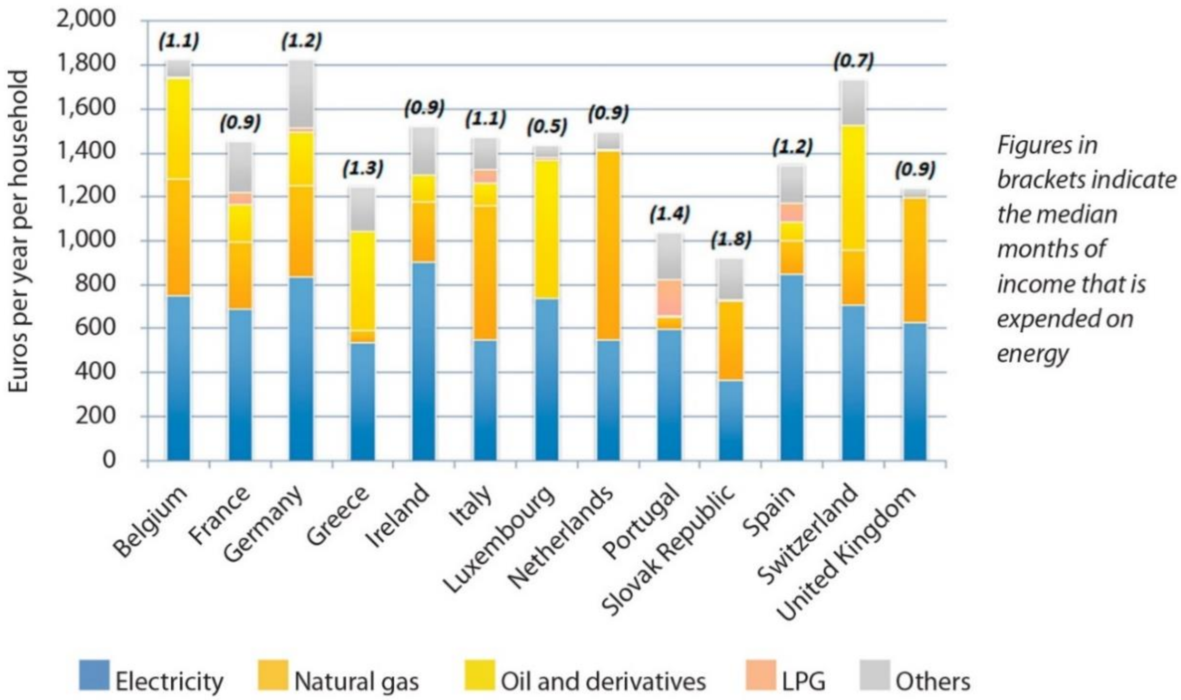


Figure 2.19. Annual household energy spend in selected countries (source: BPIE, 2013)

Economic stimulus

The employment and economic impact stimulated by investing in a more sustainable building stock can be seen across a wide range of players in the value chain, from manufacturing and installation through to provision of professional services such as financing and project management, as illustrated in Figure 2.20.

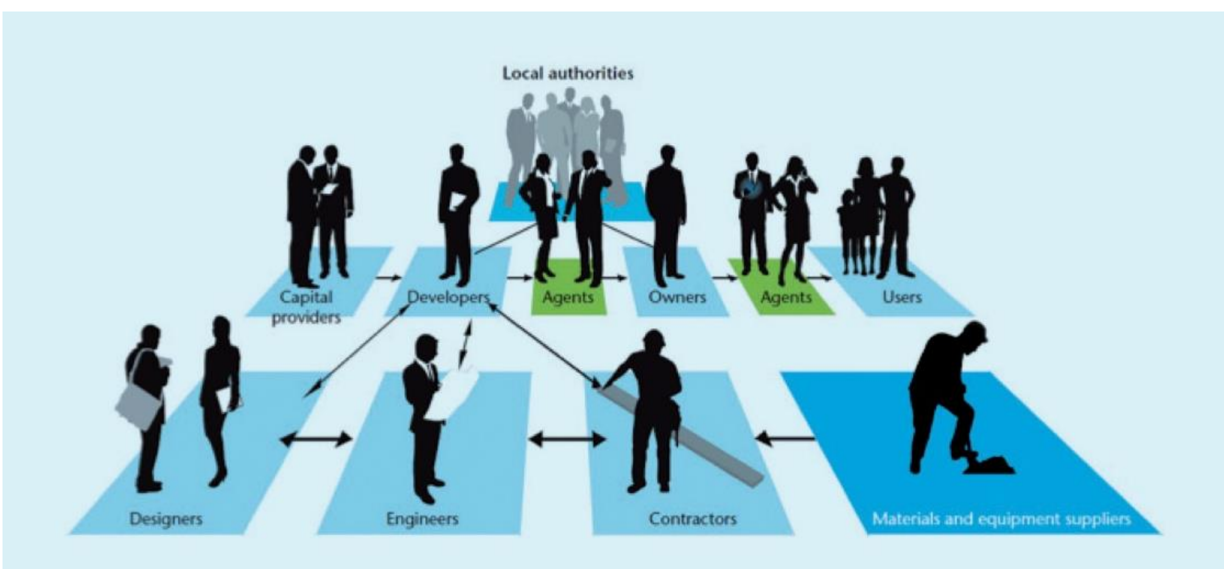


Figure 2.20. Schematic of building renovation value chain (source: BPIE, 2013)

Impact on Gross Domestic Product (GDP)

BPIE (2013) based on the Commission's EED impact assessment identified that achieving the targeted savings would result in an increase in the EU's GDP of €33.8 bn in 2020 (+2.7% compared to baseline).

Property values.

There is an emerging body of evidence that buildings with high energy performance are more valuable (in terms of resale, the rent they can command and/or in terms of occupancy levels) than their less efficient counterparts.

R&D, industrial competitiveness & export growth.

By creating the drive towards ever more efficient ways to reduce energy consumption in buildings, a major program of building renovation will spur research & development, leading to improved industrial competitiveness and export opportunities.

Impact on public finances.

According to BPIE (2013) based on a Copenhagen Economics report commissioned by Renovate Europe, investment in building retrofits, given prevailing high levels of unemployment in many Member States, will have a positive impact on public budgets, equivalent to 0.5-1.0% of GDP.

Energy import bill.

With virtually all Member States being reliant on energy imports to satisfy demand (see Figure 2.21) BPIE (2013) reported that the energy savings achieved through renovation/retrofitting will have a positive impact on a nation's balance of payments. The EU already imports the majority of its energy needs, at a cost of €355 bn annually. According to the latest IEA projections in World Energy Outlook (2012) this import dependency for both oil and gas is projected to increase substantially over the coming years.

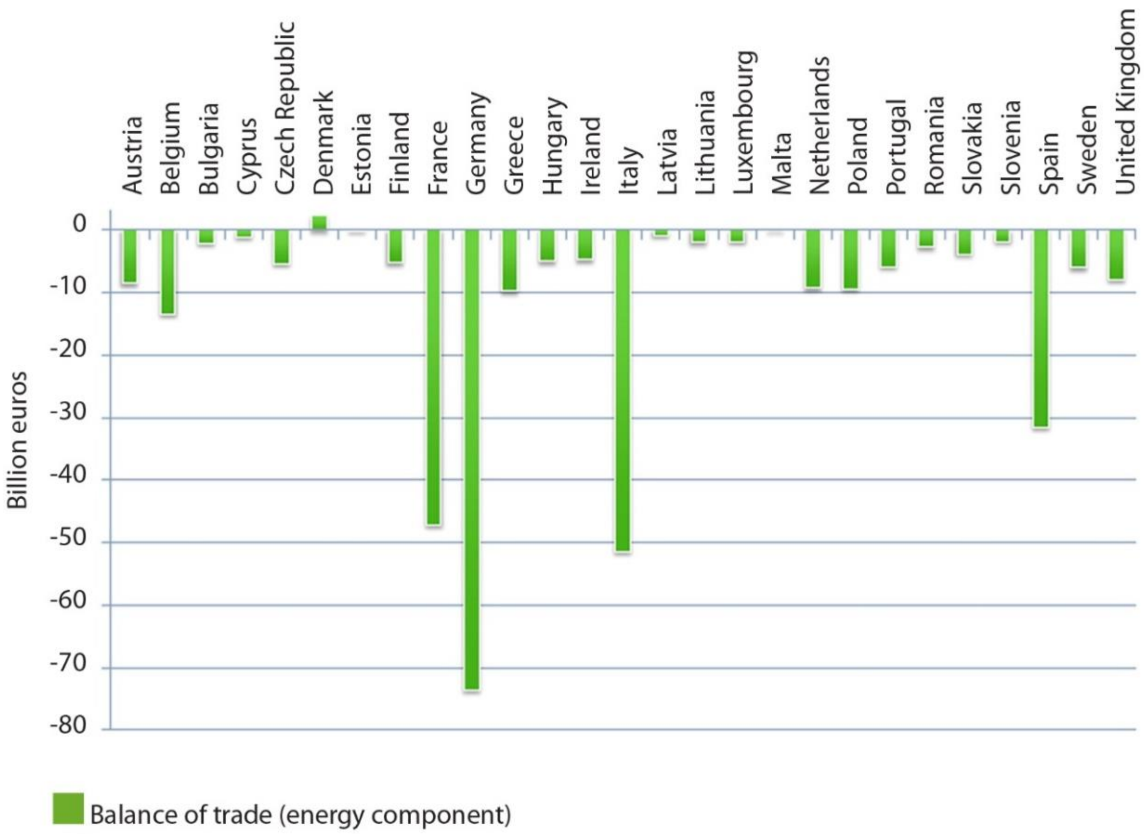


Figure 2.21. Energy bill import dependency in 25 EU Member States (source: BPIE, 2013)

In summary about benefits:

The above discussion identifies the wide array of benefits that can be achieved as a result of renovating buildings to higher energy performance standards. Some are tangible and readily quantifiable, while others are less so and may be difficult to assign a monetary value, like the social cohesion and sense of civic pride that comes with the renovation of an apartment block or a district, which has undergone regeneration. In summary then according to SBi (2014):

- Retrofitting of existing buildings has generally positive effects for the individual building owner and user, and for society as well.
- Renovation/retrofitting in some way means a reduction in future energy bills. There will be some initial costs associated with the renovation, but renovation can subsequently create a more robust financial position for the building owner and may increase the resale value of the building. Improving the financial position of building owners can also have positive benefits for society.
- A properly implemented renovation/retrofitting creates a better indoor climate and greater comfort, which can improve the wellbeing of users and the use of the buildings. Retrofitting can also give the buildings an architectural lift. It is important for renovation/retrofitting work

to be organized in such a way that all these considerations are satisfied, so that it helps to develop and improve existing building stock.

- There are substantial skills and great many companies established recently in renovation/retrofitting area in Euro zoon which working on the production of materials, components and systems for energy-efficient buildings, and there are also solid technical resources in the field. Greater investment to promote the energy renovation of buildings in Europe can help to develop and enhance these skills. Analyses from the International IEA show that there is great-unexploited potential for cost-effective reduction of energy consumption in buildings. The EU's Energy Efficiency Directive requires all Member States to draw up coherent strategies for energy renovation. This may help to provide EU firms with new sales opportunities.

2.6. Overall barriers and challenges in renovation/retrofitting process

There are many reasons why investments in energy saving measures in buildings are often overlooked, rejected or only partially realized. In a study done by BPIE (2017), they focused on the main barriers to deep renovation that municipalities in Bulgaria, Croatia, Germany, Romania, Serbia and Slovenia have to face. Subsequently, they have developed the following categories as the main topics that should be given serious consideration to facilitate a successful planning and delivery of the national renovation strategies and their renovation potential:

- Legislative and Regulatory barriers
- Fiscal/Financial
- Communication/Capacity building
- Technical
- Research and Development (R&D)
- Strategic

In another study by BPIE (2011), the authors undertook a detailed survey of the barriers and challenges to building renovation across 29 countries. Figure 2.22 and 2.23 present a schematic summary of the main categories of barriers and challenges identified. They (BPIE, 2011) reported that although financial barriers were one of the highest ranking barrier category among the country responses, alternative investments are in many cases preferred to energy saving measures due to the lack of awareness, interest or in fact, 'attractiveness' of energy efficiency as an investment option.

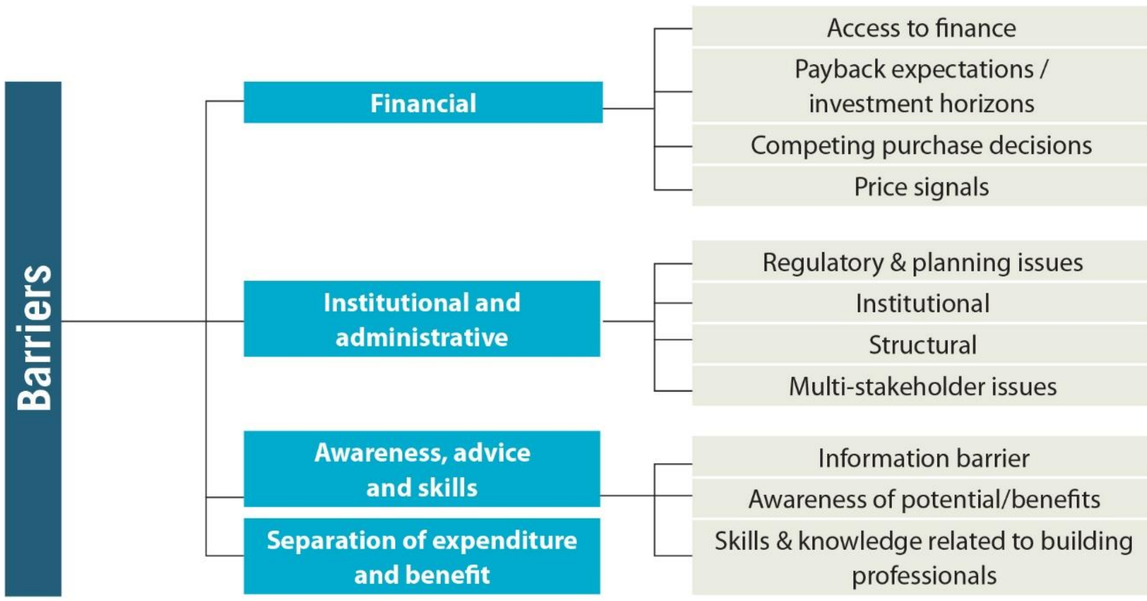


Figure 2.22. Main types of barrier encountered in building renovation (source – BPIE, 2011)

Figure 2.23. An illustration of the main risks, which need to be addressed for market uptake (source – BPIE, 2011)

2.7. Summary

This section provided a brief description about the theme of building renovation/retrofitting. The intent in this coverage has been both for background and review purposes. It is hoped that in doing so, an appreciation has been gained for building renovation context such as benefits and barriers in broader perspectives. Almost certainly, building renovation including energy improvements of existing buildings is getting more attention in many European countries as well as facing new large challenges. These initiatives can often be more cost-effective than new building projects. The existing building stock need to reach EU energy and emission reduction goals. In addition to that, it is also a necessity to ensure buildings functions, technical qualities and to provide a good living environment. That means, enhancing energy efficiency is not the only goal for renovation of existing buildings.

It seems logical that the expected average lifespan constructed by renovation interventions to be set in 30 years. The intervention in renovation can be divided in three levels:

a) urban fabric that deals with the effects the renovation process produces(methods) on the form of the city, the correlation between public and private regions and areas, on the quality of the built environment;

b) building blocks itself that deals with the renovation/retrofitting proceeding pursued according to very particular conditions which depend on the building's pathologies, the requirements to be faced, the level of performance to be accomplished;
c) building units that deals with the alternations entailed by the households in order to meet their preferences or their requirements.

There are a broad range of renovation approaches that can be applied for the renovation of existing buildings including walls insulation, replacement of existing windows, integration or replacement of existing equipment, heating/cooling system, building envelope implementation of roof and partially of facades to avoid thermal bridges, total building envelope implementation, volumetric additions, partial replacement of existing windows, partial building envelope implementation, integration of PV and solar collectors on the roof/facades etc.

There can be identified 5 key phases in development of renovation strategies including: Identifying Key Stakeholders & Information Sources; Technical & Economic Appraisal; Policy Appraisal; Drafting & Consulting on the Renovation Strategy; and Publication & Delivery.

The impacts of undertaking a holistic sustainable renovation has a great deal with Energy System Benefits, Environmental Benefits, Societal Benefits, and Economic Benefits. The main barrios can also be appreciated through ‘financial’, ‘institutional & administrative’, ‘awareness, advice & skills’ and ‘separation of expenditure and benefit’.

CHAPTER II
ENGINEERING DESIGN METHODOLOGY

CHAPTERS'S SYNOPSIS

"This chapter is an introduction to engineering design, and systematic design approaches through identifying the principles of systems theory and thinking, which is currently employed in other domains such as 'industrial design'. It therefore gives an overview of different definitions and properties of engineering design methods. These definitions and properties will be exploited in chapter 4 for the development of elements and principles of an appropriate methodology for generation of renovation scenarios.

It should be underlined that the content of this chapter was developed while the author has been exploring the mentioned topics with very limited background or previous knowledge of them. The reason for this was discussed in chapter 1, so as a necessity for carrying an inductive approach out. Therefore, the above mentioned topics have been explored and the part of major findings has been used in the latest chapters. Nevertheless, the main purpose of providing the entire exploring story is to provide readers particularly those from architecture or architectural engineering domain to get familiar with the relatedness and notion of these terms as well as performing further research in future."

3. Engineering Design (A systematic approach)

3.1. Engineering Design Overview

The subject of engineering design is certainly broad; having quite a lengthy history and one for which there are a substantial number of texts and research publications. Its inclusion as a topic for discussion here is in support of the belief that, to be successful, technological developments which purport to improve design processes must be rooted in fundamental principles and a clear understanding of the subject matter. It is not the intent of this section to provide an in-depth background, but to present sufficient discussion for understanding and an appreciation for the need and approach of this research. For this discussion, topics include: definitions of engineering design, necessity for systematic design, design theory and methodology, design processes (process models, functions and design, and synthesis approaches), knowledge in design (types as well as sources.) and design engineering methods. A more extensive background in engineering design can be obtained from notable texts such as (Suh, 1990; Pahl et al., 2006[1988]; or Hubka, 1982).

3.1.1. Defining Engineering Design

Although numerous definitions of engineering design can be found in the literature, most include common elements. Consider the following definitions:

> "(…) engineering Design is the center of the two intersecting cultural and technical streams" stated by Pahl et al. (2006) as demonstrated in Figure 3.1.

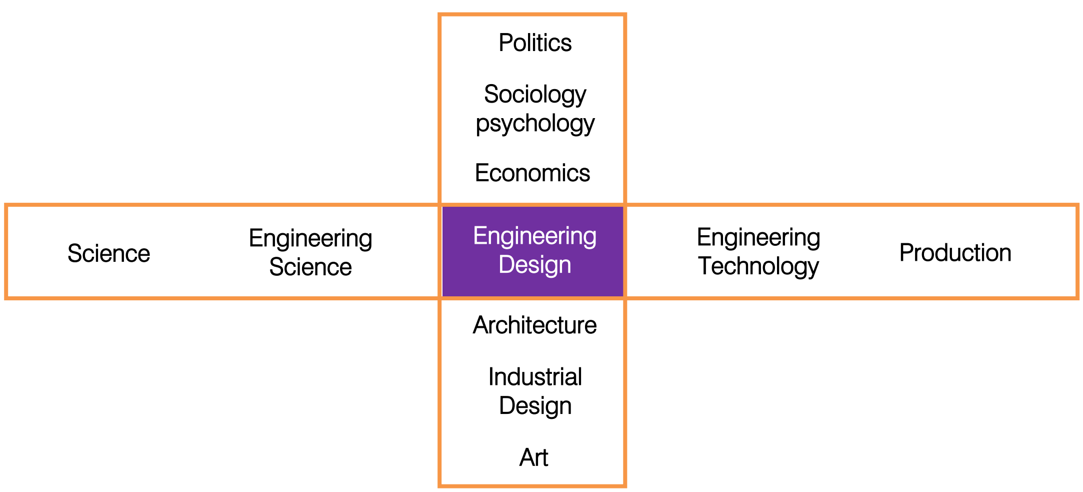


Figure 3.1. The central activity of Engineering Design (source: Pahl et al., 2006, p 1)

> "Design, as the epitome of the goal of engineering, facilitates the creation of new products, processes, software, systems, and organizations through which engineering contributes to society by satisfying its needs and aspirations." or "Design may be formally defined as the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the functional requirements (FRs) in the functional domain and the design parameters (DPs) of the physical domain, through the proper selection of DPs that satisfy FRs", stated by Suh (1990).

> "Engineering design is concerned with the design of products and systems from an engineering perspective" stated by Noble et al. (1993).

> "... a process performed by humans whereby information in the form of requirements is converted into a description of technical systems and other forms of abstractions, such as physical models and mock-ups so that these systems meet certain human needs. Moreover, this process is aided by technical and mathematical tools" stated by Verma et al. (1995).

When considered separately, defining the words engineering and design also lend insight into answering the question: What is engineering design? Webster's dictionary (Woolf, 1976) offers the following definitions:

> "engineering - the application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to man in structures, machines, products, systems, and processes."

> "design - a mental project or scheme in which means to an end are laid down."

In systematic respects,

> "Designing is the optimization of given objects within partly conflicting constraints. Requirements change with time, so that a particular solution can only be optimized for a particular set of circumstances."

Key words across all of these definitions promote the notion that engineering design is a means to an end, scientifically based, creative, and noble in its purpose as contributions are sought which satisfy human and/or societal needs. Whether it be a system, product, process, etc., engineering design serves to translate need into concepts, which are realizable. Implicitly and often understated, engineering design is also responsible; responsible for the impacts, positive and negative, on the world it serves.

Certainly, engineering design is responsible for major contributions, which have defined our modern world: transportation, medicine, architecture, utilities, communication, and agriculture, among many others. Yet, the inceptions of engineering design are also directly responsible for failures, which are capable of causing death and destruction: collapsing bridges, chemical leaks, electrical fires, nuclear power accidents, and automobile accidents. Further, and with much attention in recent years, engineering design is held increasingly responsible for the impact it has on life-cycle issues such as costs, usability, safety, manufacturability, serviceability, disposability, and quality. It is no surprise that the subject of engineering design is the focus of much research and considered an issue of national importance (National Research Council, 1991).

Good design practices can be observed, but how can the expertise and methodologies employed be captured, transferred, taught, implemented, formalized or improved? Why are some people more likely to be good designers? To seek the answers to these questions is to study necessity for systematic design, design theory and methodology.

3.1.2. Necessity for Systematic Design

In view of the central responsibility of designers for the technical and economic properties of a product, and the commercial importance of timely and efficient product development, it is important to have a defined design procedure that finds good solutions. This procedure must be flexible and at the same time be capable of being planned, optimized and verified. Such a procedure, however, cannot be realized if the designers do not have the necessary domain knowledge and cannot work in a systematic way. Furthermore, the use of such a procedure should be encouraged and supported by the organization.

Hubka (1982) distinguishes between design science and design methodology. Design science uses scientific methods to analyze the structures of technical systems and their relationships with the environment. The aim is to derive rules for the development of these systems from the system elements and their relationships.

Design methodology, however, is a concrete course of action for the design of technical systems that derives its knowledge from design science and cognitive psychology, and from practical experience in different domains. It includes plans of action that link working steps and design phases according to content and organization. These plans must be adapted in a flexible manner to the specific task at hand (Product Development Processes). It also includes strategies, rules and principles to achieve general and specific goals (Embodiment Design, Size Ranges and Modular Products, Design for Quality, and Design for Minimum Cost) as well as methods to solve individual design problems or partial tasks (Product Planning, Solution Finding and Evaluation; and Conceptual Design).

This is not meant to detract from the importance of intuition or experience; quite the contrary-the additional use of systematic procedures can only serve to increase the output and inventiveness of talented designers. Any logical and systematic approach, however exacting, involves a measure of intuition; that is, an inkling of the overall solution. No real success is likely without intuition.

Design methodology (according to Pahl et al., 2006) should therefore foster and guide the abilities of designers, encourage creativity, and at the same time drive home the need for objective evaluation of the results. Only in this way is it possible to raise the general standing of designers and the regard in which their work is held. Systematic procedures help to render designing comprehensible and also enable the subject to be taught. However, what is learned and recognized about design methodology should not be taken as dogma. Such procedures merely try to steer the efforts of designers from unconscious into conscious and more purposeful paths. As a result, when they collaborate with other engineers, designers will not merely be holding their own, but will be able to take the lead (Pahl et al., 2006).

Systematic design provides an effective way to rationalize the design and production processes. In original design, an ordered and stepwise approach - even if this on a partially abstract level - will provide solutions that can be used again. Structuring the problem and task makes it easier to recognize application possibilities for established solutions from previous projects and to use design catalogues. The stepwise concretization of established solution principles makes it possible to select and optimize them at an early stage with a smaller amount of effort. The approach of developing size ranges and modular products is an important start to rationalization in the design area, but is especially important for the production process (Size Ranges and Modular Products).

A design methodology is also a prerequisite for flexible and continuous computer support of the design process using product models stored in computer. Without this methodology, it is not possible to: develop knowledge-based systems; use stored data and methods; link separate programs, especially geometric modelers with analysis programs; ensure the continuity of data flow; and link data from different company divisions. Systematic procedures also make it easier to divide the work between designers and computers in a meaningful way.

A rational approach must also cover the cost of computation and quality consideration. More accurate and speedy preliminary calculations with the help of better data are a necessity in the design field, as is the early recognition of weak points in a solution. All this calls for systematic processing of the design documentation. A design methodology according to Pahl et al. (2006), therefore, must:

- allow a problem-directed approach; i.e. it must be applicable to every type of — design activity, no matter which specialist field it involves
- foster inventiveness and understanding; i.e. facilitate the search for optimum solutions
- be compatible with the concepts, methods and findings of other disciplines
- not rely on finding solutions by chance
- facilitate the application of known solutions to related tasks
- be compatible with electronic data processing
- be easily taught and learned
- reflect the findings of cognitive psychology and modern management science; i.e. reduce workload, save time, prevent human error, and help to maintain active interest
- ease the planning and management of teamwork in an integrated and interdisciplinary product development process
- provide guidance for leaders of product development teams.

3.1.3. Design Theory and Methodology

The study of design theory and methodology is not new. From a historical perspective, writings on the subject of mechanical design methodology are dated from ancient Greek and Alexandrian authors somewhere between 300 BC and 100 AD (Dimarogonas, 1993). Today, progress and debate continue.

Suh (1990) describes a good designer as one with the ability to identify only the most important requirements of a design task, ignoring those of secondary importance until later stages. In addition, a good designer possesses an in-depth grasp of the issues involved, and is able to operate in the conceptual world as well as the physical domain. Creative qualities include the ability to be a risk-taker, having a good memory and much knowledge from many fields, knowing how to use analogies, extrapolate, and interpolate from known applications to a new situation (Shaw, 1986).

Agogino et al.(1989) report on observations of design teams. Listing a few of these observations:

- major design decisions are made very early in the design process,
- only one or two concepts are pursued at a time,
- designers move alternatively from detailed design to global design,
- design work is divided into sub-tasks, and
- decisions made by a team are sometimes forgotten and rehashed.

Dixon (1988) discusses the inherent difficulties in the formulation of a scientific theory of design. Considered as a process, there is reason to scrutinize the validity of a single, generalizable, theory of design. Dixon emphasizes the importance and enlightenment to be gained in such a pursuit, yet places great significance on discovering and organizing design knowledge and relating it to various types of design problems (Dixon, 1992).

Kota et al. (1990) present opposing views in a debate which ultimately scrutinizes the validity and utility of design research based upon experimental or intuitive ("scruffy") approaches as opposed to design methodologies founded upon mathematically precise ("neat") theory (Kota et al., 1990). In the end, the authors agree that it is likely that both approaches will have to coexist, perhaps forever, given the complex subject of design.

With some variation, procedural design methodologies have been widely adopted by many researchers. In Germany, the Society of German Engineers (VDI) has published procedural guidelines which are cited to have been the culmination of nearly thirty years of university research and industry use (VDI-GKE, 1987). The systematic design method prescribes definitive procedural steps to guide design processes (Pahl et al., 2006). Steps are grouped into four phases of design:

1) clarification of the task and development of the design specifications,
2) conceptual design,
3) preliminary or embodiment design, and
4) final or detail design.

The steps and phases overlap using feedback loops supporting iteration. To date, the majority of work in procedural approaches have focused on design representation, synthesis mechanisms and knowledge representation schemes, which will lead to scientifically based and/or computable methodologies. Much of this research effort has been for the embodiment and detail design phases. Research for conceptual design is very immature by comparison. A more detailed treatment of these topics will be given in subsequent sections of this chapter.

Suggesting an axiomatic approach, Suh (1990) defines four distinct aspects of engineering and scientific endeavor: "the problem definition from a 'fuzzy' array of facts and myths into a coherent statement of the question; the creative process of devising a proposed physical embodiment of solutions; the analytical process of determining whether the proposed solution is correct or rational; and the ultimate check of the fidelity of the design product to the original perceived needs." The creative process is described as an ideation process, which is highly subjective and dependent upon the specific knowledge of the designer and their ability to integrate this knowledge. The analytic process is deterministic, based upon basic principles, and serves to evaluate the concepts of the creative process. Suh (1990) provides two axioms used in the analytic process for the purpose of distinguishing good designs from bad. Without these axioms, Suh considers design decisions to be made at best on an "ad hoc" or "empirical" basis. Axiom 1 is the “Independence Axiom” which states: maintain the independence of functional requirements. Axiom 2 is the “Information Axiom” which states: minimize the information content.

Others have sought to improve upon generalized methods through the classification of design problem types. Pahl et al. (2006) categorize design into three types: original design, adaptive design, and variant design. Original design involves elaborating an original solution principle for a system, adaptive design involves adapting a known system to a changed task, and variant design involves varying the size and/or arrangement of certain aspects of the system with the solution principle remaining unchanged. Condoor et al. (1992) use a similar approach, but categorize design problems according to a cognitive framework resulting in four classifications: a) variant design, b) developmental design, c) adoptive design, and d) original design. These categories help to evaluate and guide processes based upon conceptual and configurational novelty.

More recently, the methods of artificial intelligence have received considerable attention as design methodologies are sought which are computable and reflective of reasoning similar to human creative processes (Boyle, 1993). Waldron et al. (1988) propose a theoretical framework for representing the product design process based on the use of systemic theory. Takeda et al. (1992) propose a logical design process model with the potential to serve as a framework for integrating design models and design processes in the definition of an intelligent CAD system. Williams (1991) suggests an approach for designing novel devices from first principles. Design is viewed as a process of building interaction topologies (Williams, 1991).

3.1.4. Design Processes

This section provides a closer examination of design processes. Process models are central to defining the stages or phases of design and are therefore considered first. The concept of function and its role in the design process is then examined. Finally, synthesis approaches (solution methods) are discussed.

3.1.4.1. Process Models

From a very high level, researchers agree that the processes of engineering design can be grouped according to purpose. As described earlier, Suh (1990) defines four distinct aspects of engineering and scientific endeavor. Pahl et al. (2006) group design processes into four phases. Maher (Maher, 1990) describes three general phases: design formulation, design synthesis, and design evaluation.

Shigley (1977) describes a process model, which includes six broadly defined steps. In this model (see Figure 3.3), design processes begin with a recognition of need and end with a presentation of the solution.

Upon examination, all of these process models are very similar, if not the same. Following the recognition of a need, be it market, customer, or internally driven, the need is formalized into functional requirements and constraints which define the problem in terms of specifications. Solutions are then sought to satisfy the specifications (synthesis). These solutions are evaluated against the specifications resulting in: satisfaction, the need to continue the search, or the need to modify the original requirements. It is with much iteration and the application of information, knowledge, and constraints on the problem domain that the feasible design space is ultimately reduced to realize the final product definition (see Figure 3.2).

Additionally, throughout the stages of development, new design problems emerge and must also be addressed as the product design progresses to its eventual detailed definition. Finally, the designer presents the results, which document the design in terms of material selections, geometric models, circuit diagrams, software, physical component selections, and other documentation sufficient for product realization.

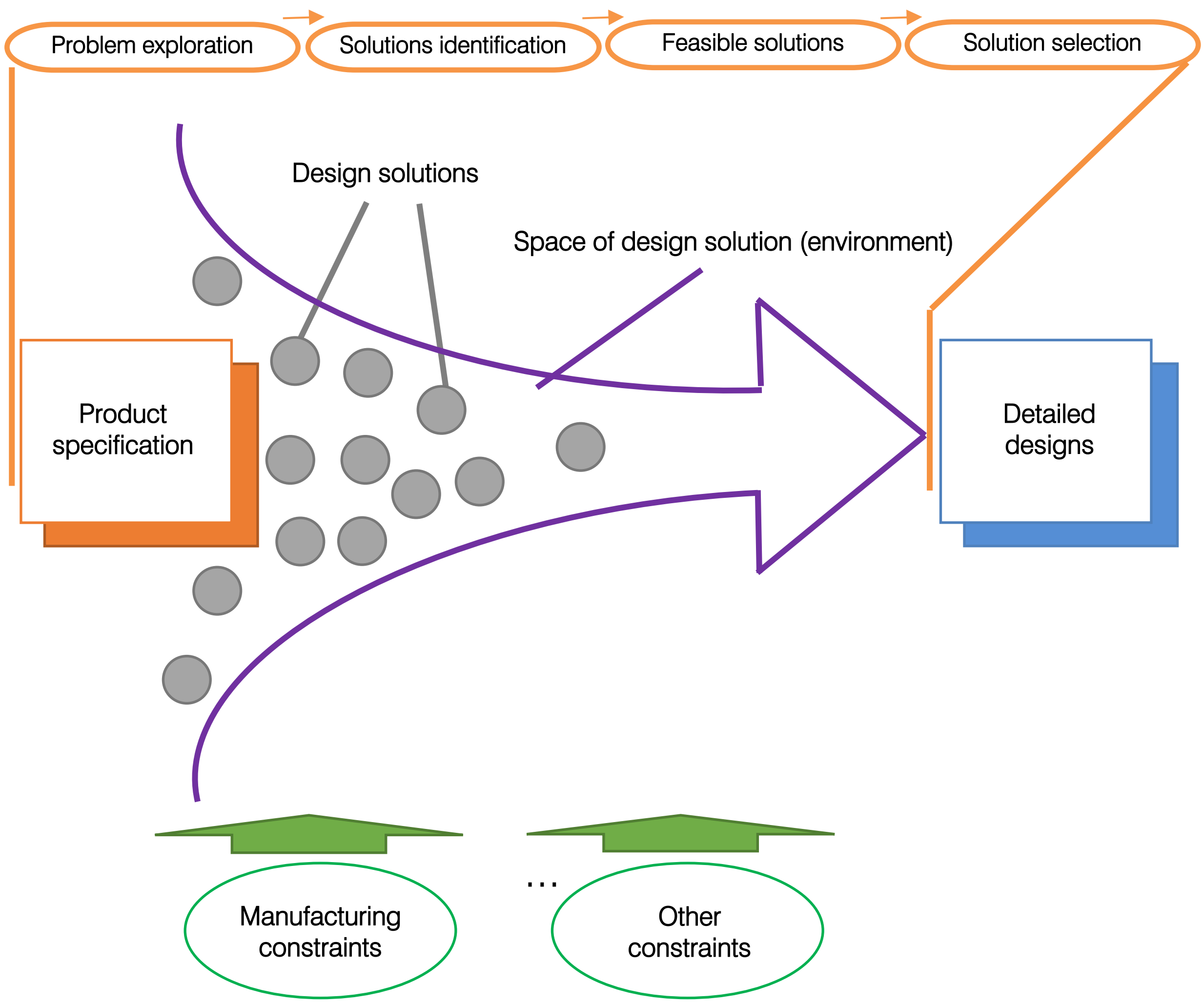


Figure 3.2. Design Process and Pruning of Feasible Solutions (according to Schmekel, 1989)

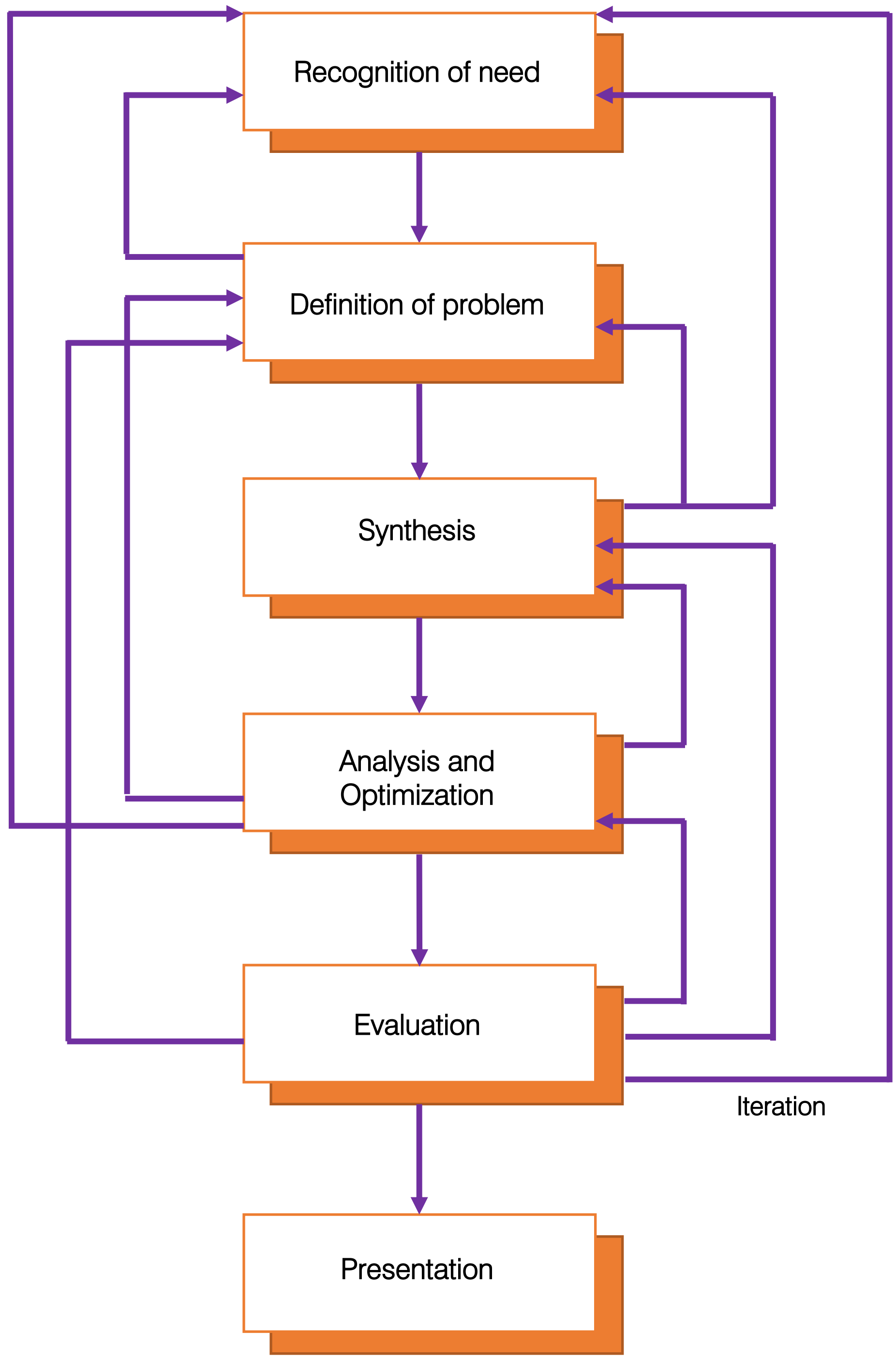


Figure 3.3. Model of Design Process (source: Shigley, 1977)

3.1.4.2. Functions and Design

As described in the previous section, function is a concept that is fundamental to engineering design processes. Suh (1990) describes design as "a continuous interplay between what we want to achieve and how we want to achieve it"; function commonly describing the need, desired intent, or purpose. The objective of design is stated in a functional domain and the solution is generated from a physical domain. The design process involves mapping from the functional domain, specified as functional requirements, to an embodiment in the physical domain, characterized in terms of design parameters. Figure 3.4 illustrates a simplified representation of this mapping. It should be noted that in present thesis, this concept is discussed further and used in chapter 6 where the functional requirements (objectives/criteria) for building renovation context are mapped out through the design elements.

The physical domain is not necessarily restricted to solutions, which are physically tangible, but may also include, among others, solutions such as software, organizational plans, or process descriptions. Though not explicitly evident in Figure 3.4, both the functional space and physical space are likely to contain decomposable hierarchies. Further, the two domains are inherently independent of each other and only related through the design. Ultimately, it is through the ongoing interlinking between the functional and physical domains, at every level of design, that solutions are iteratively refined and realized with larger detail.

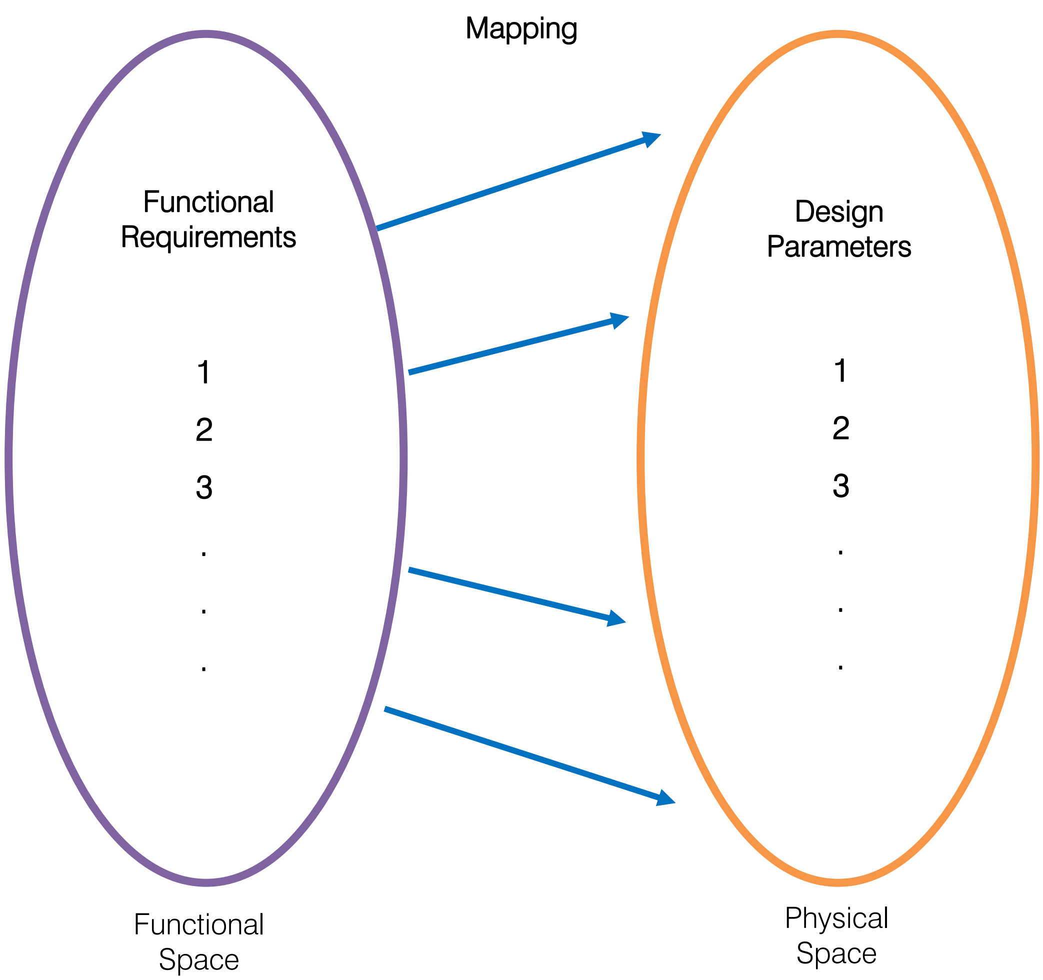


Figure 3.4. Design as a Mapping Process (according to Suh, 1990)

Beginning with problem definition, it is crucial to understand and identify the appropriate set of functional requirements. The impacts of decisions that are made very early in design based upon high-level functions are significant. Early design decisions restrict, and in many cases determine, much of the remainder of product design as well as matters related to life-cycle issues. In today's competitive marketplace it is therefore imperative that systems developed to support early design processes consider functional modeling (abstraction) and the information requirements for informed decision making (detail).

3.1.4.3. Synthesis Approaches

Boyle maintains that design in general is still a very poorly understood activity where too often researchers have limited their focus to particular design domains, notably very large scale integrated circuits (VLSI) and mechanical engineering design (Boyle, 1993). However, Boyle also states that a universal and formal model of engineering design is not realizable given the diversity of different design domains. In an effort to "escape" from domain specific research, Boyle (1993) suggests a classification that splits design into three broad methodologies:

- analytic,
- procedural, and
- experimental.

The distinction in approaches is made according to the amount of analytical knowledge that can be applied to the process of obtaining design solutions. This categorization directs the designer to the most appropriate method (synthesis approach) for solving the problem.

The analytic approach can be used for problems where the objective(s) and constraints can be specified with precise and complete models, and solved for optimality using algorithmic methods. The analytic approach can be found in the work of Fabrycky (1992), who formulates and synthesizes design solutions in what is termed the “design dependent parameter approach”.

The procedural approach is a trade-off process. It is appropriate for problems where the objectives are rarely fixed, but tend to be modified as the design proceeds and the designer obtains more information about what can realistically be achieved. All objectives are satisfied, but are rarely optimal.

The experimental approach is a search oriented process. An available set of solutions are systematically searched to find the best match of attributes with design objectives. This results in the 'best' design solution from the known search space. Noble et al. (1993) describe these approaches pictorially as shown in Figure 3.5.

Lin et al. (1993) also categorizes synthesis models into three distinct categories. Here, the approaches are given to include:

- decomposition,
- case-based reasoning, and
- transformation

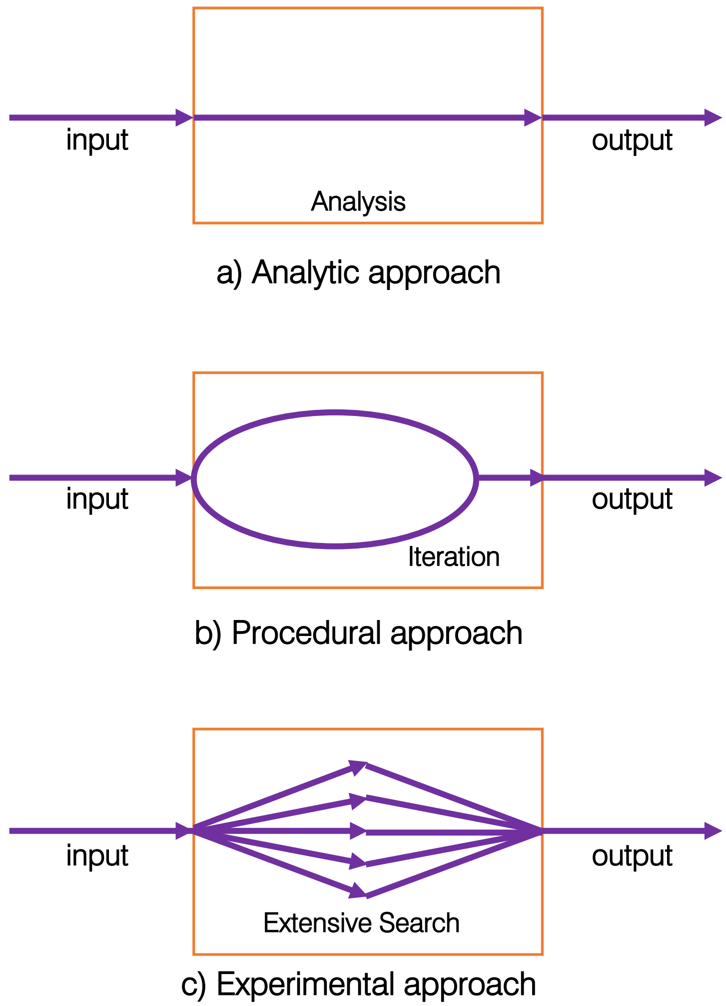


Figure 3.5. Engineering Design Approaches (according to Noble et al., 1993)

Decomposition is described as a sequence of refinement steps wherein large or complex design problems are progressively broken down into sub-problems. It is considered to be a "divide and conquer" technique which eventually leads to problem solution. Decomposition is particularly suitable for problems where the sub-problems are loosely coupled.

Case-based reasoning approaches rely heavily upon an extensive database of previous case (solution) histories. Near matches are sought with existing cases and then adapted to define a new case for the given problem situation (Pu, 1993).

Transformation involves making progressive steps from the initial set of requirements toward a design solution. At each step the complete model is transformed from the previous state on to the next. This type of synthesis model is appropriate when there is a strong connection of artifacts, which cannot be decomposed into sub-problems.

Contrasting the categorizations offered by Boyle (1993) and Lin et al. (1993), one notes the similarities. The experimental approach and case-based reasoning are both search oriented.

Similarities are also noted between the analytic approach and transformation. Less obvious, are the parallels, which can be drawn between the procedural and decomposition methods.

A more important distinction to make in this discussion is that in practice, engineering design problems usually require some combination of these approaches. The exact approach used often is related to the level of abstraction and stage within the design process. Over the life of the design project, designers may call upon all of the synthesis methods. This is certainly the case where satisfying a recognized need implies developing a complex system, such as an electro/mechanical system. It is likely that the problem will undergo decomposition into smaller subsystem design problems. Transformation (analytical) methods will be used to analyze and determine feasible solutions. Procedural approaches will be used throughout the design effort as a greater understanding of the system and firming of the specifications occurs. Search and adaptation methods, regardless of whether formally implemented in computer based tools, will be used as designers inherently draw upon previous experience when presented with similar design problems.

Numerous examples of "hybrid" design methods can be found in the literature. Roderman et al. (1993) integrate iterative refinement and decomposition in what is considered a case-based approach to aid novice mechanical designers. Bardasz et al. (1993) also use a case-based approach for mechanical design, but point to the need for a hybrid approach which could also reason from first principles of engineering. Navinchandra et al. (1991) also use a case-based approach for mechanical design. Transformation rather than pre-defined indexing is used for case retrieval. Again, combining case-based methods and transformation, Maher et al. (1993) use a hybrid approach where case transformation is treated as a constraint satisfaction problem.

3.1.5. Knowledge in Design

Engineering design can be characterized as an information-based process (Colton et al., 1994). From the earliest recognition of need, proceeding through to the completion of finalized design and documentation, information is gathered, manipulated and generated. Considered in a broader sense, information is a form of knowledge. A closer examination of knowledge types and sources follows.

3.1.5.1. Knowledge Types

Miles et al. (1994) offer two generally accepted categories of knowledge:

- declarative, and
- procedural.

Declarative knowledge is described to include facts, concepts, and relationships. This type of knowledge is gained via lectures, tutorials, and design practices; perhaps in a university setting.

Procedural knowledge is described as relating to how one performs tasks. It is most commonly acquired with experience and is therefore difficult to verbalize. Further, Miles et al. (1994) relay that 'real expertise' consists mostly of procedural knowledge.

Another classification of knowledge offered by Miles et al. (1994) includes:

- algorithmic,
- heuristic, and
- meta-knowledge.

These classifications deal with the type of approach taken to design processes. Algorithmic utilizes equations based on Newtonian physics whereas heuristic relies on `rules of thumb' from experience. Meta-knowledge deals with the knowledge of how to control procedures and methods. For Artificial Intelligence (AI) applications, this would be the knowledge used to control the inferencing procedure.

Schmekel (1989) takes a different approach to the classification of knowledge types. Four categories distinguish knowledge types ranging from the most fundamental, and therefore generalizable, to knowledge, which is highly specific to particular company practices. Briefly, these types include:

- physical knowledge - concepts of physical reality and basic sciences,
- design knowledge - concepts of shape, function, structure, and relations used in developing the product description,
- application knowledge - describes the application of a design. Includes design knowledge (shape and function) and physical knowledge (behavior), and
- company knowledge - company standards and specific product descriptions.

Similarly, in a less technical publication (Wisdom System, 1992), knowledge is classified into several types along a spectrum from broad, generic knowledge, to product specific knowledge (from implicit to explicit):

- generic - basic scientific concepts such as force, moments of inertia, etc.,
- domain - particular to a field of engineering (electrical, mechanical, etc.),
- industry - applicable to a specific industry (automobiles for example),
- company - information and standards of how products are designed specific to a given company, and
- product - particular to a given product or product-line.

Pictorially, the concepts and relation of generality and abstraction to knowledge types are represented in Figure 3.6. Following the directed arrows, it can be seen that abstraction increases as knowledge types become increasingly specific. Inversely, generality increases as knowledge types become less abstract.

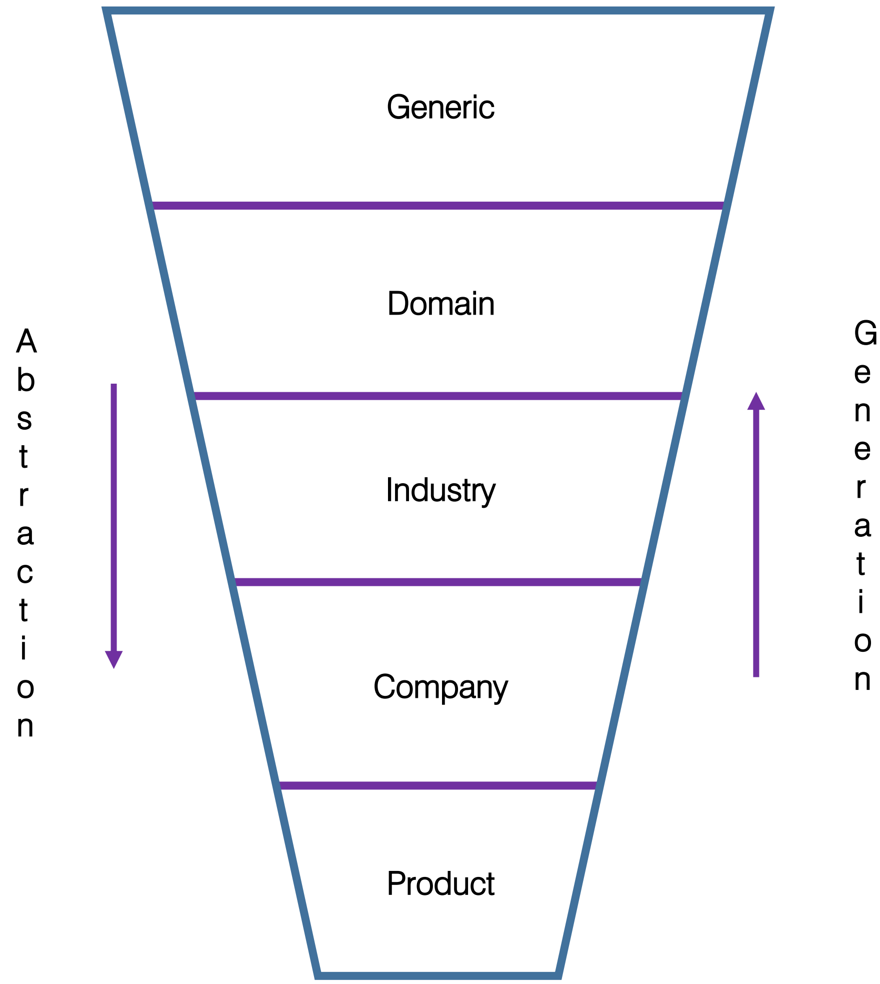


Figure 3.6. Generality and Abstraction in Design Knowledge (according to Wisdom System, 1992)

3.1.5.2. Knowledge Sources

Even more varied than the types of knowledge in design, are the sources from which this knowledge is obtained. Whether manually kept or stored in a computer, numerous sources are accessed as information is gathered, manipulated, and generated throughout design processes.

Knowledge sources can include people, databases, files, catalogs, equations, analysis results, handbooks, and other hard-copy (paper) documentation. Customer requirements, marketing requirements, existing designs, manufacturing constraints, costs, vendor data, availability, part data (ratings, features, etc.), geometric models, schematics, evaluation and/or simulation software, and personal expertise are just some of the typical inputs to informed decision making.

Clearly, availability, format, and timeliness of knowledge sources are all important factors affecting both the efficiency and effectiveness of design processes. Time spent tracking down information which is not readily available, unreliable, ambiguous, or otherwise difficult to use, extends cycle-times, leads to misinformed decisions, and is time which could have otherwise been applied to creative processes.

3.1.6. Engineering Design Methods

Pahl et al., (2006) discusses that there are three different methods working under Engineering Design domain including:

- Systems Theory
- Value Analysis
- Design Methods

3.1.6.1. Systems Theory

In socio-economic-technical processes, procedures and methods of systems theory are becoming increasingly important. The interdisciplinary science of systems theory uses special methods, procedures and aids for the analysis, planning, selection and optimum design of complex systems (Pahl et al., 2006).

Pahl et al. (2006) argue that technical artefacts, including the products of light and heavy engineering industry, are artificial, concrete and mostly dynamic systems consisting of sets of ordered elements, interrelated by virtue of their properties. A system is also characterized by the fact that it has a boundary, which cuts across its links with the environment (see Figure 3.7). These links determined the external behavior of the system, so that it is possible to define a function expressing the relationship between inputs and outputs, and hence changes in the magnitudes of the system variables.

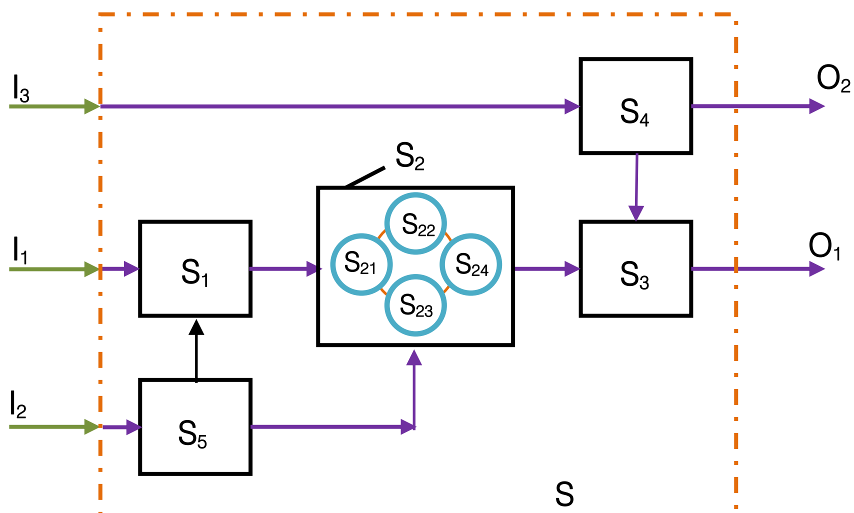


Figure 3.7. Structure of a Systems. S: system boundary; S1 – S5: subsystems of S; S21 – S24: subsystems or elements of S2; I1 – I3: inputs; O1 – O2 outputs (source: Pahl et al., 2006)

Figure 3.8 shows the steps of the systems approach. The first of these is the gathering of information about the system under consideration by means of market analyses trend studies or known requirements. In general this step can be called problem analysis. According to Pahl et al., (2006) the aim here is the clear formulation of the problem (or sub-problem) to be solved, which is the actual starting point for the development of the system. In the second step, or perhaps even during the first step, a program is drawn up in order to give formal expression to the goals of the system (problem formulation). Such goals provide important criteria for subsequent evaluation of solution variants and hence for the discovery of the optimum solution. Several solution variants are then synthesized on the basis of information acquired during the first two steps (Pahl et al., 2006).

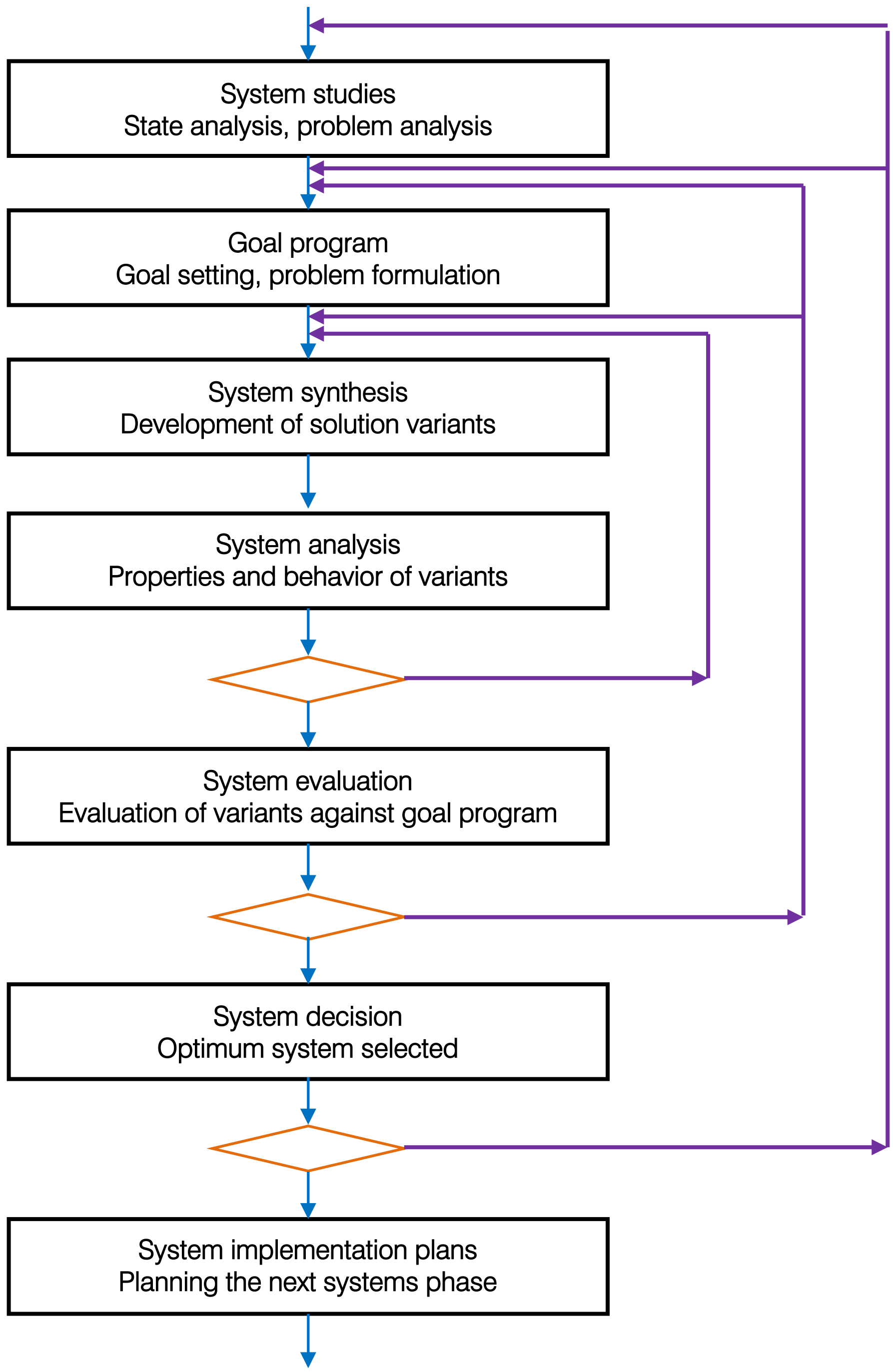


Figure 3.8. Steps of the systems approach (source: Pahl et al., 2006)

Pahl et al., (2006) state that before these variants can be evaluated the performance of each must be analyzed for its properties and behavior. In the evaluation that follows, the performance of each variant is compared with the original goals, and on the basis of this a decision made and optimum system selected. Finally, information is given out in the form of system implementation plans. Figure 3.8 shows, the steps do not always lead straight to the final goal, so that iterative procedures may be needed. Built-in decision steps facilitate this optimization process, which constitutes a transformation of information.

The authors in (Pahl et al., 2006) discuss that In systems theory process model, the steps repeat themselves in so-called life cycle phases of the system in which the chronological progression of a system goes from abstract to concrete (see Figure 3.9).

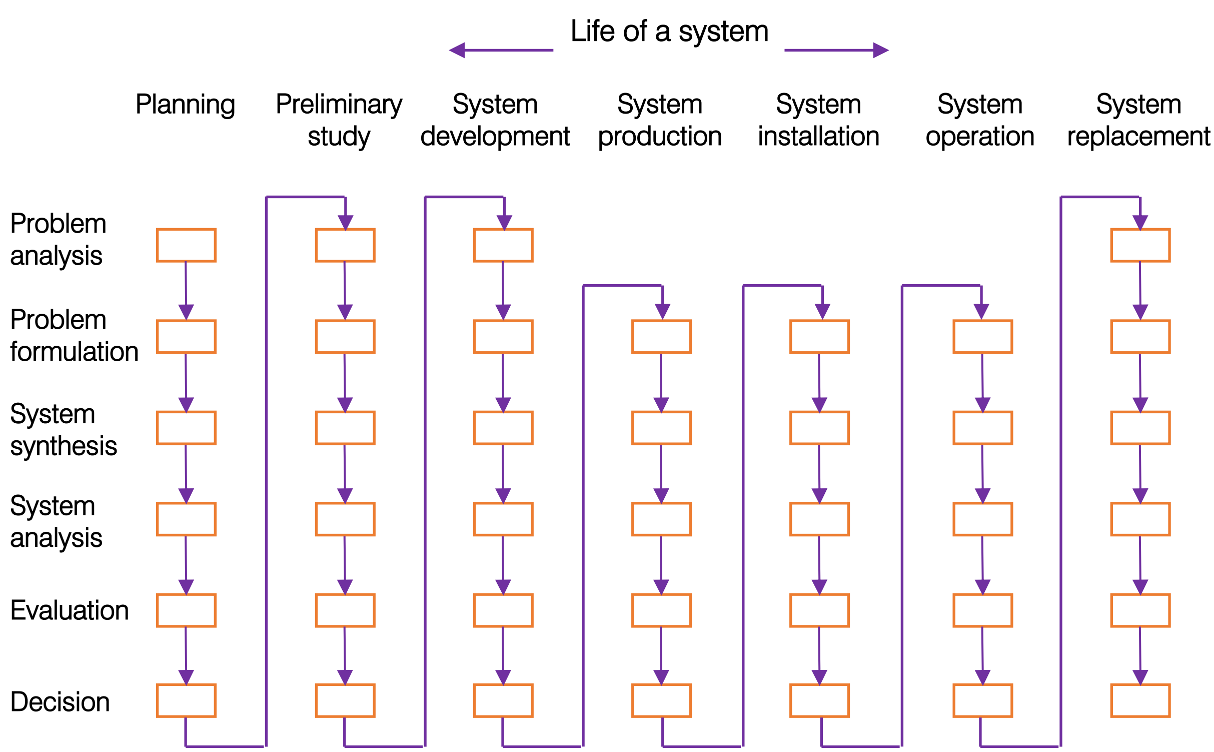


Figure 3.9. Models of the systems approaches (source: Pahl et al., 2006)

3.1.6.2. Value Analysis

According to Pahl et al. (2006), value analysis can help to diminish cost. For this reason, a systematic overall approach is proposed that is applicable, specifically, to the future development of existing products. Table 3.1 shows the basic operation steps of Value Analysis. In general, a star is made with an existing design, which is analyzed with respect to the required functions and costs. Solution ideas are then proposed to meet the new targets. Because of its emphasis on functions and the stepwise search for better solutions, Value Analysis has much in common with systematic design (Pahl et al., 2006).

Table 3.1. Basic working steps of Value Analysis. After DIN 69910 (source: Pahl et al., 2006)

Prepare project - Assemble team - Define scope of Value Analysis - Define organization procedure	Develop solution ideas - Collect existing ideas - Search for new ideas
Analyze actual state - Recognize functions - Determine function costs	Determine solutions - Evaluate ideas - Develop ideas into solutions - Evaluate and decide upon solutions
Determine target state - Define target functions - Identify additional requirements - Match target costs with target functions	Realize solutions - Detail chosen solutions - Plan their implementation

This must be underlined that the use of the Value Analysis method should not be left until after the scheme and detail drawings have been finalized. Therefore, it should be commenced during conceptual design in order to "design in" value (Gierse, 1998). In this way, Value Analysis approaches the goals of systematic design (Pahl et al., 2006).

3.1.6.3. Design Methods

Pahl et al., (2006) based on VDI Guideline 2222 (1996) identify an approach and particular methods for the conceptual design of technical products and is thus particularly proper for the development of new products. The authors argue that according to the more recent VDI Guideline 2221 (1993) a generic approach to the design of technological systems and products, emphasizing the general applicability of the approach in the field of mechanical, precision, control, software and process engineering. The approach which is demonstrated in Figure 3.10 contains seven fundamental working steps that compromised with the fundamental of technical systems and company strategy. Figure 3.10 illustrates a guideline to which the accurate working procedures can be assigned. In this light, special assertion is placed on the iterative nature of the approach and the sequence of the steps must not be considered rigid. Following Pahl et al., (2006), some steps might be omitted, and others repeated frequently. Such flexibility is in accordance with practical design experience and is very important for the application of the all design methods.

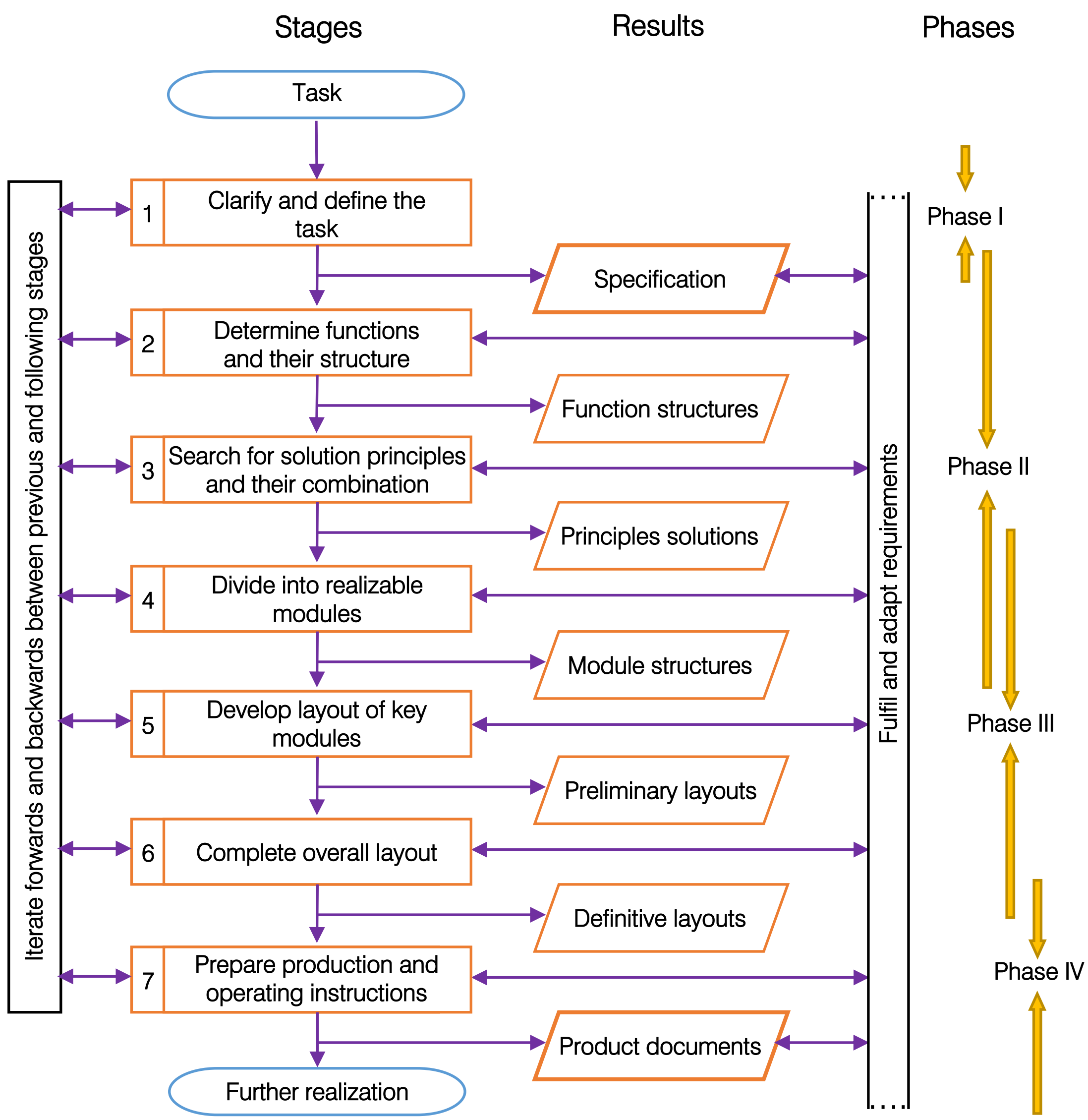


Figure 3.10. General approach to design. After VDI-Richtlinie 2221 (source: Pahl et al., 2006)

3.2. Engineering Design using Systems Theory

Following the discussions in previous section, Engineering Design can be defined as the process of devising a system to meet desired needs. It is a decision-making process, in which the basic science and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective. In this spirit and based on findings and investigations about systems engineering design methods, particularly Systems theory and its interdisciplinary nature, Figure 3.11 is concluded. To say with other words, systems theory based on its specified process and approach where the objectives enable to be identified, interacted, and adopted through an evolutionary process via application of several iterative cycles might be considered a suitable methodology to overcome the existing complexity in building renovation context. [This definition will be used later in chapter 4 of the present thesis to develop a holistic multi-methodology for renovation context]. It is then the intent of this section to present sufficient discussion for understanding and an appreciation for the need and approach of systems thinking and theory. For this discussion, topics include: definitions of systems, systems theory and thinking, complexity theory and how to design complex systems, and eventually environment of a system.

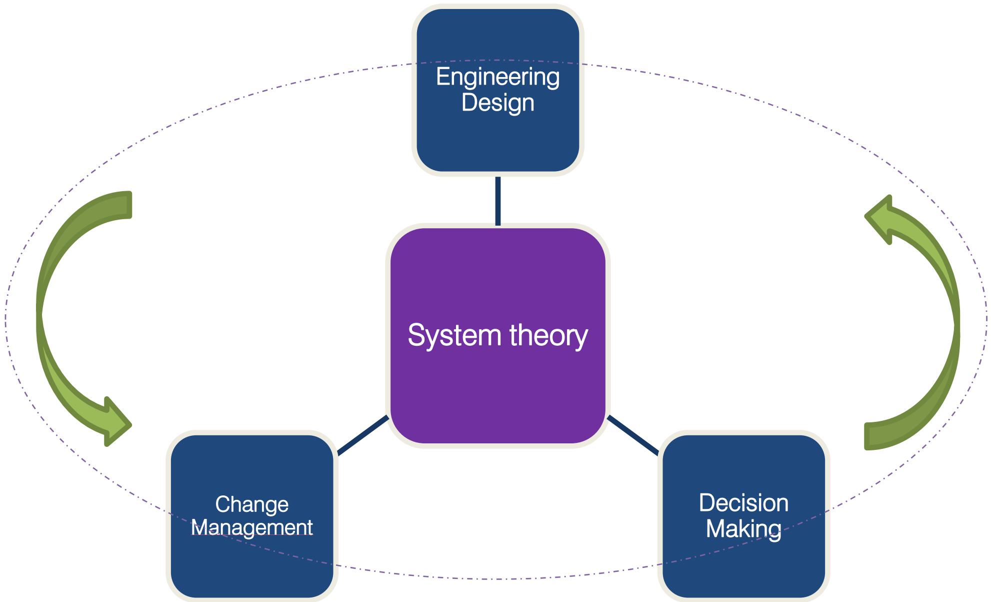


Figure 3.11. Systems theory as the major part of Engineering Methodology, Change Management and Decision Making

3.2.1. What is system?

Although numerous definitions of system can be found in the literature, most include common elements. The systems definitions are as following:

> "System is defined as a set of instruments working together as part of mechanism or interconnecting network." (Oxford dictionary[1])

> "System it is a set of interacting or interdependent components forming an integrated whole. (see Figure 3.12 & 3.13)" (Bailey, 1994)

Figure 3.12. Schematic view of a system (source: Complexity Academy, 2015)

[1] https://en.oxforddictionaries.com/definition/system

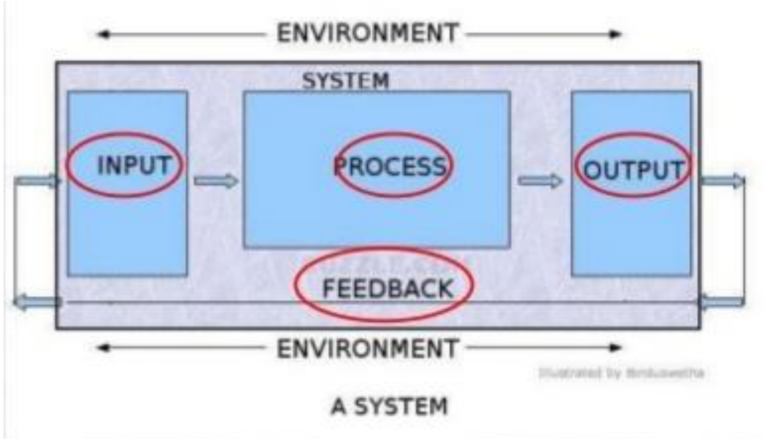


Figure 3.13. Basic elements of any system (source: Bailey, 1994)

> "A set of detailed methods, procedures and routines created to carry out a specific activity, perform a duty, or solve a problem." (Business dictionary[2])

> "An organized, purposeful structure that consists of interrelated and interdependent elements (components, entities, factors, members, parts etc.). These elements continually influence one another (directly or indirectly) to maintain their activity and the existence of the system, in order to achieve the goal of the system" (Business dictionary)

According to (Bertalanffy, 1968), there are four fundamental types of systems:

- natural systems, e.g. a biological organism
- designed physical systems, e.g. a building
- designed abstract systems, e.g. a mathematical equation, and
- human activity systems, e.g. a team engaged on a task, or a healthcare organization.

All systems have (a) inputs, outputs and feedback mechanisms, (b) maintain an internal steady-state (called homeostasis) despite a changing external environment, (c) display properties that are different than the whole (called emergent properties) but are not possessed by any of the individual elements, and (d) have boundaries that are usually defined by the system observer (Weinberg, 2001). Systems underlie every phenomenon and all are part of a larger system. Systems stop functioning when an element is removed or changed significantly. Together, they allow understanding and interpretation of the universe as a meta-system of interlinked wholes, and organize our thoughts about the world. When speaking of groups of elements, Bertalanffy (1968) makes three distinctions: 1) concerning the number of elements; 2) concerning their species; and 3) concerning their relations. Bertalanffy (1968) calls the characteristics of the first two groups summative, and the characteristics of the third group constitutive. The constitutive characteristics

[2] http://www.businessdictionary.com/definition/system.html

"are those which are dependent on the specific relations within the complex; for understanding such characteristics we therefore must know not only the parts, but also relations" (Bertalanffy, 1968).

Weinberg (2001) proposes another definition; he divides objects of examination into three groups, or regions including first, "Organized Simplicity" (machines), second, "Unorganized Complexity" and finally "Organized Complexity" (Systems), (see Figure 3.14). In this classification system is defined where it consists of number of objects that are organized, but whose organization is too complex for analytical procedures.

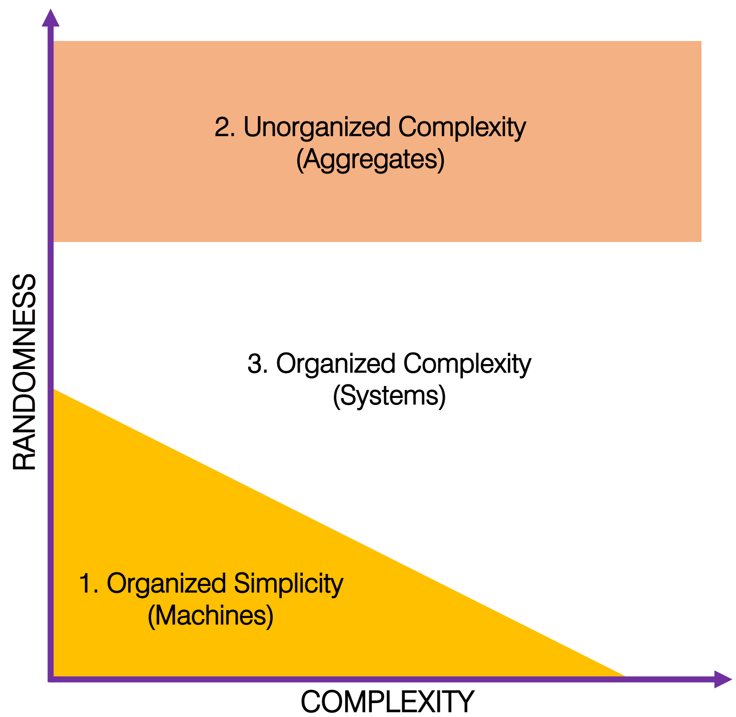


Figure 3.14. Weinberg's classification of objects and phenomena. The vertical axis (randomness) reflects the number of relations between objects – the more random an object, the less relations between its elements. The horizontal axis reflects the complexity of relations (source: Weinberg, 2001).

Laszlo (1996) considered systems as something that exists in our mind and not in the world, such as a 'theological system' or a 'system of logic'. Nowadays we call systems many things whose existence is independent of our thinking – a political system, an economic system, a social system, an ecological system, a biological system, an astronomical system or a computer system. Laszlo (1996) defines systems by distinguishing 'wholes' and 'heaps'.

> "'Wholes' and 'heaps' are not mysterious metaphysical notions but clearly, even mathematically, definable states of complex entities. The decisive difference is that wholes are not the simple sum of their parts, and heaps are. Take, for example, a pile of rubbish. Adding another can or removing a pop bottle makes only a quantitative difference to the pile – it becomes that much bigger or smaller. No other characteristic of it changes." (Laszlo, 1996)

Bertalanffy (1968) offers also a definition of a system that is narrower that "elements in relation". According to this alternative definition, a system may be understood as a model – a representation of some universal traits of a class of natural phenomena.

3.2.2. What is systems theory?

Systems theory is the interdisciplinary study of systems in general, with the goal of discovering patterns and elucidating principles that can be discerned from, and applied to, all types of systems at all nesting levels in all fields of research (Bertalanffy, 1968). Systems theory can reasonably be considered a specialization of systems thinking or as the goal output of systems science and systems engineering, with an emphasis on generality useful across a broad range of systems (versus the particular models of individual fields).

Systems theory is a science, which has the comparative study of systems as its object. There are different types of systems: organisms (animals, humans, particularly cognitive mechanisms in organisms), machines (particularly computers), physicochemical systems, psychic systems and social systems. Stichweh (2011) discuss that such a comparative research program for heterogeneous types of systems presupposes a highly general concept of systems, for which numerous features have been proposed: a) the interdependency of the parts of a system; b) the reference of any structure and process in a system to the environments of the system; c) equilibrium and adaptedness and continuous re-adaptations to environmental demands as core elements of the understanding of a system; d) self-organization of a system as the principal way it responds to external intervention; e) complexity as trigger mechanism for system-formation and as the form which describes the internal network structures of connectedness among system elements.

According to Bertalanffy (1968) system theory is modeling devise that accommodates the interrelationships and overlap between separate disciplines consists of two features (see Figure 3.15):

- Primarily, it is interdisciplinary;
- Secondary, it is a science of systems indecomposable entities or 'wholes'.

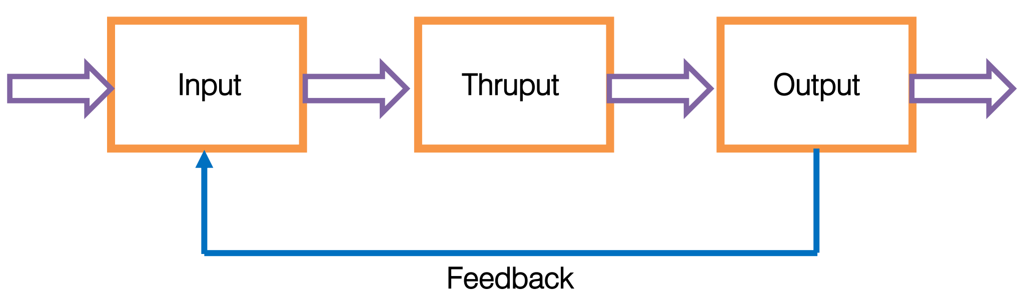


Figure 3.15. Von Bertalanffy's Systems Theory (according to Bertalanffy, 1968)

In addition to this, systems theory focuses on three activities (Weinberg, 2001) as following:

- Plenary systems thinking, which is about methods and approaches;
- Plenary systems application;
- Plenary systems research, which is about creating new laws and refining old ones.

3.2.3. What is systems thinking?

In system theory, systems thinking is defined as a framework of thinking or an approach to thinking about systems. It is based on the principle that systems are wholes and that their elements should be examined in terms of their relevancy with each other. It is an approach for developing models to promote our understanding of events, patterns of behavior resulting in the events, and even more importantly, the underlying structure responsible for the patterns of behavior (Gharakhani, 2014). That is to say that it is a powerful approach for understanding the nature of why situations are the way they are, and how to go about improving results (Bailey, 1994). When we speak of a 'problem' in this respect, it does not necessarily mean that there is something wrong. *It means there is a situation that needs to be understood and a solution to be determined*; a new opportunity or idea that is worthy of further consideration.

Systems thinking has been defined as an approach to problem solving that attempts to balance holistic thinking and reductionistic thinking. By taking the overall system as well as its parts into account, systems thinking is designed to avoid potentially contributing to further development of unintended consequences. There are many methods and approaches to systems thinking (what systems thinking researchers call a "pluralism"). Recent scholars, however, are focused on the "patterns that connect" this pluralism of methods, this search for universal patterns that cut across the pluralism of individual methods of systems thinking is called "universality" (see Figure 3.16).

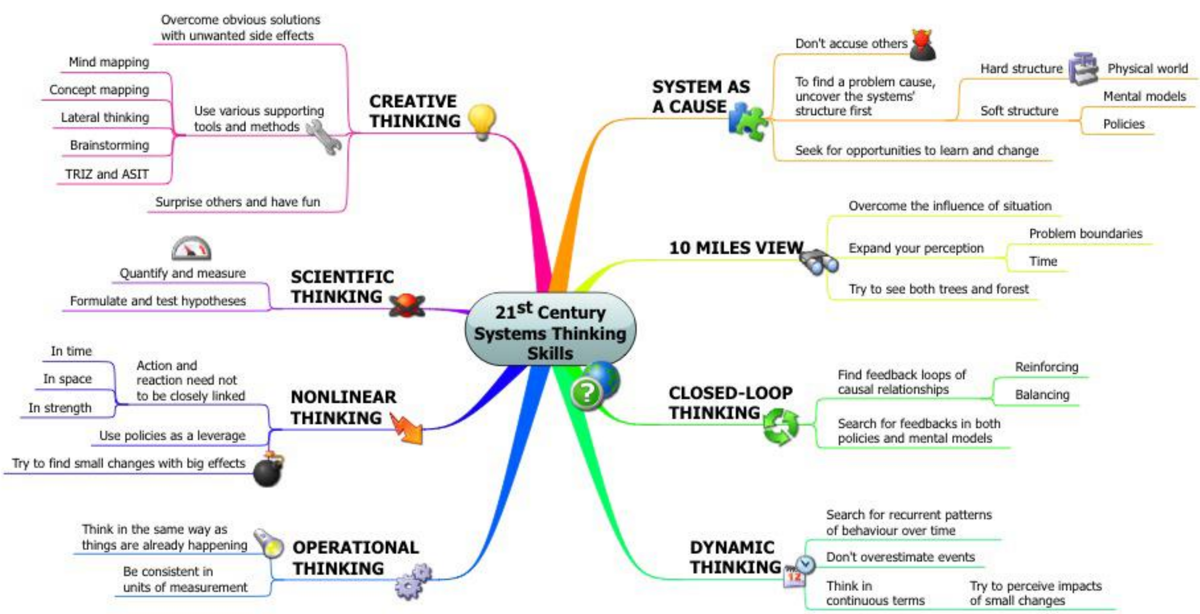


Figure 3.16. 21st century Systems thinking skills (This is an overview of systems thinking skills. It is inspired by works of Barry Richmond, George Richardson and of course Peter Senge. Author: Viktor Vojtko[3])

A key to find out about systems thinking is that it represents an alternative to our modern scientific way of thinking that is primarily focused upon breaking things down into their constituent parts in order to analyze them and then tries to understand the whole system as simply the sum of these individual elements (Gharakhani, 2014). This approach results in a vision of a world that is made of

[3] http://www.vivasystems.cz

isolated components that interact in a pre-determined linear fashion; what is sometimes called the clockwork universe (Davis, 1991). The overall functioning of the system is then achieved by defining and overarching bottom-up plans based on how these components feedback together. In order to achieve this overall functionality of the system, it is important the elements can be constrained that is to say that they are relatively static and their behavior can be pre-determined and thus controlled (Cheung, 2008). This approach works well when we are dealing with sets of things that do not have emergent attributes; but because some systems (in fact many systems) have this emergent properties as an integrity, this method which is also called 'reductionism' does not always work best (Bailey, 1994). In which cases we need to use systems thinking that places a greater emphasis upon understanding systems in their entirety and within the environment that gives them context (see Figure 3.17). Comparing to the previous approach which is based on components analysis, the second one stands on the synthesis between the elements and called 'holism' that is realized as modern philosophy (Stanford Encyclopedia of Philosophy, 2004; Noorani, 2009) to 21st century.

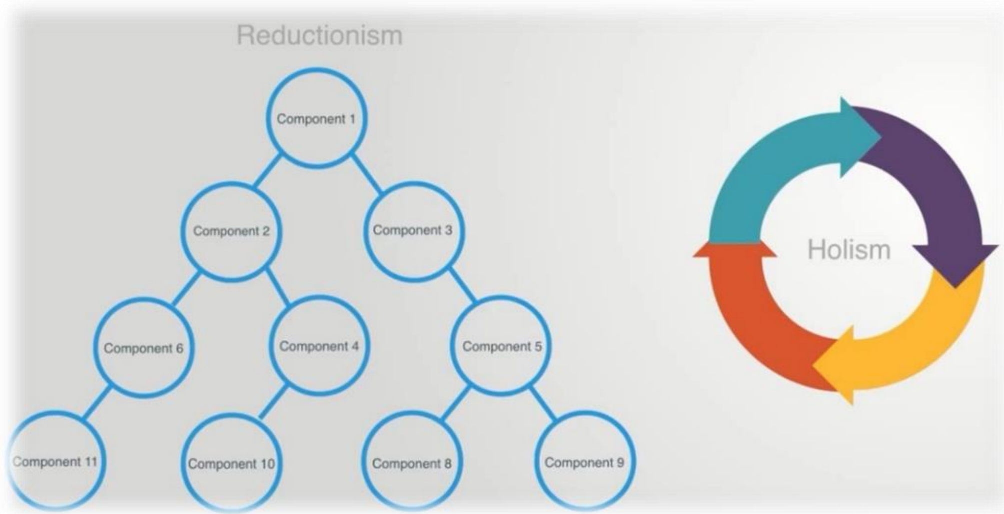


Figure 3.17. Reductionism (fundamental of modern science) [Analysis approaches (e.g. physic)], VS. Holism (new era to 21st century) [Synthesis approaches (e.g. ecosystems, computer networks, social systems)] (source: Complexity Academy, 2015)

3.2.3.1. Application of Systems Thinking

Systems thinking enables effectual understanding, management, design, and modification systems. It enables seeing complex situations and experiences as a whole. The whole cannot be seen unless it is viewed over the time, from multiple perspectives, from the outside (objectively – micro scale insight), and from the inside (macro scale insight). Systems thinking, thinking types, systems thinking tools, and levels of understanding are all part of the overall process for comprehending complex systems (Stroh, 2000).

Systems thinking looks for patterns in complexity in those things that look complex on the surface but in fact have some simpler order beneath the surface. This is referred to as apparent complexity (Frensch et al., 1995). It applies to those cases where apparent complexity is high and inherent complexity is low (Stroh, 2000). Systems thinking results into the - more effective problem solving - decision making, communications, design, planning and more effective organizational development. It is then increasingly being used to tackle a wide variety of subjects in fields such as computing, engineering, epidemiology, information science, health, manufacture, management, sustainable development, and the environment.

Advantages of using systems thinking is around:

- More effective problem solving
- More effective decision making
- More effective communications
- More effective planning
- More effective organizational development

3.2.3.2. Hard and Soft Systems Thinking

A frequent problem comes across when discussing hard and soft system themes with people is that the terms 'hard' and 'soft' are rarely defined clearly. Checkland (2004) describe is a more useful way of characterizing hard and soft systems views. Instead of the rather vague association of soft with the social world, people, and human intentionality, the soft systems view moves away from this ontological commitment and treats the definition as a question of epistemology, i.e. what can we know or find out about the world? The following quote from Checkland (2004) addresses this epistemological position; it is:

> "(…) phenomenologist, social constructivist, avoiding ontological commitment – sees the perceived (social) world as: culturally extremely complex; capable of being described in many different ways; and sees the "system" as one useful concept in ensuring good-quality debate about intentional action. The two observers both agree that the notion "system" can be useful, O seeing it simply as a name for (parts of) the real world, E seeing it as a useful intellectual device to help structure discussion, debate and argument about the real world." stated by Checkland (2004)

where observer O corresponds to the ontological position and observer E to the epistemological (Checkland, 2004), see Table 3.2 and Figure 3.18.

Table 3.2. Comparisons between Hard and Soft Thinking

Hard Systems Thinking	Soft Systems Thinking
- Oriented to goal seeking - Assumes the world contains "systems" that can be engineered - Assumes systems models to be models of (part of) the world (ontologies) - Talks the language of "problems" and "solutions" - Philosophically: positivistic - Sociologically: functionalist - Systematically: lies in the world	- Oriented to learning - Assumes the world is problematical but can be explored using systems models of concepts of purposeful activity to define "action to improve" - Assumes systems models to be devices: intellectual constructs to help debate (epistemologies) - Talks the language of "issues" and "accommodations" - Philosophically: phenomenological - Sociologically: interpretive - Systematically: lies in the process of inquiry into the world

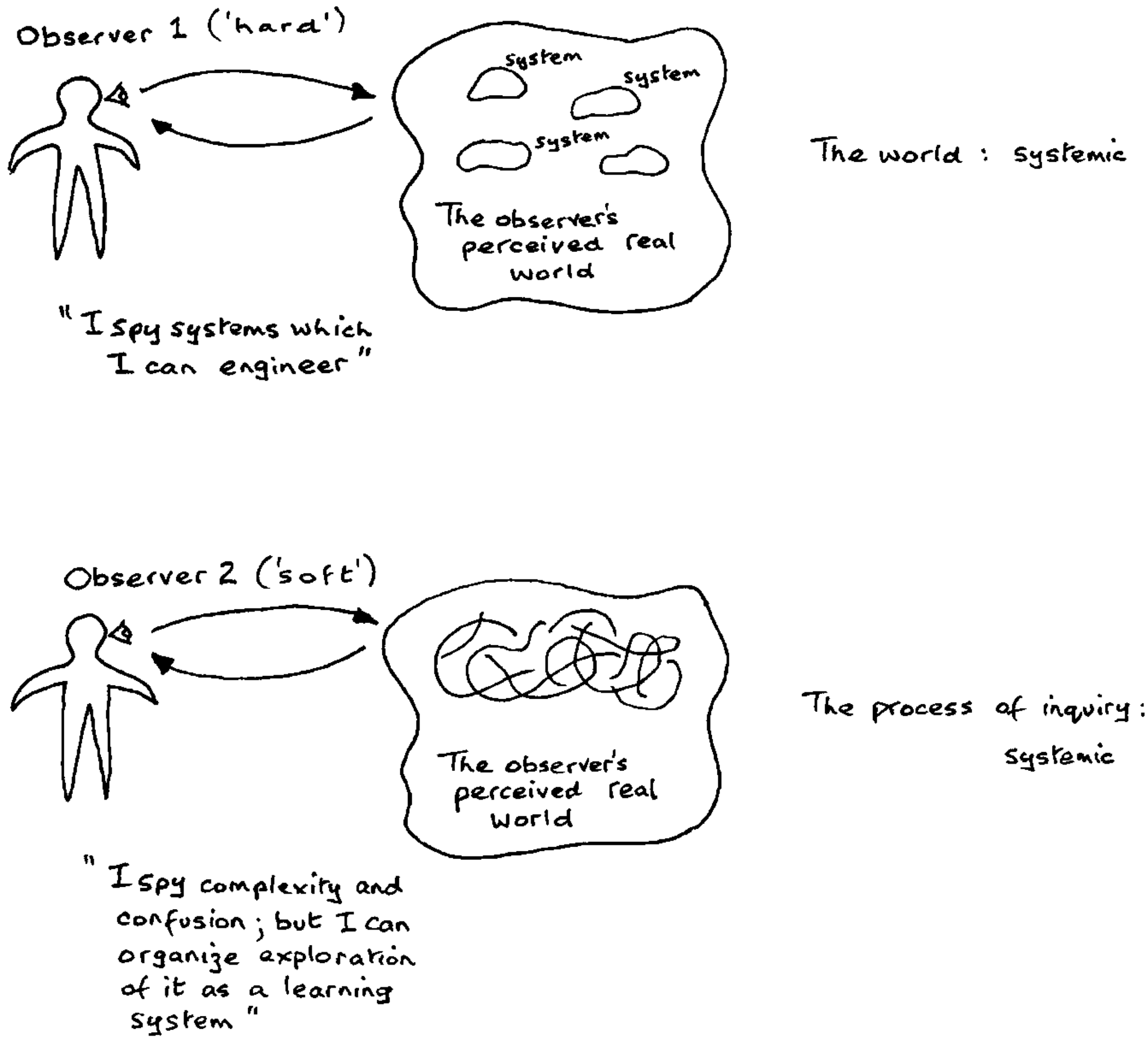


Figure 3.18. The hard and soft systems stances (source: Checkland, 2000)

3.2.3.3. Hard and Soft Systems Methodologies

In systems theory (and also similar approaches based on the same fundamental ideas, such as RAND Corporation systems analysis and classic OR - Operation Research) the word 'system' is used simply as a label for something taken to exist in the world outside ourselves. The taken-as-given assumption is that the world can be taken to be a set of interacting systems, some of which do not work very well and can be engineered to work better. In the thinking embodied in SSM the taken-as-given assumptions are quite different. The world is taken to be very complex, problematical, and mysterious. However, according to Checkland (2000), the process of inquiry into it, is assumed that, can itself be organized as a learning system. Thus, the use of the word 'system' is no longer applied to the world, it is instead applied to the process of our dealing with the world. It is this shift of systemicity (or 'systemness') from the world to the process of inquiry into the world which is the crucial intellectual distinction between the two fundamental forms of systems thinking, 'hard' and 'soft' (Checkland, 2000).

Systems thinking exploit a variety of methods that can be distincted into hard systems and soft systems. Hard Systems (HS) involves simulations, often using computers and the techniques used in operations research. Hard systems consider the "How?" meaning, how to best attain and examine the selected option of expansion and analysis. Hard Systems methodologies are beneficial for problems that can justifiably be quantified (Checkland, 2004). However, it cannot easily take into account unquantifiable factors (opinions, culture, politics, etc), and may treat people as being inactive, rather than having complex incentives. HS have an explicit objective governed by fixed rules such as those encountered in decision making (Pidd, 2004). OR is a hard, well defined system. Examples of areas that apply hard systems methodology are:

- Project Management
- Forecasting
- Simulation
- Mathematical Programming
- Decision Theory

Another characteristic of hard systems that it is:

- Stochastic – Statistically based on probability
- Deterministic – fixed inputs and known outputs

Soft Systems Methodologies (SSM) are used to tackle systems that cannot easily be quantified, particularly those involving public interacting with each other or with "systems". Useful for comprehending motivations, viewpoints, and interactions but, obviouly, it does not give quantified answers. Soft Systems is a field that the academic Checkland (2004) has carried out much to develop. But Soft Systems looks at the "What?" of the system; what to do to gain an improvement, usually analysis before application or implementation? SSM considers the following:

- Systems that could be envisaged
- Human activity
- Clarification of the problem
- Improve the understanding
- Based on Ideas:
- Examine
- Learn about and Study
- Understand
- Select and Focus

Hard systems analysis addresses those elements of enterprise that have a tangible form. These techniques address these problems (Morecroft, 2007):

- Identify cost/savings
- Improve methods
- Develop User Requirements

whereas soft system analysis attempts to (Morecroft, 2007):

- Understanding complexity
- Promote learning
- Identifying weakness
- Understanding relationships

Therefore, the differences between hard and soft systems methodologies can be described as following:

Hard systems - rigid techniques and procedures to provide unambiguous solutions to well-defined data and processing problems, focused on computer implementations (see Table 3.3)
Soft systems - a loose framework of tools to be used at the discretion of the analyst, focused on improvements to organizational problems (see Table 3.3)

Table 3.3. Comparisons between Hard and Soft Approaches (Source: Morecroft, 2007)

Hard Systems Approaches	Soft Systems Approaches
- More traditional way of viewing systems in Computing Science - Systems analysis (structured methods), systems engineering, operations research assume: • Objective reality of systems in the world • Well-defined problem to be solved • Technical factors foremost • Scientific approach to problem-solving • An ideal solution	- Engineering approach can be inappropriate for 'soft problems' (with fuzzy requirements). - Approaches (Soft Systems Methodology, Soft OR) assume: • Organizational problems are 'messy' or poorly defined • Stakeholders interpret problems differently (no objective reality) • Human factors important • Creative, intuitive approach to problem-solving • Outcomes are learning, better understanding, rather than a 'solution
- Problem has a definite solution	- There are many 'problems' to be solved
- Problem has a number achievable goals	- Goals cannot be measured
- They answer the 'how' questions	- Emphasis is placed on 'what' as well as 'how'
- Has a deterministic complexity	- Has a unpredictable, nondeterministic, non-definable complexity
- Likely to have defined parameters for failure	- Less easily dealt with

3.2.3.4. Soft systems thinking approaches

Churchman's (1971) Social Systems Design is recognized as a major influence on research in complex problem solving and Decision Support Systems (DSS). An element of his approach is the insistence that the systems designer's first obligation in carrying out a systems study is not to the decision makers, rather it is to the "clients", customers, or beneficiaries of the system (Churchman, 1971). The above requirement, together with Churchman's recommendation to strive for "whole systems improvement" influenced the work in the three cases discussed in (Petkov et al., 2007).

Strategic Assumptions Surfacing and Testing (SAST) (based on Mason et al., 1981) is an operationalization of many of the ideas of Churchman. The SAST methodology can be regarded as having four major stages: group formation of stakeholders with similar vested interests, assumption surfacing, dialectical debate, and synthesis. Assumption surfacing is conducted by applying the Nominal Group Technique (NGT). Petkov et al. (2007) discuss that a corner stone of SAST is the assumption that opposing viewpoints can be brought together through dialectical debate. On the basis of the fact that stakeholders may have an overarching common goal associated with the improvement of the current situation, one can employ only the first two stages of the SAST methodology. However, the case that involves very diverse stakeholders and intervention involves using all four stages of SAST.

Interactive Planning (IP) (based on Ackoff et al., 1993) is a broad systemic approach to planning involving the following stages: formulation of the mess, ends planning, means planning, resource planning, design of implementation and control. Petkov et al. (2007) argue that phase 2, ends planning, has several steps itself: preparation of a mission statement, development of a list of desired properties stakeholders agree should be built into the system, preparation of idealized design of the organization, formulation of the closest approximation to the design that is believed to be attainable and identifying the gaps between the approximation and the current state of the system (Jackson, 2003). An idealized design is the design for the enterprise that the stakeholders would replace the existing system with today, if they were free to do so (Jackson, 2003). It can be conducted without any considerations for constraints in the process or by taking the features of the internal and external environment into account. Ackoff et al. (1993) assumes that one may apply any of the existing approaches that are relevant for a specific stage of IP.

Soft Systems Methodology (SSM) was developed by Checkland in the 1970s as a strategy for handling complex problems, including those involving socio-technical systems (Checkland et al., 1999). Instead of being based upon the paradigm of "optimization", it is rather founded on the paradigm of "learning". The original methodology can be described as a seven-stage process of analysis which uses the concept of a human activity system as a means of getting from "finding out" about a situation to "taking action" to improve the situation (Checkland et al., 1999). The essence of stages 1 and 2 is to find out what the problem is. That is summarized in a "rich picture" which expresses the features of the situation. Rich pictures are cartoon-like images that capture the structure of a problem, the processes involved and the relationships between structure and processes. They are better means for recording relationships and connections than is linear prose (Checkland et al., 1999).

In stage 3, the root definitions describing the new system are formulated by identifying six CATWOE analysis elements (Checkland et al., 1999):

- Customers: the victims/beneficiaries of the purposeful activity.
- Actors: those who are involved in the activities.
- Transformation process: the purposeful activity transforming an input into an output.
- Weltanschauung: the view of the world that makes the root definition meaningful in context.

- Owners: who can stop the activity.
- Environmental constraints, affecting the situation.

In stage 4, the conceptual models for the future solutions are built by drawing out the minimum number of verbs that are necessary to describe the activities that would have to be present to carry out the tasks named in the root definition. In the fifth stage, these models are compared with reality. The last stage involves the implementation of changes that are both desirable and feasible. This formulation of SSM is known these days as "mode 1" SSM (Checkland et al., 1999). Mode 2 SSM was introduced as a two-stream inquiry in 1990: a logic-based stream of analysis and a stream of cultural analysis, including also social system analysis and political system analysis (Checkland et al., 1999).

Petkov et al. (2007) argue that what unites SAST, Interactive planning and SSM is their focus on the systemic enquiry as a learning process, through which the stakeholders get to understand better the problem situation through the intervention. Another distinctive feature of soft systems thinking is its support for multiple perspectives (Linstone, 1984). The three perspectives for analyzing complex problems, as defined by Linstone (1984), are the Technical, Organizational and Personal Perspectives. All of the above considerations reflect Churchman's idea:

> "The systems approach starts when you look at a problem through the eyes of another". stated by Churchman (1971).

3.2.3.5. "Four Main Activities Method" of SSM

Soft systems methodology (SSM) is an approach to organizational process modeling and it can be used both for general problem solving and in the management of change. It was developed in England by academics at the University of Lancaster Systems Department through a ten year action research program. Checkland (2000) has a section to his paper, which collects four different representations of SSM between 1972 and 1990 and correctly suggests that these 'show how the methodology has become less structured and broader as it has developed' (Checkland, 2000). They are as followings:

- 1972 — Blocks and Arrows
- 1981 — Seven Stages4
- 1988 — Two Streams
- 1990 — Four Main Activities

[4] 7-stage representation of SSM (Checkland et al., 1981):

1) Enter situation considered problematical
2) Express the problem situation
3) Formulate root definitions of relevant systems of purposeful activity
4) Build conceptual models of the systems named in the root definitions
5) Comparing models with real world situations
6) Define possible changes which are both possible and feasible
7) Take action to improve the problem situation

In this thesis there is no space to describe all of these methodologies in detail except the most recent developed one which is called “Four Main Activities”.

In the book by Checkland et al. (1990) an updated description of SSM is given based on "several hundred applications of the approach by a wide range of people and groups in many different countries" and "SSM is no longer perceived as a seven-stage problem-solving methodology" but "is now seen as one option in a more general approach" (see Figure 3.19).

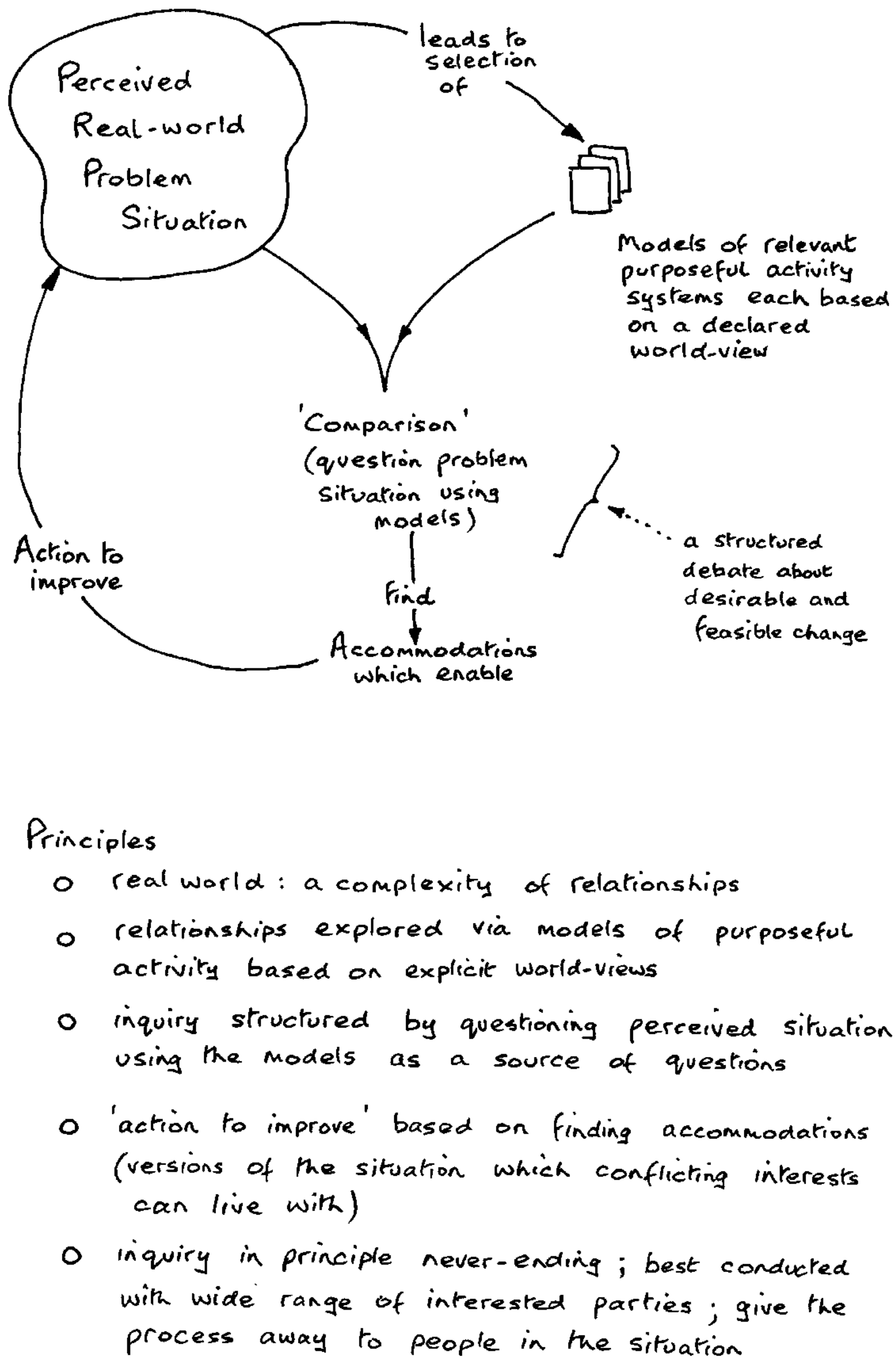


Figure 3.19. The inquiring/learning cycle of SSM (source: Checkland, 2000)

The version presented was the four-activities model (Checkland et al., 1990) of which Figure 3.18 in this chapter is a contemporary form. This is iconic rather than descriptive, and subsumes the cultural stream of analysis in the four activities, which it implies rather than declares.

The four activities are, however, capable of sharp definition:

1) Finding out about a problem situation, including culturally/politically;
   - *Rich Picture Building:* the rich pictures will draw attention to the (usually) many people or groups who could be seen as stake-holders in any human situation, and Analysis One's list of possible, plausible 'problem owners', selected by the 'problem solver', is always a main source of ideas for 'relevant systems' which might usefully be modelled (See Figure 3.20 and 3.21 – an example in NHS [National Health Services]).
   - *Analyses One, Two and Three*

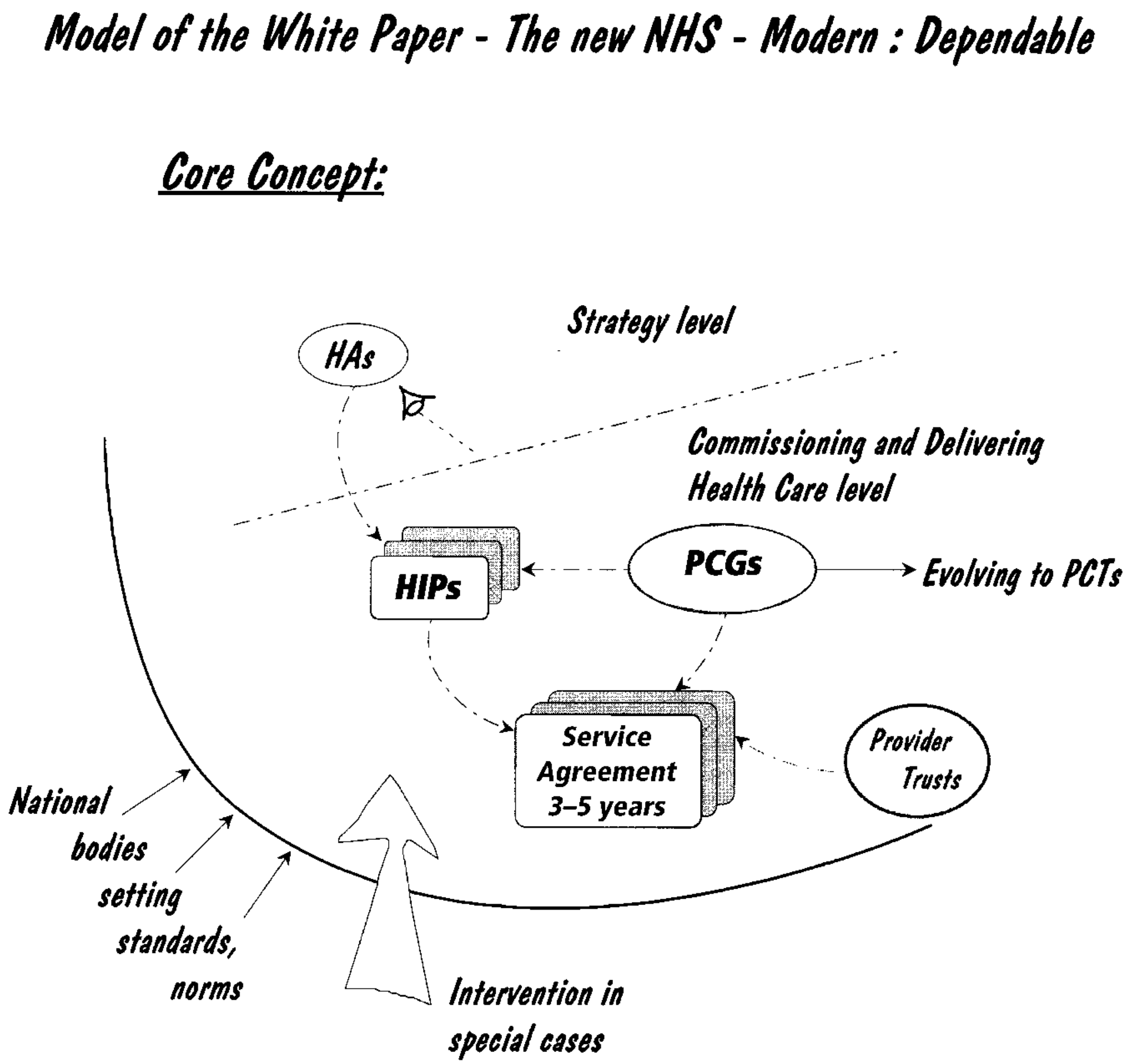


Figure 3.20. The core concept of the NHS White Paper 1997 (HA=health authority; HIP =health improvement plan; PCG =primary care group; PCT =primary care trust) (source: Checkland, 2000)

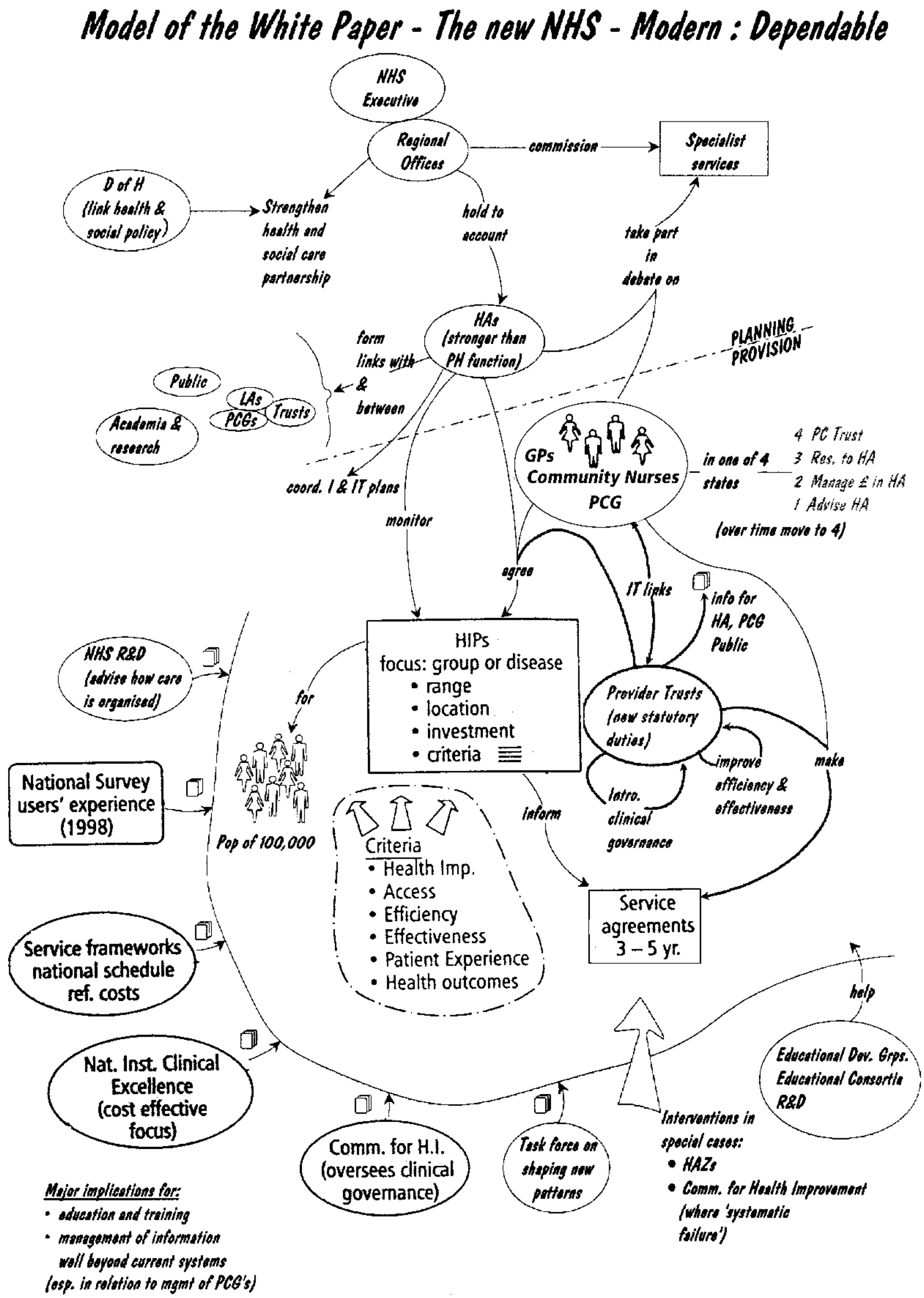


Figure 3.21. The White Paper concept of the New NHS 1997 (D of H=Department of Health; HAZ=health action zone; HI =health improvement; PH=public health) (source: Checkland, 2000)

2) Formulating some relevant purposeful activity models;
   - *The Role of Modelling in SSM:* The purposeful activity models used in SSM are devices — intellectual devices — whose role is to help structure an exploration of the problem situation being addressed. Models in SSM are accounts of concepts of pure purposeful activity, based on declared world-views, which can be used to stimulate cogent questions in debate about the real situation and the desirable changes to it. They are thus not models of (…) anything; they are models relevant to debate about the situation perceived as problematical. They are simply devices to stimulate, feed and structure that debate.
   - *Root Definitions, CATWOE[5] and Multi-level Thinking:* To build a model of a concept of a complex purposeful activity for use in a study using SSM, we require a clear definition of the purposeful activity to be modelled. These definitional statements, SSM's 'root definitions', are constructed around an expression of a purposeful activity as a transformation process T. Any purposeful activity can be expressed in this form, in which an entity, the input to the transforming process, is changed into a different state or form, so becoming the output of the process. A bold sparse statement of T could stand as a root definition, for example 'a system to make electric toasters', but this would necessarily yield a very general model. Greater specificity leads to more useful models in most situations, so the T is elaborated by defining the other elements which make up the mnemonic CATWOE. In recent years, experience has shown the value of not only including CATWOE elements in definitions but also casting root definitions in the form: do P by Q in order to contribute to achieving R, which answers the three questions: What to do (P), How to do it (Q) and Why do it (R)? 'Do P by Q' is richer, answering the question: how? And also forcing the model builder to be sure that there is a plausible theory as to why Q is an appropriate means of doing P (See Figure 3.22). The formal aim of this kind of thinking prior to building the model is to ensure that there is clarity of thought about the purposeful activity which is regarded as relevant to the particular problem situation addressed. The idea of levels, or layers (or 'hierarchy', though that word tends to carry connotations of authoritarianism which are not relevant here) is absolutely fundamental to systems thinking. Figure 3.22 summarizes the importance of thinking consciously at several different levels, and also makes the point that different people might well make different judgments about which level to take as that of 'the system'. 'What' and 'how', 'system' and 'sub-system' are relative, not absolute concepts.

[5] There are six elements of CATWOE (Jarvis, 2009):

- Customers - Who are the beneficiaries of the highest level business process and how does the issue affect them?
- Actors - Who is involved in the situation, who will be involved in implementing solutions and what will impact their success?
- Transformation Process - What is the transformation that lies at the heart of the system - transforming grapes into wine, transforming unsold goods into sold goods, transforming a societal need into a societal need met?
- World View - What is the big picture and what are the wider impacts of the issue?
- Owner - Who owns the process or situation being investigated and what role will they play in the solution?
- Environmental Constraints - What are the constraints and limitations that will impact the solution and its success?

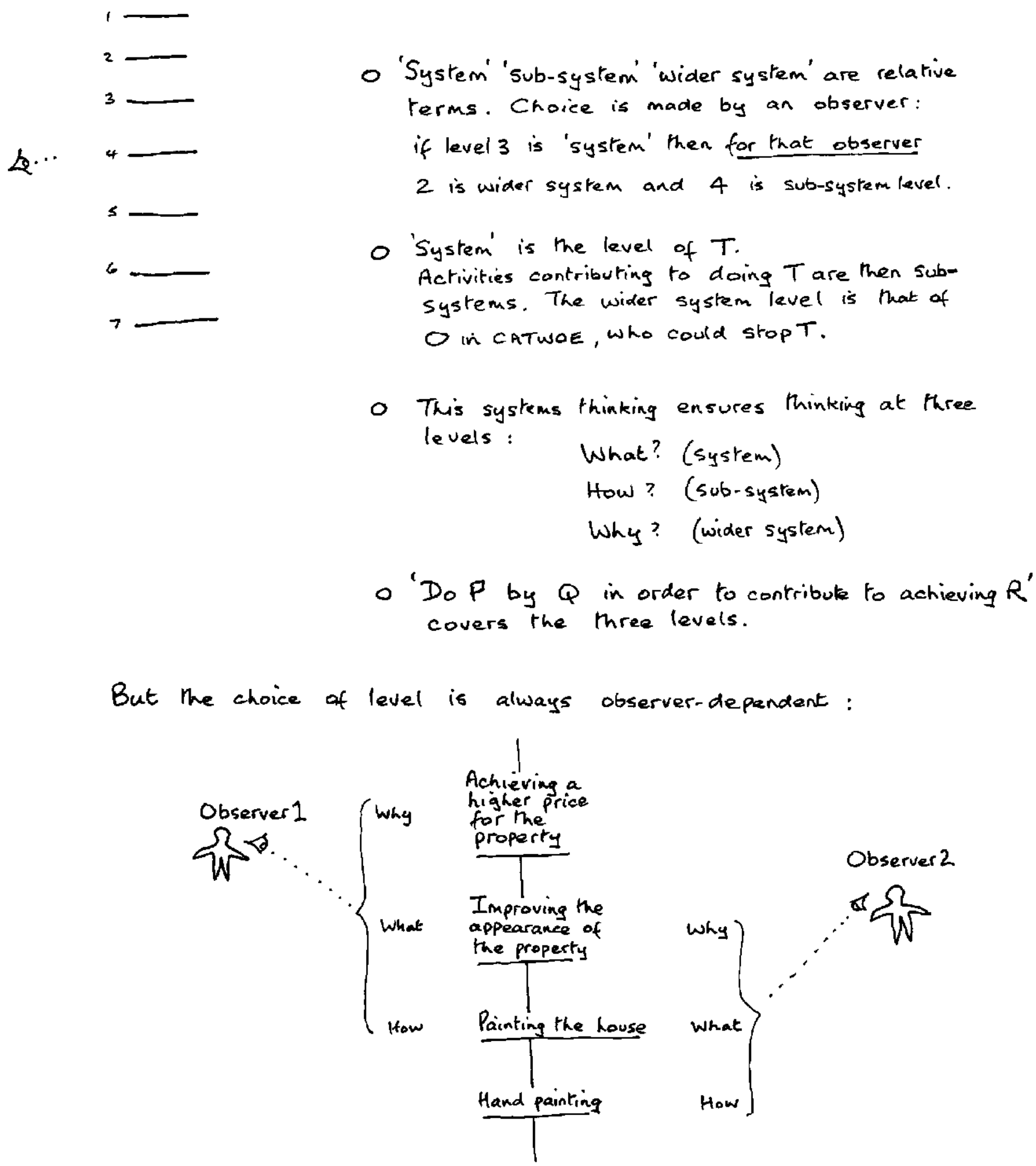


Figure 3.22. Systems thinking entails thinking in layers defined by an observer (source: Checkland, 2000)

- *Measures of Performance:* the core systems image is that of the whole entity which can adapt and survive in a changing environment. So our models, to use systems insights, need to be cast in a form which in principle allows the system to adapt in the light of changing circumstances. That is why models of purposeful activity are built as sets of linked activities (an operational system to carry out the T of CATWOE) together with another set of activities which monitor the operational system and take control action if necessary. Since there is no such thing as completely neutral monitoring, it is necessary to define the criteria by which the performance of the system as a whole will be judged. Hence the core structure of the monitoring and control sub-system is always the same: a 'monitor' activity contingent upon definition of the criteria by which system performance will be judged, and an activity rendered as 'take control action' which is contingent upon the monitoring. Measuring the performance of a logical machine can be expressed through an instrumental logic which focuses on three issues: checking that the output is produced; checking whether minimum resources are used to obtain it; and checking, at a higher level, that this transformation is worth doing because it makes a contribution to some higher level or longer-term aim. This gives definitions of the '3Es' which will be relevant for every model: the criteria of efficacy (E_1), efficiency (E_2), and effectiveness (E_3), first developed in 1987 (Forbes et al., 1987; Checkland et al., 1990; SSMA, pp. 38, 39). This core set of criteria can be extended in particular cases — for example by adding E_4 for ethicality (is this transformation morally correct?) and E_5 for elegance (is this an aesthetically pleasing transformation?).

- *Model Building:* Given the preliminary thinking expressed in root definition, CATWOE, the three Es and PQR, assembling an activity model ought not to be difficult: simply a matter of assembling the activities required to obtain the input to T, transform it, and dispose of the output, ensuring that activities required by the other CATWOE elements are also covered; then link the activities according to whether or not they are dependent upon other activities. Because most practitioners initially 'feel their way' to a method of modelling comfortable for them, it may be helpful to provide some templates which derive purely from the logic of the process and which may provide help for those just starting to use the process of SSM. Two such templates are provided here; they are meant to be abandoned as experience grows. Figure 3.23 sets out a logical procedure for modelling purposeful activity systems in a series of steps; Figure 3.24 expresses the process in Figure 3.23 as a partial activity model. In Figure 3.24 the process form emphasizes the exercise of judgment during modelling. Iteration around activities 2, 3, 4 continues until it is felt that the minimum but necessary cluster of activities has been assembled; the wider iterations around activities 1 to 6, and around 1-6-4-5 represent the checks that the model is defensible in relation to the concept being expressed.

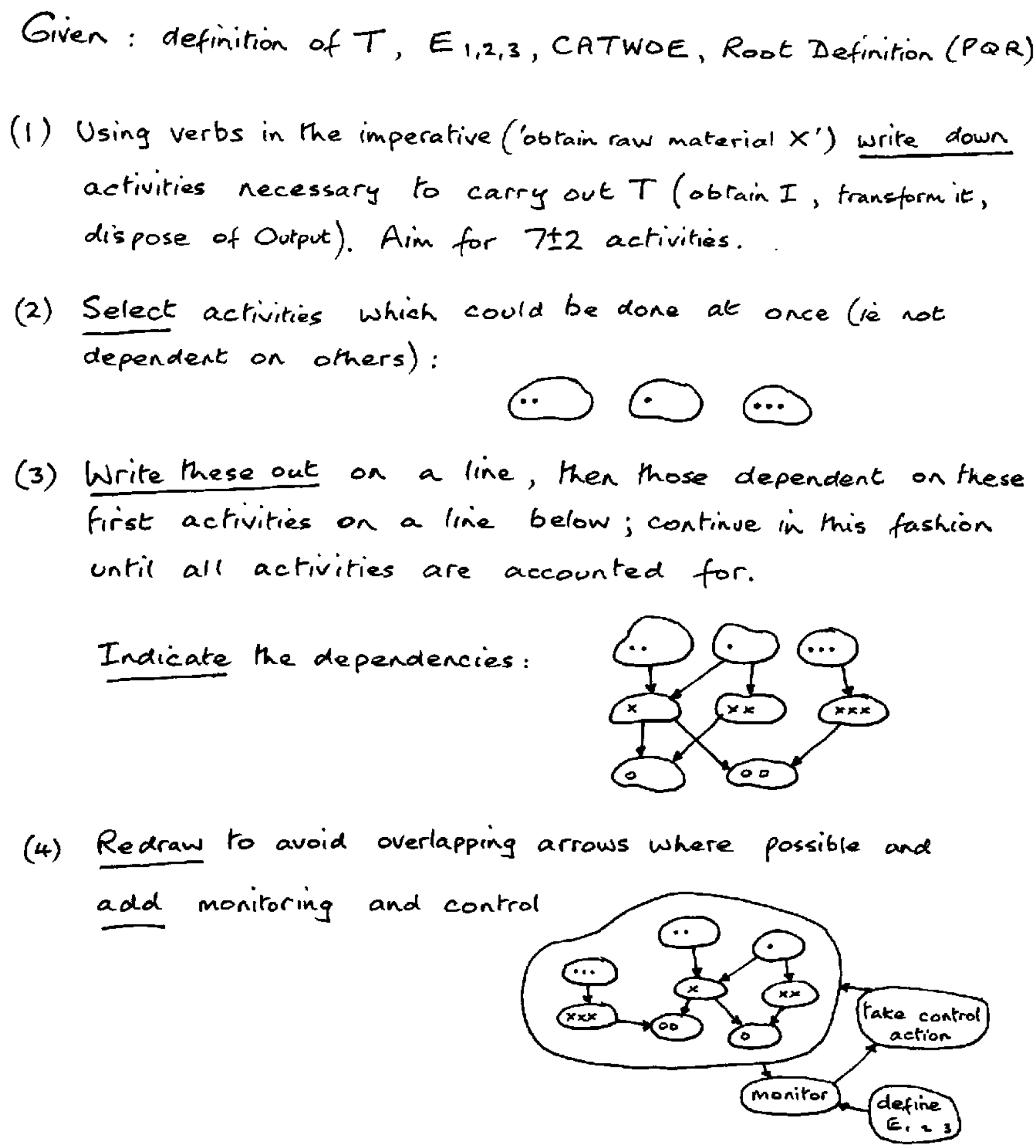


Figure 3.23. A logical procedure for building activity models (source: Checkland, 2000)

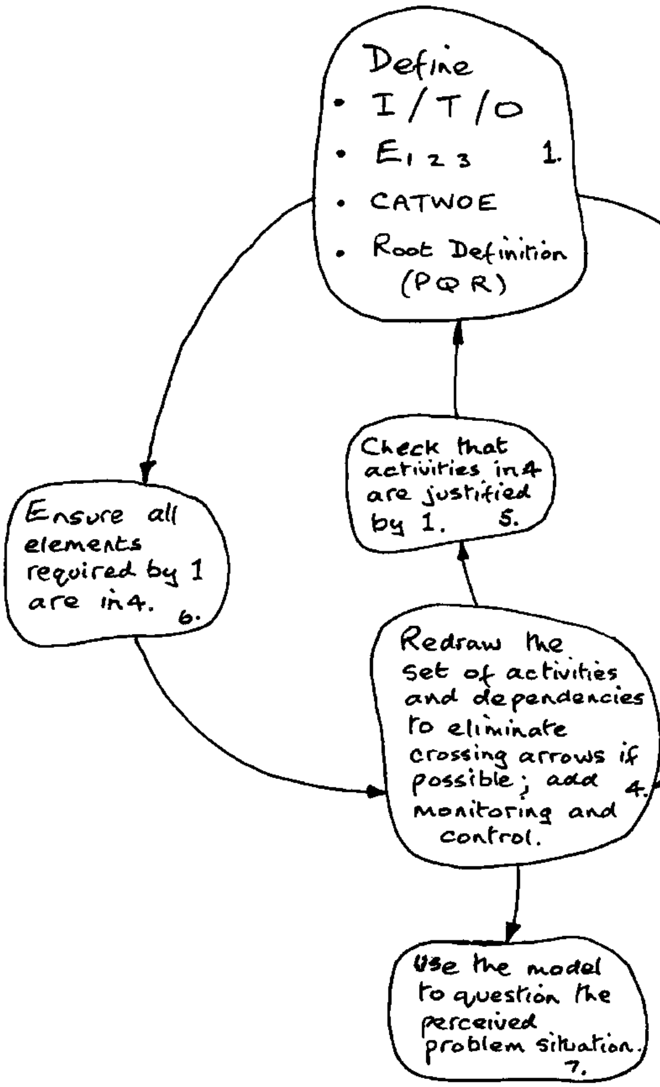


Figure 3.24. The process of modelling in SSM, embodying the logic of Figure 3.23. (source: Checkland, 2000)

3) Debating the situation, using the models, seeking from that debate both
    a. changes which would improve the situation and are regarded as both desirable and (culturally) feasible, and
    b. the accommodations between conflicting interests which will enable action-to improve to be taken;

   ((a) and (b) of course are intimately connected and will gradually create each other.)

4) Taking action in the situation to bring about improvement.

   In the first (action-oriented) case the change sought can usefully be thought about in terms of structural change, process change and changes of outlook or attitude. Normally in human affairs any explicitly organized change will entail all three, and the relationship and interactions between the three need careful thought. In general, thinking about desirable and feasible change can initially be structured in the way shown in Figure 3.25. A most important feature of this is the need in human affairs to think not only about the substance of the intended change itself but also about the additional things you normally have to do in human situations to enable change to occur. The second broad category of use to which SSM-style activity models can be put is to use them to make sense of complex situations (though that sense making may of course also lead on to action being taken). It is significant that this category of use has grown markedly in the last decade of SSM development, as concepts such as 'organization', 'function', 'profession' and 'career' have all become more fluid.

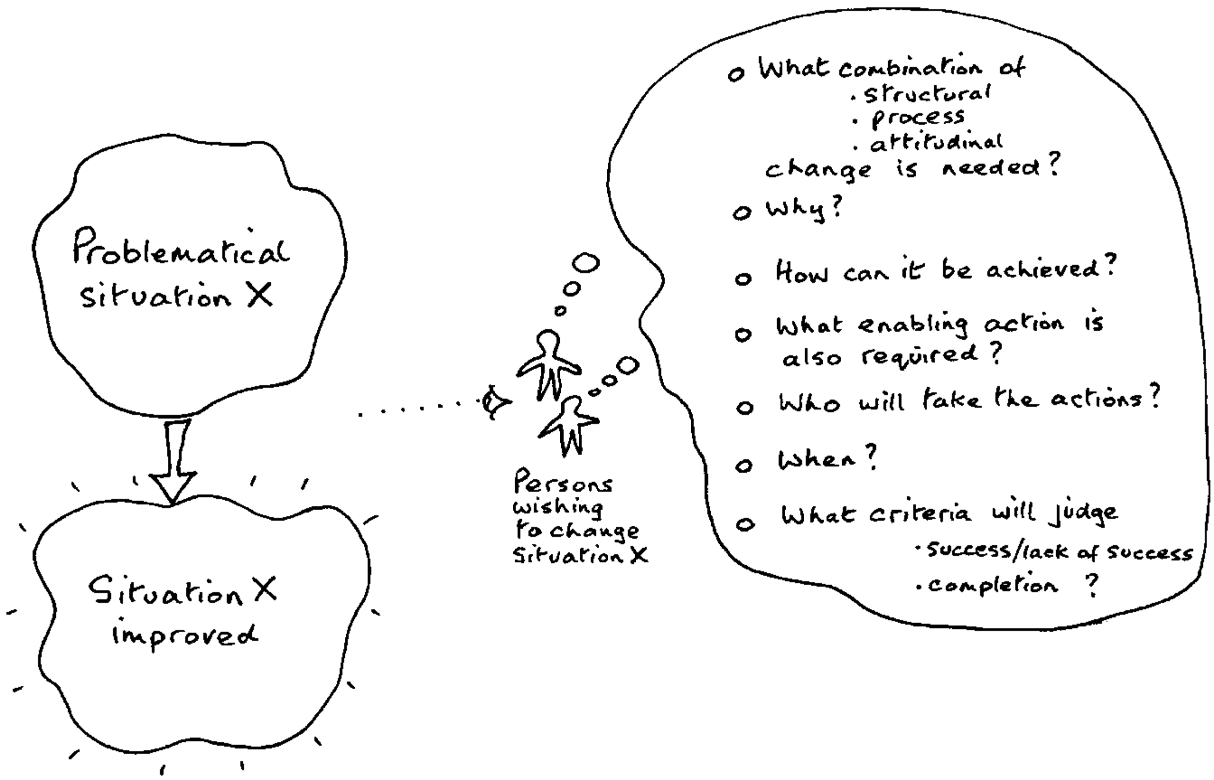


Figure 3.25. Thinking about desirable and feasible change (source: Checkland, 2000)

3.2.3.6. Evolutionary Systems

Evolutionary systems are a type of system, which reproduce with mutation whereby the fittest elements survive, and the less fit die down (see Figure 3.26). Bánáthy (1996) discussed that evolutionary systems are characterized by "moving equilibria and the dynamics of co-evolutionary interactions which cannot be foreseen ex ante." Bánáthy (1996) developed a methodology that is applicable to the design of complex social systems. This technique integrates critical systems inquiry with soft systems methodologies. Evolutionary systems, similar to dynamic systems are understood as open, complex systems, but with the capacity to evolve over time. Bánáthy uniquely integrated the interdisciplinary perspectives of systems research (including chaos, complexity, and cybernetics), cultural anthropology, evolutionary theory, and others.

Figure 3.26. Concept of Evolutionary Systems (source: Complexity Academy, 2015)

3.2.4. The Environment of a system

Generally speaking, the environment of a system is coterminous with the reality outside the system. The definition of a system as a set of interconnected elements can be supplemented in a following way: "A system may be defined as a set of elements standing in interrelation among themselves and with environment" (Williamson et al., 2003). This extended definition incorporates connections between the elements of a system with the reality outside – the environment. But even though the elements of the system interact with the environment, their internal connections are stronger (see Figure 3.27).

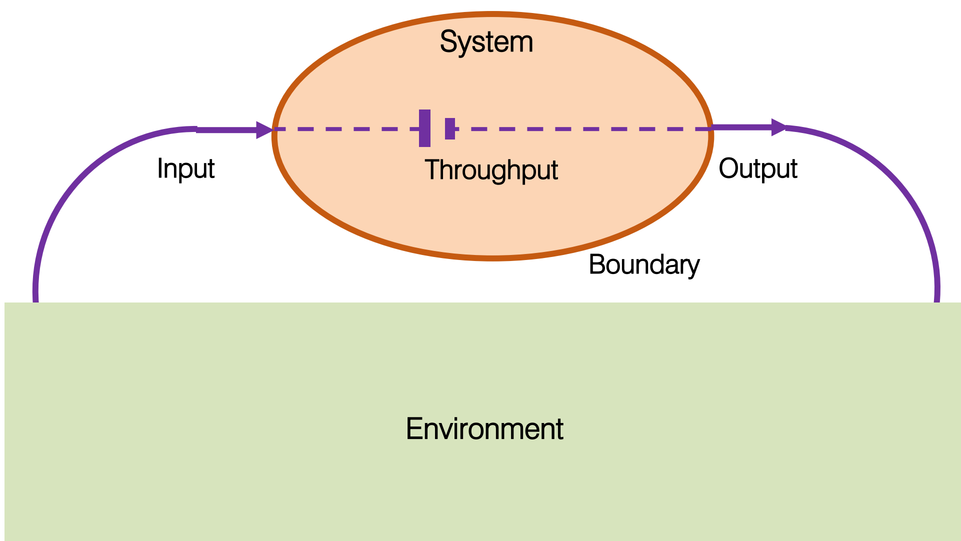


Figure 3.27. Environment of a system

Although different types of systems (from a cell to the human body, soap bubbles to galaxies, ant colonies to nations) look very different on the surface, they have remarkable similarities. At the most basic level, systems are divided into two categories: (1) Closed systems: theoretical systems that do not interact with the environment and are not influenced by its surroundings. Only the components within the system are significant. Example: a sealed jar--nothing enters or exits the jar, but whatever is inside can interact. (2) Open systems: real-world systems whose boundaries allow exchanges of energy, material and information with the larger external environment or system in which they exist.

Williamson et al. (2003) discuss that there are three types of systems in terms of their interaction with the environment (see Figure 3.28):

1) Open systems: systems that interact with their environments (by exchanging energy, matter or information with the environment)
2) Close systems: The notion of a closed system appears in thermodynamics and it denotes a system that exchanges energy but not matter with the environment. One example is a fluid compressed by a piston in a cylinder.
3) Isolated systems: systems that do not exchange energy, matter or information with the outside world, and thus, the elements of the isolated system do not interact with the environment. The isolated systems do not exist in physical reality (except the universe itself); they are only useful concepts, approximations of real phenomena. An example of such a conceptual isolated system can be a model of our solar system.

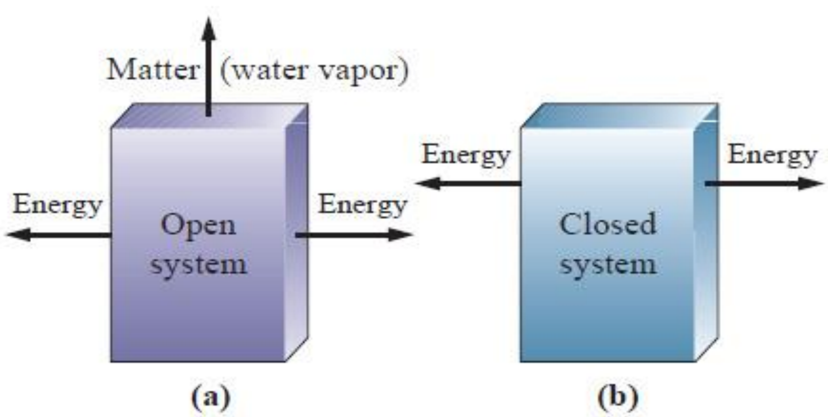


Figure 3.28. Types of the systems based on their interactions with their environment (source: Williamson et al., 2003)

3.2.4.1. Natural and Artificial Systems Environment

The environment of transformation for artificial systems is a mental space, while the environment of change for natural system is a physical space (Estkowski, 2013). In both conditions change is caused by forces from the environments:

- In the case of artificial systems, the environment is distinguished by a socio-cultural space (in the case of buildings, the environment is defined more individually by a specific physical site and user intentions)
- In the case of natural systems – the environment is defined by a physical space (the mechanism of development is not caused by deliberate and conscious human action, but by a 'blind' process of eliminating less fitted organism).

3.2.4.2. Boundary of a system

A system is a set of interconnected elements, which is discernible from its surroundings. The strongly related elements that make a system can be referred to as an 'inside', while the environment of the system can be referred to as an 'outside' (see Figure 3.29). The inside is separated from the outside – there is a boundary between the system and its environment. According to Cabrera (2006), a boundary is not itself an object, but it is rather a distinction between the object and what is not.

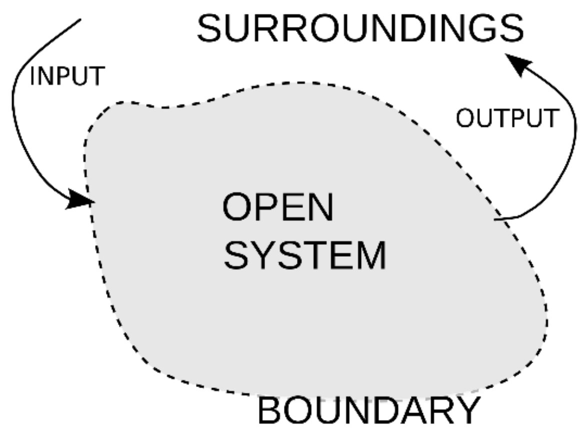


Figure 3.29. Boundary of a system – a space between an 'inside' and an 'outside'

There are systems that do not exist in the physical space: conceptual systems. A plan of construction of an artificial system is a mental construct (Estkowski, 2013). It is a system of interconnected representations, conceptualizations and images referred to as a physical space – a model of an artefact. In this case, the boundary can be understood in three ways:

- 'Physically' – in an intuitive way, like in the case of the physical objects, i.e., the outer surfaces of constitutive elements of the object are their boundaries. A model of a car would have boundaries defined by its physical realization, though the former is a mental construct. The boundaries of a car model would dynamically follow the alterations of the model during the design process.

- ‘Functionally’ – as in the ‘Minimal Cell Model’, i.e., as embracing only the elements of the system that are necessary to its function. Unlike the cells, models of artefacts are somehow difficult to examine following principles of functionality. The reason for this is that the necessary functions of an artefact are not as easy to determine as a function of a cell. For example, is it sufficient that a car transports people or should it provide comfort and safety for the passengers?
- ‘Inclusively’ – in a complex, comprehensive way, where the physical and functional boundaries would only be a point of departure for a much more comprehensive definition. The definition would include a net of references for each element of a designed artefact. In a mental model, the elements of an artefact do not exist independently as abstract entities, but they are defined through a net of references to a broader, ‘existential’ space (function in society, symbolic connotations). In other words, they are symbols, attaining a meaning and thus boundaries through an act of interpretation.

3.2.5. What is a complex system and complexity theory?

Some of the systems we have to design and develop today are highly complex. They may consist of million or even billions of components (constituents); many different stakeholders with miscellaneous objects, dense network of interconnections and interdependencies that may be unknown and still evolving over time (Complexity Academy, 2015). Complexity science is not a single theory— it encompasses more than one theoretical framework and is highly interdisciplinary, seeking the answers to some fundamental questions about living, adaptable and changeable systems (MacLennan, 2007). The truly grasping and experiencing the complexity of these systems is intimating to save a list.

The only way to overcome this complexity of the real world that surrounds us is through abstraction (see section 3.2.4.3); that is to say conceptual models capture the underlying features whilst tightening away the details (see Figure 3.30). In the world of complex systems design it is complexity theory that offers us these basic abstract conceptual models to work with (Frensch et al., 1995).

Figure 3.30. Using Abstraction to overcome the existing complexity of the systems (source: Complexity Academy, 2015)

Complexity theory has emerged out of a number of different areas over the past few decades, in particular from ecology, society, engineering, and so on (Jones et al., 2005). All of these very different areas have found themselves trying to model, design and manage what we now call complex systems (Bar-Yam, 2002) that could be defined as systems composed of many different parts that are highly interconnected and interdependent and are capable of adaptation (see Figure 3.31).

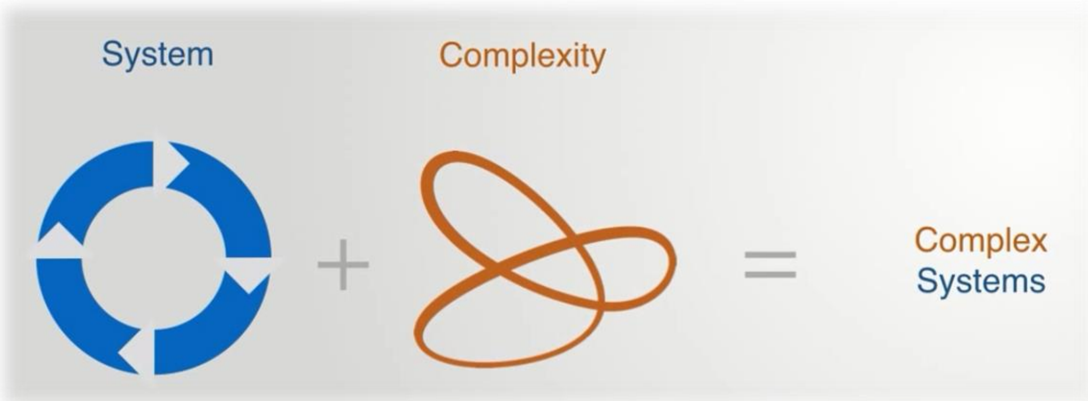


Figure 3.31. The definition of Complex Systems (source: Complexity Academy, 2015)

The fact that the elements within a system perform some collective function is that systems are set to be greater than the sum of its parts. That is to say that the system as a whole has properties and functionality that none of its constitution elements possess. This is called the concept of emergence in systems theory (see Figure 3.32).

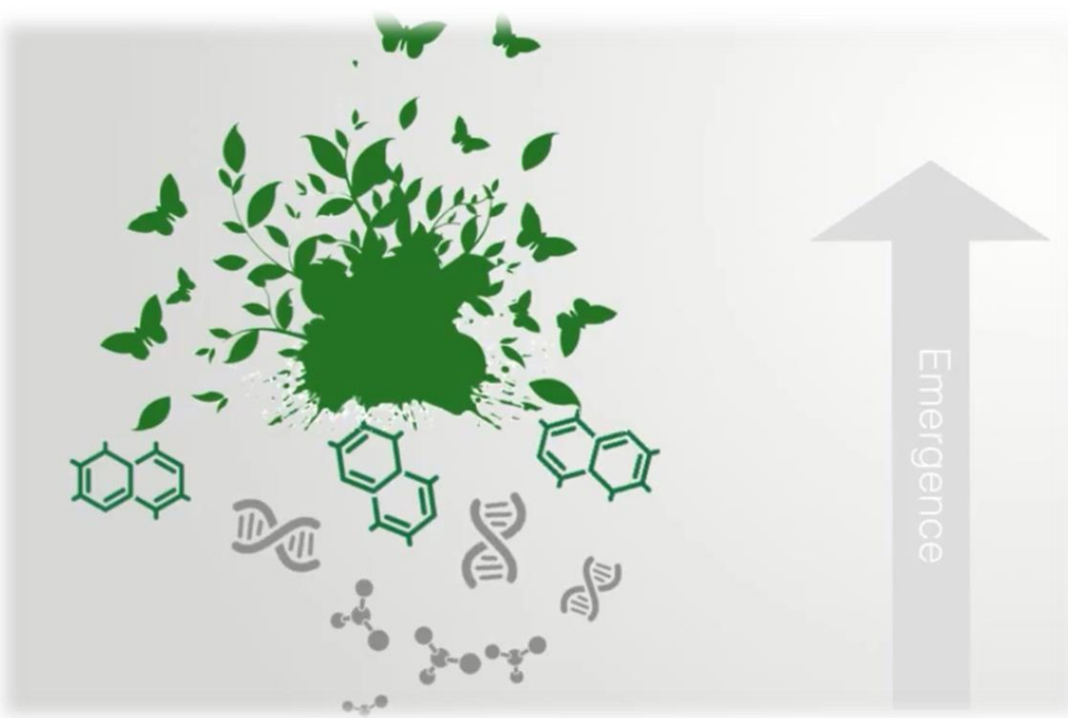


Figure 3.32. Concept of Emergence in Systems Theory (source: Complexity Academy, 2015)

Systems have a number of properties that make them complex. In summary, they include:

- The number of elements within our systems; so more parts are there then more complex it will be (see Figure 3.33);

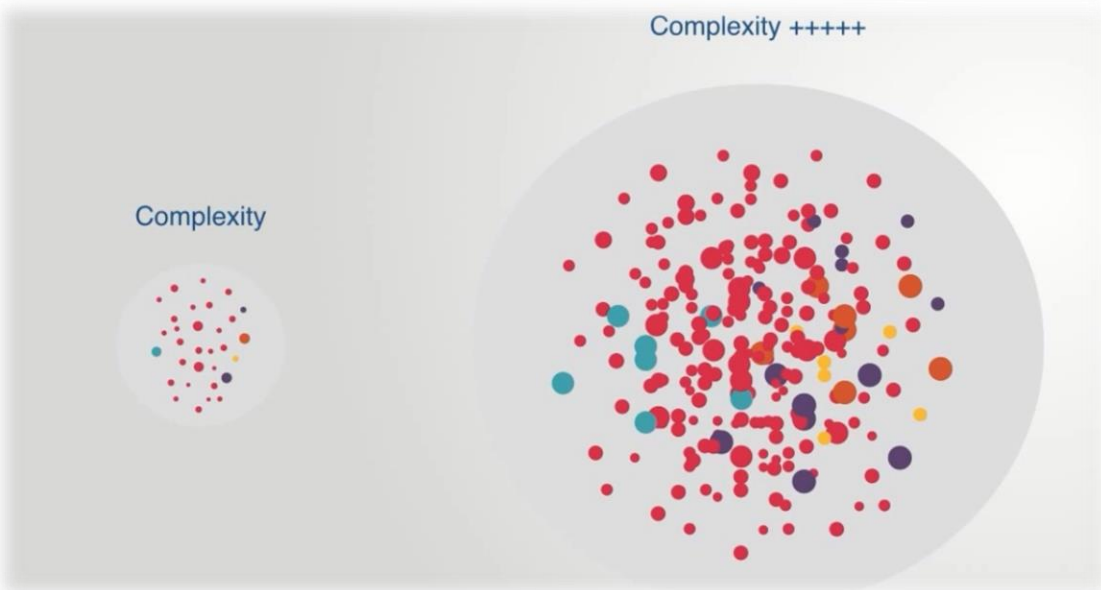


Figure 3.33. Complexity of the Systems increases when the number of elements increases (source: Complexity Academy, 2015)

- Complexity is a product of the degree of connectivity between its elements; the more interconnected and interdependent they are, the more complex our system will be (see Figure 3.34).

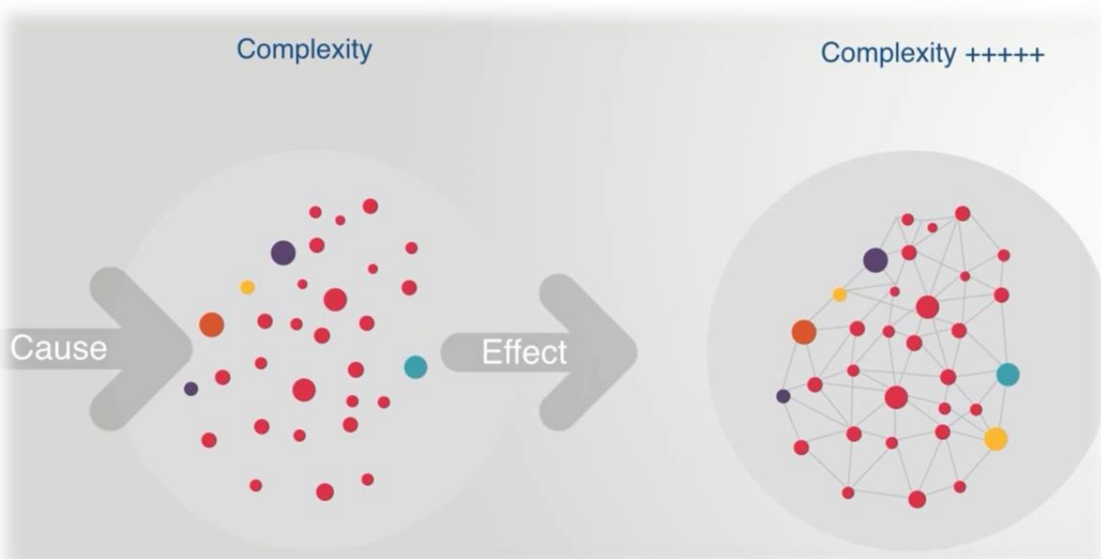


Figure 3.34. Complexity of the Systems increases when the number of elements increases (source: Complexity Academy, 2015)

So simple systems are linear and complex systems are nonlinear, which is the key property of complex systems (see Figure 3.35).

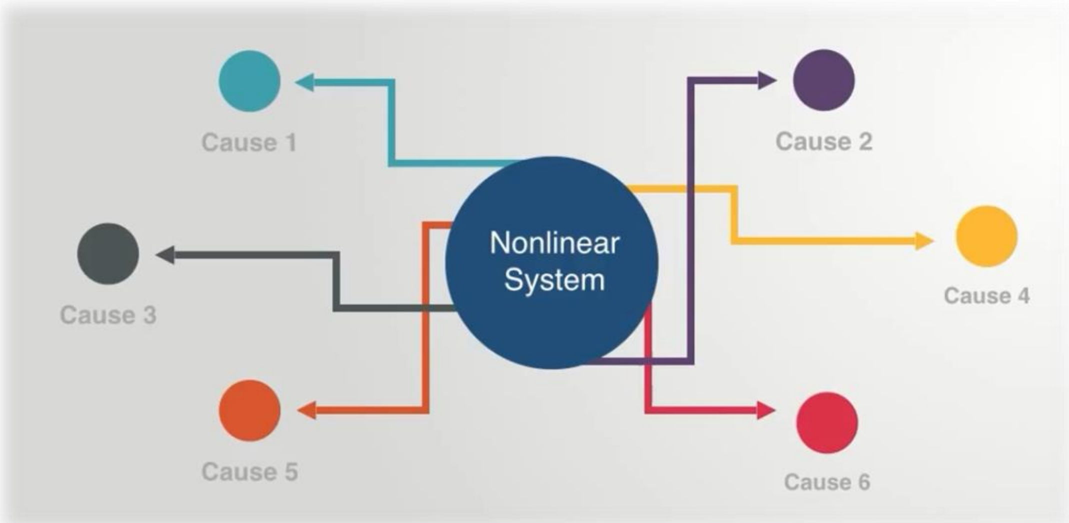


Figure 3.35. Nonlinearity in Complex systems (source: Complexity Academy, 2015)

- Complexity is a product of the diversity between the elements and concept of homogeneity versus heterogeneity; to say with other words, elements in complex systems are more heterogeneous (see Figure 3.36).

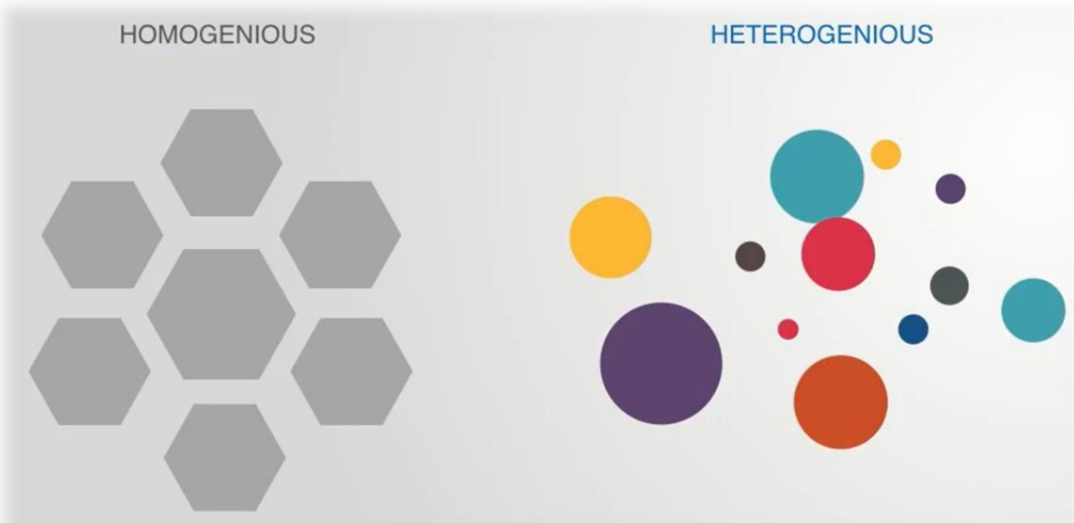


Figure 3.36. Diversity of Components in Complex systems (source: Complexity Academy, 2015)

- Complexity is the product of Degree of autonomy and adaptation of the elements within the system. When the elements have a very low level of autonomy then the system can be designed, managed and control centrally in a top-down fashion. However, as we increase the autonomy of the elements, this becomes no longer possible, as control and organization become distributed and this is increasingly interactions on the local levels that come to define how the system develops (see Figure 3.37).
  This gives rise to another important feature of complex systems that is Self-organization. When elements have the autonomy to adopt locally, they can self-organized the form of

global patterns, the process through which take places called emergence. Thus as opposed to simple linear systems where order typically comes from some form of top-down centralized coordination, patterns of order within complex systems emerge from a bottom-up. Self-organization will be another requiring theme in exploration of complex systems design.

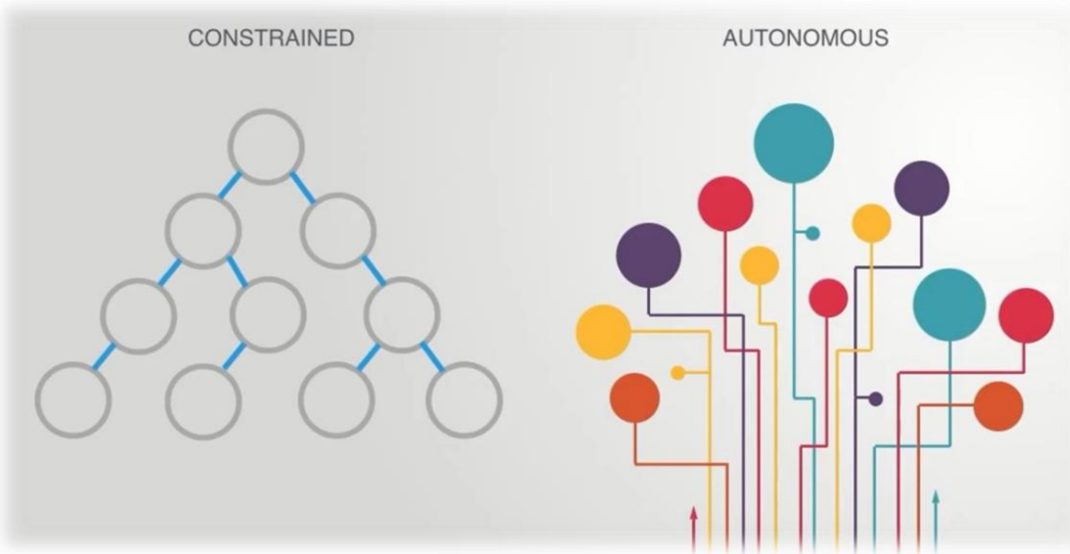


Figure 3.37. Concept of Autonomy of the elements in Complex systems (source: Complexity Academy, 2015)

Following the discussion by Complexity Academy (2015), complex systems can be defined as systems composed of multiple and diverse parts that are highly interconnected and capable of adaptation (i.e. financial markets with lots of different highly interconnected trades adapting to each other's behavior as they interact through buying and selling, or an eco-system with multiple different components that are all interdependent and adapting to each other and their environment or a supply chain network with a many different producers and distributers interacting and adapting to each other in order to deliver a product etc.), see Figure 3.38.

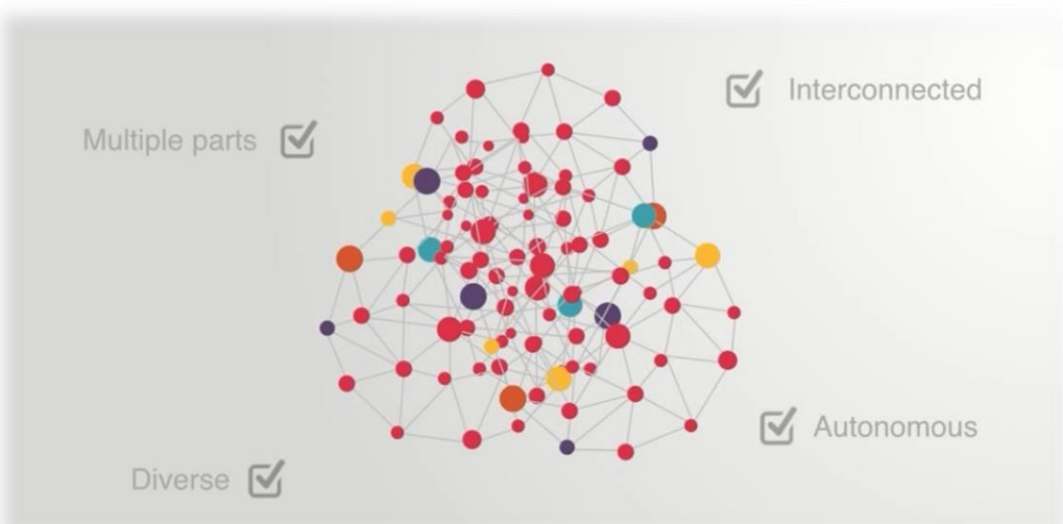


Figure 3.38. Complex systems constituent's properties (source: Complexity Academy, 2015)

3.2.6. Principles of using Systems Thinking

Stowell (2012) argue that the systems thinking approach incorporates several tenets:

- *Interdependence of objects and their attributes* - independent elements can never constitute a system
- *Holism* - emergent properties not possible to detect by analysis should be possible to define by a holistic approach
- *Goal seeking* - systemic interaction must result in some goal or final state
- *Inputs and outputs* - in a closed system inputs are determined once and constant; in an open system additional inputs are admitted from the environment
- *Transformation of inputs into outputs* - this is the process by which the goals are obtained
- *Entropy* - the amount of disorder or randomness present in any system
- *Regulation* - a method of feedback is necessary for the system to operate predictably
- *Hierarchy* - complex wholes are made up of smaller subsystems
- *Differentiation* - specialized units perform specialized functions
- *Equifinality* - alternative ways of attaining the same objectives (convergence)
- *Multi-finality* - attaining alternative objectives from the same inputs (divergence)

Considering use of systems thinking especially in design process, there are methods and techniques, which are used in order to understand and explore the complexity of the system, including Ethnographic Studies, Risk Analysis, Scenario Thinking etc. Systems Oriented Design (SOD) by Sevaldson et al. (2010) is one of the well developed methods in Industrial Design domain which follows similar principles. SOD is a new version of systems thinking and systems practice that is developed from within design thinking and design practice. It is systems thinking and systems practice tailored by and for designers. It draws from designerly ways of dealing with super-complexity derived from supreme existing design practices as well as refers to established perspectives in modern systems thinking, especially SSM, Critical Systems Thinking and Systems Architecting. Further on it is based on design skills like visual thinking and visualization in processes and for communication purposes. For this purpose, SOD uses GIGA-mapping, ZIP-Analysis, Rich Design Space, Incubation Techniques or War rooms, and Layered Scenario Mapping (Sevaldson et al., 2010; Sevaldson, 2013).

3.3. Summary

This section provided an overview about engineering design, and systematic design approaches through identifying the principles of systems theory and thinking, which is currently employed in other domains such as 'industrial design' and 'mechanical design'. The intent in this broad coverage has been both for background and review purposes. It is hoped that in doing so, an appreciation has been gained for engineering design and the approaches that have been investigated to provide more details about its methods.

Almost certainly, the debate among researchers over whether methods should focus on approaches that are purely scientific in nature or whether there is benefit to heuristic methods will likely continue indefinitely (the difference is highlighted further in chapter 4). In either case, it is clear that much is to be gained from advances pertaining to knowledge organization, model representation, and synthesis methods.

A systematic design methodology should allow for a problem-directed approach and foster inventiveness and understanding. It has to compatible with the concepts, methods and findings of other disciplines. It should not rely on finding solutions by chance and it should facilitate the application of known solutions to related tasks. A design methodology should be compatible with electronic data processing, be easily taught and learned and lastly reflect the findings of cognitive psychology and modern management science; i.e. reduce workload, save time, prevent human error, and help to maintain active interest.

Designers need better methods to cope with complex systems. Research is still needed to assist modeling in the early stages of conceptual design. Beyond models for abstraction (functional model representations), methods are also needed to bridge the gap between abstraction and detail, i.e., methods that support informed decision making and integrated design processes.

Contrary to ideal models of design processes, complex problems are not 'solved' in abstraction and then passed on to a more detailed level of design. In addition to evaluating feasible functional alternatives, other factors such as cost, size, availability, quality, assembly, the age of the technology, and numerous other life-cycle factors require consideration early in decision processes.

Systems theory and thinking Engineering Design realm from provides methods from, which are relevant for approaching a holistic building design. Particularly, the existing complexity in the problems of building design are similar to problems of systems theory in the following areas:

- specialization form disciplines are involved (interdisciplinarity),
- there are a number of objectives which need to be met,
- many objectives may rule out each other,
- a solution might partly define a problem.

Using systemic approaches through an adaptive procedure consisting of the iterative cycles enables us to capture and address the complexity of the concepts towards considering cause-effect relationships of decisions where the new actions and decisions needs to be taken. Hereafter, the designer will be on the way primarily to integrate various disciplines of knowledge such as social issues beside financial barriers to create seamless frame of understanding of everything. Application of systematic design methodologies for building renovation will be discussed further in section 5 of the present thesis.

Described with more details in previous chapter, this thesis presents a new framework capable of bridging the gap between Transformational (cultural) and Incremental (technological/physical) which in other words can be referred to “soft” and “hard”; blending SSM and MCDM approaches in an integrated methodology for design stage renovation projects. The variations between soft systems and hard systems were covered in this section, comprehensively. It is hoped that in doing so, an appreciation has been gained for their variations and internal insights and mechanisms while they face a problem. Nevertheless this will be elaborated in subsequent chapters (see chapter 4), it is obvious that mixing these approaches in an integrated methodology and transforming it into a multi-methodology reflect the conflicting nature of the problems and guiding decision makers in complex situations and harness their potential to support learning about the problem and hence more effective decision support. The mixing and application of these methods in this thesis and therefore for development of a *Holistic Multi-methodology for Building Renovation – HMSR* is discussed further in section 6.

CHAPTER III
MULTIPLE CRITERIA DECISION MAKING (MCDM)

CHAPTER'S SYNOPSIS

"The purpose of this chapter is to introduce the reader into a theme of decision-making and particularly Multiple Criteria Decision Making (MCDM) and to position its various methods in the broader operational field. These definitions and properties will be exploited in chapter 4 for the development of elements and principles of an appropriate methodology for generation of renovation scenarios.

It should be underlined that the content of this chapter was developed while the author has been exploring the mentioned topics with very limited background or previous knowledge of them. The reason for this was discussed in chapter 1, so as a necessity for carrying an inductive approach out. Therefore, the above mentioned topics have been explored and the part of major findings has been used in the latest chapters. Nevertheless, the main purpose of providing the entire exploring story is to provide readers particularly those from architecture or architectural engineering domain to get familiar with the relatedness and notions of these terms as well as performing further research in future."

4. Decision-making using Multiple Criteria Decision Making (MCDM)

The outcomes of our decisions directly affect our occupational and personal lives. Decisions can be tough, and making well/beneficent decisions can be very inestimable (Parnell et al., 2013). Howard (1966) describes a decision as an irrevocable allocation of resources. Generally, decisions are made by people conceded with the authority and accountability to make decision. Many decisions involve people who are individuals and organizations that could be influenced by the subsequent outcomes of the decision. Some decisions are simple due to the number of involved decision-makers, the values are clear, good alternatives are readily identified, and there are few uncertainties. Nevertheless, some more complex decisions involve more decision-makers with potentially incompatible objectives, complex alternatives, substantial uncertainties, and major results. The discipline of *decision analysis*, has been developed to help decision makers with these complex decisions (Parnell et al., 2013). There are many definitions of *decision analysis*. Although numerous definitions of engineering design can be found in the literature, most include common elements. Consider the following definitions:

> Howard (1966), the inventor of the term *decision analysis*, describes it as "a body of knowledge and professional practice for the logical illumination of decision problems."
>
> Raiffa (1968) defines *decision analysis* as an approach that "prescribes how an individual faced with a problem of choice under uncertainty should go about choosing a course of action that is consistent with personal basic judgments and preferences."
>
> Keeney et al. (1976) states an intuitive and a technical explanation. He defines *decision analysis* as "a formalization of common sense for decision problems that are too complex for informal use of common sense". Parnell et al., 2013 argued that Keeney's technical explanation is "a philosophy, articulated by a set of logical axioms, and a methodology and collection of systematic procedures, based on those axioms, for responsibly analyzing the complexities inherent in decision problems."
>
> Phillips (2005) emphasizes that *decision analysis* is a sociotechnical process to provide visions to decision makers in organizations.
>
> As well, Clemen et al. (2001) discuss that *decision analysis* provides effective methods for organizing a problem into a structure that can be analyzed. In particular, elements of a decision's structure include the possible courses of action, the possible outcomes that could

> result, the likelihood of those outcomes, and eventual consequences (e.g., costs and benefits) to be derived from the different outcomes."

> Having a discussion over previous definitions, Parnell et al. (2013) address the following definition of *decision analysis* as "a philosophy and a social-technical process to create value for decision makers and stakeholders facing difficult decisions involving multiple stakeholders, multiple (possibly conflicting) objectives, complex alternatives, important uncertainties, and significant consequences. *Decision analysis* is founded on an axiomatic decision theory and uses insights from the study of decision making."

Parnell et al. (2013) continue that in *decision analysis* a good decision is different from a good outcome. A good decision is one that is logically consistent with our preferences for the potential outcomes, our alternatives, and our assessment of the uncertainties. A good outcome is the occurrence of a favorable event—one that we like. We believe that consistently making good decisions will lead to more good outcomes than otherwise. The authors (Parnell et al., 2013) mention that consistently making good decisions will lead to make better outcomes. Nevertheless, due to the uncertainty, we can not conclude that a good decision always lead to a good result. Parnell et al. (2013) argue that

> "since many individuals and social organizations are involved in complex decisions, to be successful, *decision analysis* must use a socio-technical process to help those individuals and organizations make decisions. Socially, the goal of *decision analysis* is to provide reliable, understandable, and timely visions to decision makers and key stakeholders in organizations. Technically, *decision analysis* is a processes research/management science discipline that uses probability, value, and utility theory to analyze complex alternatives, under substantial uncertainty, to provide value for stakeholders with multiple (and possibly conflicting) objectives."

Decision analysis relies on the reasonable axioms of multiple-choices, and hence *decision analysis* identifies decisions that are logically consistent with the existing priorities, various alternatives, and their evaluation of the uncertainties. For further exploration of this discussion, topics include: a briefly investigation Multiple Criteria Decision Making (MCDM) and its various methods.

4.1. Multiple Criteria Decision Making (MCDM)

Multiple Criteria Decision Making (MCDM) or Multiple Criteria Decision Analysis (MCDA) is a sub-discipline of Operations Research (OR) that explicitly considers multiple criteria in decision-making environments. Whether in our daily lives or in professional settings, there are typically multiple (conflicting) criteria that need to be examined in making decisions (Triantaphyllou et al, 1998). Cost or price is one of the main criteria usually. Some measure of quality is typically another criterion that is in conflict with the cost. In purchasing a car, cost, comfort, safety, and fuel economy may be some of the main criteria, which can be considered.

We usually weigh multiple criteria implicitly and we may be convenient with the outcomes of such decisions that are made based on only intuition. In making the decision of whether to construct a machine manufacturing factory and where to construct it or to renovate a district social housing sector or not, there are not only very complex issues involving multiple criteria, but there are also multiple stakeholders who are profoundly influenced by the results. In order to get more informed and better decisions we need structuring of the problems through consideration of multiple criteria. MCDM in this regard, facilitates also the process of resolving the trade-off between criteria (typically based on the preferences of a decision maker) when a solution works well with all criteria. MCDM have been categorized into different groups and methods. The more popular MCDM categories are Multiple Objective Decision Making (MODM) and Multiple Attribute Decision Making (MADM) (Climaco, 1997). MODM can be used for decision problems in which the decision space is continuous while MADM can be used for problems with discrete decision spaces (Triantaphyllou et al, 1998). Taha et al. (2013) discuss that the decision problem in MADM is characterized by the evaluation of a set of alternatives against a set of criteria rather than, as in MODM, the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints. Furthermore according to Xu et al. (2001), there are two distinctive types of MCDM problems due to the diverse problems settings: one type having a limited number of alternative solutions and the other an infinite number of solutions. Generally, in problems associated with selection and evaluation, the number of alternative solutions is finite. In problems related to design, an attribute may take any value in a confine. Therefore, the potential alternative solutions could be infinite. If this is the case, the problem is referred to as multiple objective optimization problems instead of multiple attribute decision problems.

4.1.1. Main features of MCDM

Although MCDM problems could be very different in context, Xu et al. (2001) discuss that they share the following common features:

Multiple attributes/criteria often form a hierarchy.

Almost any alternatives, such as an organization, an action plan, or a product of any kind, can be evaluated on the basis of attributes. An attribute is a property, quality or feature of alternatives in question. Some attributes may break down further into lower levels of attributes, called sub-attributes. To evaluate an alternative, a criterion is set up for each attribute. Because of the one to one correspondence between attribute and criterion, sometimes attributes are also referred to as criteria and used interchangeably in the MCDM context. MCDM itself can also be referred to as MADM if there are a limited number of alternatives.

Conflict among criteria.

Multiple criteria usually conflict with one another. For example, in renovation of an existing building, the criteria of better energy efficiency might aim to increase cost rating due to the use of better materials or building elements (i.e. application of double glazing windows).

Hybrid nature

- Incommensurable units.
  An attribute may have a various unit of measurement. For instance, in the renovation of exiting building, energy consumption is measured by KW per hour, and cost is expressed by Euro etc. In various decision issues, attributes may even be non-quantitative, such as the spatial quality of an internal or external space of a building, which should be demonstrated in a non-numerical way.
- Mixture of qualitative and quantitative attributes.
  It is possible that some attributes can be measured numerically and other attributes can only be characterized subjectively. For example, the cost of a renovation scenario is numerical and the indoor comfort rating is qualitative.
- Mixture of deterministic and probabilistic attributes.
  For example, in the renovation approaches selection, the price is deterministic and energy consumption could be non-deterministic. Energy consumption changes depending on building users consumptions habits.

Uncertainty

- Uncertainty in subjective judgments
  It is ordinary that people may not be 100% confident when making subjective judgments.
- Uncertainty due to lack of data or incomplete information
  Sometimes information of some attributes may not be fully presented or even not available at all.

Large Scale

A factual life MCDM problem may consist of hundreds of attributes. For instance, in the European Foundation for Quality Management (EFQM) business excellence model, there are 3 levels of criteria, 9 criteria in level 1, 32 in level 2, and 174 in level 3. In a supplier evaluation model for a large international company, there are 10 level 1 criteria and more than 900 sub-criteria.

Assessment may not be conclusive

Due to lack of information, the contradiction among criteria, the uncertainties in subjective judgment and different preferences among various decision makers, the final evaluation outcomes may not be conclusive. There could be many solutions to a MCDM problem as will be listed below.

4.1.2. MCDM solutions

MCDM problems may not always have a conclusive or unique solution. Hwang et al., (1981) discuss that there are various names are given to various solutions depending on the nature of the solutions including:

Ideal solution

All criteria in a MCDM problem can be classified into two classes. Criteria that are to be maximized are in the profit criteria category, although they may not necessarily be profit criteria.

Likewise, criteria that are to be minimized are in the cost criteria category. An ideal solution to a MCDM problem would maximize all profit criteria and minimize all cost criteria (Xu et al., 2001). Generally, this solution is not acquirable.

Non-dominated solutions

If a desired solution is not obtainable, the decision maker may look for non-dominated solutions. An alternative (solution) is dominated if there are other alternatives that are better than the solution on at least one attribute and as good as it on other attributes (Xu et al., 2001). An alternative is called non-dominated if it is not dominated by any other alternatives.

Satisfying solutions

Satisfying solutions are a reduced subset of the feasible solutions with each alternative exceeding all the anticipated criteria. A satisfying solution may not be a non-dominated solution. Whether a solution is satisfying depends on the level of the decision maker's expectation.

Preferred solutions

A preferred solution is a non-dominated solution that best satisfies the decision maker's expectations.

4.1.3. Compensatory and non- compensatory MCDM methods

There are two types of MCDM methods. One is compensatory and the other is non-compensatory (Hwang et al., 1981).

4.1.3.1. Non-compensatory Methods

Non-compensatory methods do not permit tradeoffs between attributes (Xu et al., 2001). An undesirable value in one attribute cannot be offset by a desired value in other attributes. Each attribute must stand on its own. Thus, Xu et al. (2001) argue that comparisons are made on an attribute-by-attribute basis. The MCDM methods in this category are credited for their simplicity. Examples of these methods include:

Dominance method

Eliminate all dominated alternatives. There could be more than one solutions created by this method.

Max-min method

Find the weakest attribute value (min) of each alternative and then choose the alternative with the best (max) weakest attribute value. The reason is that a chain is as strong as its weakest link. This method is suitable only when attribute values are comparable with one another, either measured in the same unit or converted to a common scale.

Max-max Method

In opposite to the Max-min method, the Max-max method selects an alternative by its best attribute value. It is also applicable only when attributes are comparable.

Conjunctive constraint method

By setting up a minimum standard for each attribute, the alternative selection or assessment process is simplified to compare each attribute against its standard. If the standard reflects the decision maker's anticipations, the obtained solutions are satisfying solutions.

Disjunctive constraint method

This method assesses an alternative on its best attribute regardless of all other attributes. These methods may have their application domains in which they are rational, but they may not be very helpful for general decision-making.

4.1.3.2. Compensatory Methods

Xu et al. (2001) argue that compensatory methods permit tradeoffs between attributes. A slight reduction in one attribute is acceptable if it is compensated by some addition in one or more other attributes. Compensatory methods can be subdivided into the following 4 subgroups (Xu et al., 2001).

Scoring Methods

The scoring method selects or assesses an alternative as claim by its score (or utility). Utility or score is used to explicit the decision maker's superiority. It converts attribute values into a common preference scale such as [0,1] so that comparisons between different attributes becomes feasible. A very reputable method in this category is the Simple Additive Weighting method. This method estimates the total score of an alternative as the weighted sum of the attribute scores or utilities. The Analytical Hierarchy Process (AHP) is another popular method in this category. This method estimates the scores for each alternative based on pairwise comparisons (Saaty, 1988).

Compromising Methods

The compromising method picks out an alternative that is closest to the ideal solution. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method belongs to this category. This method first normalizes the decision matrix of a MCDM problem. Then based on the normalized decision matrix, it estimates the weighted distances of each alternative from an ideal solution and a nadir solution. A solution relatively close to the ideal solution and far from the nadir solution is evaluated to be the best (Hwang et al., 1981).

Concordance Methods

The concordance method creates a preference ranking which best satisfies a given corresponded measure. The Linear Assignment Method is one of the instances in this category. In this method, it is believed that an alternative having many highly ranked attributes should be ranked high (Hwang et al., 1981).

Evidential Reasoning Approach

The Evidential Reasoning (ER) approach is the latest development in the MCDM area (Yang et al., 2000). It is different from the above 3 conventional methods. Instead of reporting a MCDM problem with a decision matrix, the ER approach uses an extended decision matrix, in which each attribute of an alternative is defined via a distributed evolution using a belief structure.

4.1.4. Some MCDM Application Areas

Some of the industrial engineering applications of MCDM comprise the use of *decision analysis* in integrated manufacturing (Putrus, 1990), in the assessment of technology enterprise decisions (Boucher et al., 1991), in sustainable energy decision-making (Pohekar et al., 2004; Wang et al., 2009), in renewable energy analysis (Taha et al., 2013), layout design (Cambron et al., 1991), in energy planning matters (Loken, 2007), (Wang et al., 2009b), and also in other engineering issues (Wang et al., 2002). MCDM plays a critical role in many real life issues. It is not an exaggeration to argue that almost any local or federal government, industry, or business activity involves, in one way or the other, the assessment of a set of alternatives in terms of a set of decision criteria. Very often, these criteria are conflicting with each other. Even more often, the pertinent data are very expensive to collect (Triantaphyllou et al., 1998).

4.2. MCDM's mechanism and methods

Wang et al. (2009) state that compared to single criteria approach, the distinctive advantage of MCDA methods is to employ multi-criteria or attributes to obtain an integrated decision-making (DM) outcome.

Generally, the MCDA problem for sustainable retrofitting DM involves *m* alternatives evaluated on *n* criteria. The grouped decision matrix can be expressed as follows:

$$
\begin{array}{ll}
 & \text{criteria} \quad C_1 \quad C_2 \quad \cdots \quad C_n \\
 & (\text{weights} \quad w_1 \quad w_2 \quad \cdots \quad w_n) \\
\text{alternatives} & - - - - - - - - - - - - \\
X = \begin{matrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} & \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}_{m\times n}
\end{array}
\qquad \textit{Eq. (1)}
$$

where x_{ij} is the performance of *j*-th criteria of *i*-th alternative, w_j is the weight of criteria j, n is the number of criteria and m is the number of alternatives.

Considering the Eq. (1), it can be realized that the DM problem involves alternatives, criteria, criteria weights. Figure 4.1 in the following demonstrates the MCDM process (following Wang et al., 2009, Wang et al., 2008) including: a) alternatives' formulation and criteria selection, b) criteria weighting, c) evaluation, and d) final treatment and aggregation. Following the steps (Wang et al., 2008), the alternatives are formulated for multiple DM problem from a set of selected criteria and to normalize the original data of criteria. In next step, the criteria weights are determined to show the relative importance of criteria in MCDA. Then, the acceptable alternatives are ranked by MCDA methods with criteria weights. Finally, the alternatives' ranking is ordered. If all alternatives' ranking orders in different MCDA methods are just the same, the DM process is ended. Otherwise, the ranking results are aggregated again and the best scheme is selected. The three main sections in MCDA corresponding its usage are presented and reviewed in the following sections respectively.

4.2.1. Methods of criteria selection

Wang et al. (2009) consider that due to the existence of various criteria in a common MCDM problems, there are methods particularly to select the ''major'' criteria, distinguish the main and secondary and construct the reasonable criteria systems. Consider the following methods from (Wang et al., 2009):

Delphi method

The Delphi method is a systematic and interactive method, which relies on a panel of independent experts (Ye et al., 2006; Jin et al., 2008; Guo et al., 2007). Delphi is based on the principle that forecasts from a structured group of experts are more accurate than those from unstructured groups or individuals (Rowe et al., 2001). The carefully selected experts answer questionnaires for criteria selection to evaluate retrofitting systems in two or more rounds. After each round, the summaries of the experts' selection from the previous round as well as the reasons they provided for their judgments are fed back to the experts. Thus, participants are encouraged to revise their earlier answers in light of the replies of other members of the group. It is believed that during this process the range of the selected criteria will decrease and the group will converge towards the ''correct'' criteria. Finally, the process is stopped after a pre-defined stop criteria (e.g. number of rounds, achievement of consensus, and stability of results). Delphi has been widely used in social, ecological and economic works. Similarly, Delphi method can also be applied in the weighting and evaluation in the latter sections.

Least Mean Square (LMS) method

The principle of LMS method is that one criteria contributes less importance to results and it can be ignored when its performances of alternatives are almost same or near although the criteria is vital in evaluation (Ye et al., 2006; Guo et al., 2007). To lessen its relativity with other criteria, the criteria can be removed. Let

$$s_j = \sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(x_{ij} - \overline{x_j}\right)^2} \quad (j=1, 2, ..., n) \qquad \textit{Eq. (2)}$$

where x_{ij} the i-th sample of the j-th criteria, $i = 1, 2, ..., m$, and $\bar{x}_j = (1/m)\sum_{i=1}^{m} xij$.

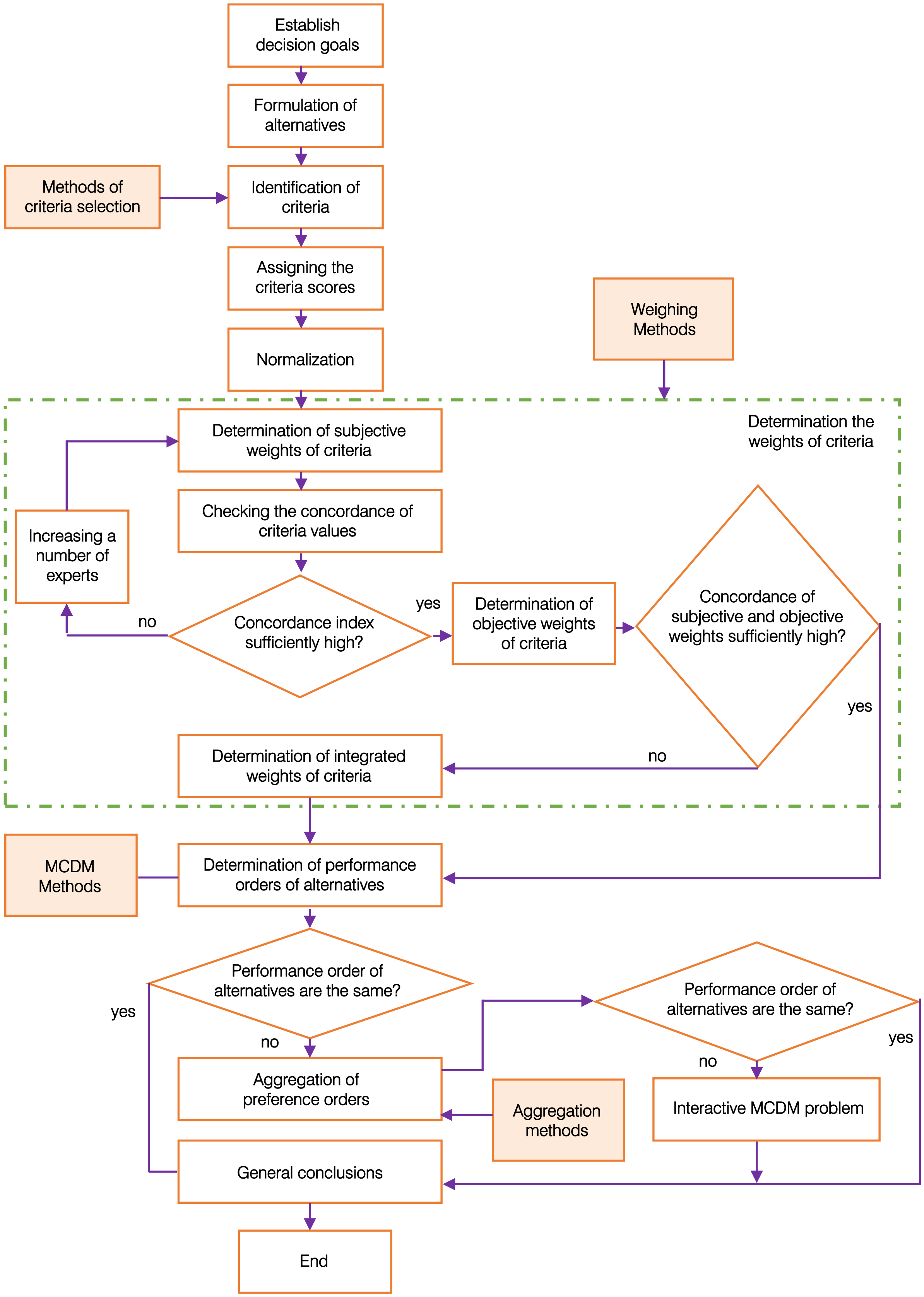


Figure 4.1. MCDM process (source: Wang et al., 2009)

If there exists k to make $s_k = min_{1\leq j\leq n}\{s_j\}$ and $s_k \approx 0$, the k criteria that corresponds to s_k can be removed. This method can be also used to elicit the selected weights (the m alternative in the selected n criteria form to the new group decision matrix and then the calculated standard deviation in Eq. (2) again is normalized to get the weights).

Minmax deviation method

Minmax deviation method is similar to LMS method (Ye et al., 2006; Guo et al., 2007). The judgment standard is the deviation values of criteria. The maximum deviation of criteria x_j can be calculated as

$$r_j = \max_{1\leq i,\ l\leq m} \cdots \{|x_{ij} - x_{lj}|\} \qquad \text{Eq. (3)}$$

Likewise, if there exists k to make $r_k = min_{1\leq j\leq n}\{r_j\}$ and $r_k \approx 0$, the k criteria that correspond to r_k can be removed. Similarly, this method can be also used to elicit weights.

Correlation coefficient method

Correlation analysis adopts the correlation coefficient to show the interaction between criteria. The correlation coefficient between criteria C_i and criteria C_j can be calculated as

$$r_{ij} = \frac{cov\,(C_i\,, C_j)}{\delta_{C_i}\delta_{C_j}} \qquad \text{Eq. (4)}$$

where $cov\,(C_i, C_j)$ is he covariance of C_i and C_j, and δci and δc_j are the standard deviation of C_i and C_j respectively.

The correlation coefficients between n criteria can form to a $n\times n$ matrix, $R_{n\times n}$. When $r_{ij} = 1$, criteria C_i are completely related to criteria C_j. However, the correlation coefficient includes more or less influence because other criteria are not constant. To reflect the interaction well, the partial correlation coefficient is considered to determine the interaction between criteria and computed as

$$\varepsilon_{ij} = \frac{-R_{ij}}{\sqrt{R_{ii}R_{jj}}} \qquad \text{Eq. (5)}$$

where R_{ij}, R_{ii}, R_{jj} are algebraic complements of elements, r_{ij}, r_{ii}, and r_{ij} in matrix $R_{n\times n}$. Greater the partial correlation coefficient is, more correlative the two criteria. When $\varepsilon_{ij} = 1$, criteria C_i is completely related to criteria C_j and one of the two criteria can be removed.

Wang et al. (2009) discuss that based on the elementary methods; some specific methods were developed and extended to various complex systems, such as grey relational method, Analytic Hierarchy Process - AHP, clustering method, principal component analysis and rough set method. The principle of all selection methods is to eliminate the relevance between criteria and select the independent criteria.

4.2.2. Weighting methods

All factors have their internal impact reclassified to a common scale so that it is necessary to determine each criteria's relative impact in MCDM problems (Wang et al., 2009). Weight is assigned to the criteria to indicate its relative importance. Wang et al. (2009) discuss that there are three factors that are usually considered to obtain the weights: a) the variance degree of criteria, b) the independency of criteria, and c) the subjective preference of the decision-makers. Jia et al. (1998) classify them into two methods: the equal weights and the rank-order weights (see Table 4.1).

Table 4.1. The weighting methods (source: Wang et al., 2009)

Categories	Weighting methods	
Equal weights	--	--
Rank-order weights	Subjective	AHP
		Simos
		Pair-wise comparison
		Priority given to one indicator with others being the same
		Others
	Objective	Entropy method
	Combination	Additive synthesis

Equal weights method

The criteria weight in equal weights method is defined as

$$w_i = \frac{1}{n} \quad , \qquad i=1, 2, ..., n, \qquad\qquad Eq.\ (6)$$

The method requires minimal knowledge of the decision maker's priorities and minimal input from decision maker.

Rank-order weighting method

The criteria weight in equal weights method is defined as the equal weights method has also been criticized because it ignores the relative importance among criteria. Following this argument, the rank-order weighting method was proposed and criteria weights are distributed as

$$W_1 \geq W_2 \geq \ldots \geq W_n \geq 0 \qquad\qquad Eq.\ (7)$$

where $\sum_{i=1}^{n} W_i = 1$.

The rank-order weighting methods are classified into three categories: a) subjective weighting method, b) objective weighting method and c) combination weighting method. Criteria weights determined by the subjective weighting methods depend only on the preference of decision-makers, not on the quantitative measured data of energy projects. Contrarily, the objective weights are obtained by mathematical methods based on the analysis of the initial data. The subjective weighting methods explain the evaluation clearly while the objectivity ones are relatively weak. Additionally, the judgments of decision makers sometimes absolutely depend on their knowledge or information. Thus, the criteria weights' errors in some extent are unavoidable. Wang et al. (2009) argue that none of the two approaches is perfect. It may be suggested that an integrated method could be most appropriate for determining the criteria weights.

Wang et al. (2009) discuss that the weighting stage in Figure 4.1 also displays the process that combined three weighting categories. First, the subjective weights are determined by experts and the concordance of criteria values is checked by the decision-maker. When the concordance index is not sufficiently high, more experts are needed to modify the subjective weights to get the high concordance. Then, the objective weights of criteria are calculated in measured data. Finally, the concordance of subjective and objective weights is checked in a similar way. If the concordance cannot get satisfied, the combination methods are applied to determine the integrated weights of criteria. Table 4.2 summarizes the weighting methods in MCDM problems (following Ye et al., 2006).

Table 4.2. Weighting methods in MCDA DM (source: Wang et al., 2009)

Categories	Weighting methods
Subjective weighting	Simple multi-attribute rating technique (SMART)
	SMARTER
	Swing
	Trade-off
	SIMOS
	Pair-wise comparison
	AHP
	Least-square method
	Eigenvector method
	Delphi method
	Consistent matrix analysis
	PATTERN
Objective weighting	Least mean square (LMS) method
	Minmax deviation method
	Entropy method
	TOPSIS method
	Vertical and horizontal method
	Variation coefficient
	Multi-objective optimization method
	Multiple correlation coefficient
	Principal component analysis
Combination weighting	Multiplication synthesis
	Additive synthesis
	Optimal weighting based on sum of squares
	Optimal weighting based on minimum bias
	Optimal weighting based on relational coefficient of gradation

4.2.2.1. Subjective weighting methods

The following part introduces briefly some commonly used subjective weighting methods.

SMART

In Simple Multi-Attribute Rating technique (SMART), the participants are asked to rank the importance of the changes in the criteria from the worst criteria levels to the best levels (Edwards et al., 1994). Then they assign 10 points to the least important criteria, and increasing number of points (without explicit upper limit) are assigned to the other criteria to address their importance relative to the least important criteria. The weights are calculated by normalizing the sum of the points to one. The idea of SMARTER is to use the centroid method so that the weight of a criteria ranked to be *i*-th is

$$w_i = \frac{1}{n}\sum_{k=i}^{n}\frac{1}{k} \qquad \textit{Eq. (8)}$$

Pair-wise comparison

Wang et al. (2009) address that in the pair-wise comparison method, participants are presented a worksheet and are asked to compare the importance of two criteria at a time: ''which one of these two criteria is more important, and how much more important?'' Then the relative importance is scored. The scales can be various, for example, a scale of 0 (equal importance) to 3 (absolutely more important) is commonly adopted. The results are consolidated by adding up the scores obtained by each criteria when preferred to the criteria it is compared with. The results are then normalized to a total of *1.0*. This weighting method provides a framework for comparing each criteria against all others, and helps to show the difference in importance between criteria. However, it does not allow you to check the consistency of participants' preferences, especially, their transitivity.

AHP

Analytic Hierarchy Process (AHP) method builds on the pair-wise comparison model for determining the weights for every unique criteria. AHP was proposed primarily by Saaty (1980). The matrix of pairwise comparisons when there are *n* criteria at a given level can be formed as:

$$\mathrm{D} = \begin{bmatrix} C_1/C_1 & C_1/C_2 & \cdots & C_1/C_n \\ C_2/C_1 & C_2/C_2 & \cdots & C_2/C_n \\ \vdots & \vdots & \ddots & \vdots \\ C_n/C_1 & C_n/C_2 & \cdots & C_n/C_n \end{bmatrix} \qquad \textit{Eq. (9)}$$

Xu et al. (2006) discuss that the relative importance can be scaled in Table 4.3. Based on the matrix, criteria weights can be calculated in some methods, such as arithmetic mean method, characteristic root method, and least square method. Since the numeric values are derived from the subjective preferences of individuals, it is impossible to avoid some inconsistencies in the final matrix of judgments (Mu et al., 2017). Therefore, individual judgments will never agree perfectly, the degree of consistency achieved in the pair-wise comparison is measured by a consistency ratio indicating whether the comparison made is sound.

Table 4.3. The AHP pair-wise comparison scale (source: Wang et al., 2009)

Intensity of weight	Definition	Explanation
1	Equal importance	Two criteria contribute equally to objectives
3	Weak/moderate importance of on over another	Experience and judgment slightly favored one criteria over another
5	Essential or strong importance	Experience and judgment strongly favor one criteria over another
7	Very strong or demonstrated importance	A criteria is favored very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one criteria over another is of the highest possible order of affirmation

2, 4, 6, 8	Intermediate values between the two adjacent scale values	Used to represent compromise between the priorities listed above
Reciprocals of above non-zero number		If criteria *i* has one of the above non-zero numbers assigned to it when compared to criteria *j*, then *j* has the reciprocal value when compared with criteria *I*

4.2.2.2. Objective weighting methods

Wang et al. (2009) consider the objective weighting method elicits the criteria weights using the measurement data and information and reflects the difference degree. The following part from (Wang et al., 2009) introduces briefly some commonly used objective weighting methods.

Entropy method

The entropy shows that how much the criteria reflects the information of system and how great the uncertainty of criteria is.

A vector of $x_j = (x_{1j}, x_{2j}, \ldots, x_{mj})$ characterizes the set *X* in terms of the *i*-th criteria, defined as follows:

$$X_j = \sum_{i=1}^{m} x_{ij}, \quad j = 1, 2, \ldots, n, \qquad \text{Eq. (10)}$$

Then the entropy measure of *j*-th criteria contrast intensity is

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \frac{d_{ij}}{D_j} \ln \frac{d_{ij}}{D_j} \qquad \text{Eq. (11)}$$

Finally, the normalized weights can be calculated as

$$w_j = \frac{1-e_j}{\sum_{j=1}^{n}(1-e_j)} \qquad \text{Eq. (12)}$$

TOPSIS method

Hwang et al. (1981) have addressed the principle of Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method about the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense. The weighted distance between alternative Ai and the ideal solution A* is defined as follows:

$$h_i = \sum_{j=1}^{n} w_j^2 \, (x_{ij} - x_j^*)^2 \qquad \text{Eq. (13)}$$

Then the following optimal model is solved and the weights can be elicited.

$$\left.\begin{aligned} &\min \sum_{i=1}^{m} h_i = \sum_{i=1}^{m} \sum_{j=1}^{n} w_j^2 \, (x_{ij} - x_j^*)^2 \\ &s.t. \ \sum_{j=1}^{n} w_j = 1, \quad w_j \geq 0 \end{aligned}\right\} \qquad \text{Eq. (14)}$$

Vertical and horizontal method

Vertical and horizontal method is also an optimal weighting method. The weights can be solved from the optimal mathematic model as:

$$\left.\begin{array}{l} max\, s_x^2 = \sum_{i=1}^{m}(z_i - \bar{z})^2/m \\ s.t.\ \sum_{j=1}^{n} w_j^2 = 1\ , \quad w_j \geq 0 \end{array}\right\} \quad \text{Eq. (15)}$$

where $z_i = \sum_{j=1}^{n} w_j x_{ij}$ and $\bar{z} = (1/m) \sum_{i=1}^{m} z_i$.

Wang et al. (2009) state that TOPSIS method and vertical and horizontal method both reflect the difference of alternatives' whole performances as possible, while LMS method, minmax deviation method and entropy method reflect the criteria relative importance based on the difference of alternatives to a criteria. In another word, TOPSIS method and vertical and horizontal method base on the integrated evaluation values while other methods base on the difference of single criteria.

4.2.2.3. Vertical and horizontal methods

According to Wang et al. (2008), combination weighting methods have two basic combinations: multiplication synthesis and additive synthesis. The principle of multiplication synthesis is expressed as

$$w_j = \frac{w_{1j} - w_{2j}}{\sum_{j=1}^{n} w_{1j} - w_{2j}} \quad \text{Eq. (16)}$$

where w_{1j}, w_{2j}, and w_j are subjective weight, objective weight and combination weight of the *j*-th criteria respectively.

While the additive synthesis is written as

$$w_j = k w_{1j} + (1 - k) w_{2j} \quad \text{Eq. (17)}$$

where k is the linear combination coefficient and $k \geq 0$.

The combination coefficient can be determined by various methods, such as optimization based on sum of squares, minimum bias and relational coefficient of gradation (Wang et al., 2008).

4.2.3. Multi-criteria *decision analysis* methods

Multi-criteria decision analysis methods are used to estimate the preference orders of alternative after determining the criteria weights to get the ranking order in Eq. (1).

Table 4.4 also summaries all related MCDA methods that are divided into three categories: a) elementary methods, b) methods in unique synthesizing criteria and c) outranking methods.

Table 4.4. MCDA methods (source: Wang et al., 2009)

Categories	Weighting methods
Elementary	Dominance
	Maximin
	Maximax
	Conjunctive
	Disjunctive
	Lexicographic
	Elimination by aspects
	Linear assignment
	Weighted additive
	Weighted product
Unique synthesizing criteria	Analytical hierarchy process (AHP)
	TOPSIS
	SMART
	Grey relational analysis
	Data envelopment analysis
	Multi-attribute value theory (MAVT)
	Multi-attribute utility theory (MAUT)
	Utility theory additive (UTA)
	Fuzzy weighted sum
	Fuzzy maximum
Outranking	ELECTRE I, IS, II, III, IV, TRI
	PROMETHEE I, II
	ORESTRE

4.2.3.1. Elementary methods

Wang et al. (2009) discuss that the elementary methods in Table 4.4 includes ten methods, the former three methods are defined as non-preference information methods without decision maker, and other methods are multi-attribute information methods with decision maker. Conjunctive and disjunctive methods belong to screening methods that the acceptable alternative must exceed given performance thresholds for all criteria. Lexicographic, elimination by aspects and linear assignment method are ordinal partiality methods. The latter two methods need the criteria preference of decision maker.

WSM

In Weighted Sum Method (WSM), the score of an alternative is calculated as

$$S_i = \sum_{j=1}^{n} w_j x_{ij}, \qquad i = 1, 2, ..., m \qquad \textit{Eq. (18)}$$

then the resulting cardinal scores for each alternative can be used to rank, screen, or choose an alternative. The best alternative is the one whose score is the maximum.

WPM

The Weighted Product Method (WPM) is similar to WSM. The main difference is that instead of addition in the calculation there is multiplication. The score of alternative *i* can be calculated as:

$$S_i = \prod_{j=1}^{n} x_{ij}{}^{w_j} \qquad i = 1, 2, ..., m \qquad \text{Eq. (19)}$$

As Wang et al. (2009) mention, the alternative having the maximum score is the best scheme. Because of the exponent property, this method requires all ratings be greater than 1. For example, when a criteria has fractional ratings, all ratings in that criteria are multiplied by 10 to meet this requirement. Alternative scores obtained by the weighted product method do not have a numerical upper bound. The decision maker may also not find any true meaning in those scores. Hence, it may be convenient to compare each alternative score with the standard score. If an alternative is compared to the ideal alternative for the only comparison purpose, the ratio is given by

$$R_i = \frac{S_i}{S^*} = \frac{\prod_{j=1}^{n} x_{ij}{}^{w_j}}{\prod_{j=1}^{n} x_j^{*}{}^{w_j}} \qquad i = 1, 2, ..., m \qquad \text{Eq. (20)}$$

where x_j^* is the most favorable performance for criteria *j*. It is found clearly that the preference of alternative *i* increases when R_i approaches to 1.

4.2.3.2. Unique synthesizing criteria methods

The following part introduces briefly some commonly used unique synthesizing criteria methods.

AHP

Wang et al. (2009) state that AHP is widely used for practical MCDA method in various domains, such as social, economic, agricultural, industrial, ecological and biological systems, in addition to energy systems (following Pilavachi et al., 2009). It is a descriptive *decision analysis* methodology that calculates ratio-scaled importance of alternatives through pair-wise comparison of evaluation criteria and alternative. It involves decomposing a complex decision into a hierarchy with goal (objective) at the top of the hierarchy, criteria and sub-criteria at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy.

AHP is a type of weighted sum method. The weights obtained in AHP method was represented in Table 4.3. After obtaining the weights, each performance at the given level is then multiplied with its weight and then the weighted performances are summed to get the score at a higher level. The procedure is repeated upward for each hierarchy, until the top of the hierarchy is reached. The overall weights with respect to goal for each decision alternative is then obtained. The alternative with the highest score is the best alternative.

TOPSIS

TOPSIS was introduced as a weighting method in section 4.2.2.2. In addition, it can also be used as a MCDA method. TOPSIS (Hwang et al., 1981) is based on the concept that the ideal alternative has the best level for all criteria, whereas the negative ideal is the one with all the worst criteria values.

Wang et al. (2008) state that the principle is simple: the selected best alternative should have the shortest distance from the positive ideal solution in geometrical sense while it has the longest distance from the negative solution. The method assumes that each criteria has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions.

The positive distance between alternative S_i and the ideal solution S^+ is defined as follows:

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(x_{ij} - x_j^+)^2} \qquad \textit{Eq. (21)}$$

where x_j^+ is the *j*-th criteria's performance of the ideal solution S^+.

The negative distance is similarly calculated as follows:

$$S_i^- = \sqrt{\sum_{j=1}^{n}(x_{ij} - x_j^-)^2} \qquad \textit{Eq. (22)}$$

where x_j^- is the *j*-th criteria's performance of the negative ideal solution S^-.

Finally, the relative closeness degree of S_i and S^+ is defined to:

$$r_i = \frac{S_i^-}{S_i^- + S_i^+} \qquad \textit{Eq. (23)}$$

The best alternative is one that has the maximum closeness degree and has the shortest distance to the ideal solution.

Grey relation method

The principle of grey relation method (Lin et al., 2004) is similar to TOPSIS. The grey relation degree is defined in the method to show the closeness between the alternatives. Usually, the ideal solution is defined and the alternatives relation degree with it are calculated. The grey relational coefficient of the *j*-th criteria between alternative A_i and the ideal solution A^* can be calculated as

$$a(A_j^*, A_{ij}) = \frac{min_j min_i\left|x_j^* - x_{ij}\right| + \varepsilon\, max_j max_i\left|x_j^* - x_{ij}\right|}{\left|x_j^* - x_{ij}\right| + \varepsilon\, max_j max_i\left|x_j^* - x_{ij}\right|} \qquad \textit{Eq. (24)}$$

where x_j^* is the most favorable performance for criteria *j*, ε is the distinguishing coefficient, 0< ε<1, $min_j min_i\left|x_j^* - x_{ij}\right|$ is secondary smallest error of A_i and A^*, and $max_j max_i\left|x_j^* - x_{ij}\right|$ is secondary biggest error.

According to Wang et al. (2009), the grey relational degree is equal to the weighted sum of its grey relational coefficients. The alternative with the maximum relation degree has shortest distance from the ideal solution while it has the longest distance from the worst solution. Thus, the best alternative is selected according to the grey relation degree.

MCDA combined fuzzy methodology

Wang et al. (2009) argue that the classic MCAD methods generally assume that all criteria and their respective weights are expressed in crisp values and, thus, that the rating and the ranking of the alternatives can be carried out without any problem. In a real-world decision situation, the application of the classic multi-criteria evaluation methods may face serious practical constraints from the criteria perhaps containing imprecision or vagueness inherent in the information. Due to the availability and uncertainty of information as well as the vagueness of human feeling and recognition, like "equally", "moderately", "strongly", "very strongly", "extremely" and a "significant degree", it is relatively difficult to provide exact numerical values for the criteria, make an exact evaluation and convey the feeling and recognition of objects for decision makers.

Hence most of the selection parameters cannot be given precisely and the evaluation data of the alternative suppliers' suitability for various subjective criteria and the weights of the criteria are usually expressed in linguistic terms by the decision makers. Furthermore, it is also recognized that human judgment on qualitative criteria is always subjective and thus imprecise.

Fuzzy set theory introduced by Zadeh (1965) can just solve the problem and it plays a significant role in this kind of decision situation.

ELECTRE

Elimination at choice translating reality (ELECTRE) families (Benayoun et al., 1966; Roy et al., 1968) have included ELECTRE I, II, III, IV, TRI and some improved ELECTRE methods. Wang et al. (2009) argue that for most ELECTRE methods, there are two main stages. These are the construction of the outranking relations and the exploitation of these relations to get the final ranking of the alternative. Different ELECTRE methods may be different in how they define the outranking relations between alternatives and how they apply these relations to get the final ranking of the alternatives.

ELECTRE concentrates the analysis on the dominance relations among the alternatives. The basic concept of ELECTRE is how to deal with outranking relation by using pair-wise comparisons among alternatives under each criteria separately. It is based on the study of outranking relations, exploitation notions of concordance. These outranking relations are built in such a way that it is possible to compare alternatives. It uses concordance, discordance indexes and threshold values to analyze the outranking relations among the alternatives. The concordance index for a pair of alternatives A_i and A_k measures the strength of the hypothesis that alternative A_i is at least as good as alternative A_k. There are no unique measures of concordance. In ELECTRE II, the concordance index $C(A_i,A_k)$ for each pair of alternatives (A_i,A_k) is defined as follows:

$$C(A_i,A_k) = \frac{\sum_{j \in Q(A_i,A_k)} w_j}{\sum_{j=1}^{n} w_j} \qquad \textit{Eq. (25)}$$

where $Q(A_i,A_k)$ is the set of criteria for which A_i is equal of preferred to (i.e., at least as good as) A_k, and w is the weight of the *j*-th criteria. The discordance index $D(A_i,A_k)$ is defined as follows:

$$D(A_i,A_k) = \frac{max_{j \in Q'(A_i,b)} \left| x_{bj} - x_{A_i j} \right|}{max_{j=1}^{n} \left| x_{bj} - x_{A_i j} \right|} \qquad \textit{Eq. (26)}$$

where x_{aj} and x_{bj} represent the performances of alternative A_i and A_k in terms of criteria *j* respectively, $Q'(A_i,A_k)$ is the set of criteria for which A_i is worse than A_k, and *n* is the number of criteria. The formula can be only used when the scores for different criteria are comparable.

After computing the concordance and discordance indices for each pair of alternatives, the graphs for strong and weak relationship can be painted respectively by comparing these indices with the threshold values. Then these graphs are employed to obtain two complete preorders based on descending and ascending distillation chains. Finally, the comparison of the two complete preorders is used to elaborate the final ranking order of alternatives.

PROMETHEE

Bran (1984) elaborate on preference ranking organization method for enrichment evaluation (PROMETHEE) method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. The author mention that it is well adapted to problems with a finite number of alternatives and for producing are to be ranked considering several, sometimes-conflicting criteria. The principle is the construction and the exploitation of a valued outranking relation π. Two complete preorders can be obtained by ranking the alternatives according to their incoming flow and their outgoing flow. Wang et al. (2009) argue that the intersection of these two preorders yields the partial preorder of PROMETHEE I where incomparabilities are allowed. The ranking of the alternatives according to their net flow yields the complete preorder of PROMETHEE II.

Like to ELECTRE method, it also performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. However, ELECTRE method only pay attention to the preference and ignore the difference level between alternatives when determining the ranking order. PROMETHEE introduces the preference functions to measure the difference between two alternatives for any criteria. Brans (1984) has offered six generalized criteria functions including usual criteria, quasi criteria, criteria with linear preference, level criteria, criteria with linear preference and indifference, and Gaussian criteria. Multi-criteria preference index for a pair of alternatives A_i and A_k is defined as

$$\pi(A_i,A_k) = \frac{\sum_{j=1}^{n} w_j p_j(A_i,A_k)}{\sum_{j=1}^{n} w_j} \qquad \textit{Eq. (27)}$$

where $p_j(\mathrm{a},\mathrm{b})$ is the preference functions for alternatives *a* and *b*.

Then the incoming flow is calculated as:

$$\varphi^{+}(A_i) = \sum_{k=1}^{m} \pi(A_i, A_k) \qquad k = 1, 2, ..., m \qquad \textit{Eq. (28)}$$

and the outgoing flow is calculated as

$$\varphi^{-}(A_i) = \sum_{k=1}^{m} \pi(A_k, A_i) \qquad k = 1, 2, ..., m \qquad \textit{Eq. (29)}$$

Finally, the net flow is equal to the difference of incoming flow and outgoing flow. After obtaining all net flows of alternatives, the alternative having maximum net flow is considered as the best.

4.2.4. Aggregation methods

According to Wang et al. (2009), the decision maker usually selects the best alternative based on the ranking orders after the calculation in a selected MCDA method. However, the creditability of DM is necessarily verified so that the results of the ranking orders are computed by a few MCDA methods sometimes. The application of various MCDA methods of calculation may yield different results (preference ranking order). The question ''which method is most suitable to solve the problem?'' is most important, but difficult to answer. Therefore, the ranking results are necessarily aggregated again and the best scheme from the alternatives is selected as displayed in Figure 4.1. The methods used to aggregate the preference orders were called as aggregation methods in this article by (Wang et al., 2009). The aggregation methods can be divided into two categories: a) voting method and b) mathematical aggregation method. The mathematical aggregation methods are classified to two sub-categories, ''hard aggregation method'' and ''soft aggregation method'' based on with or without the decision-makers.

4.3. Summary

The discussion overviewing decision-making and Multiple Criteria Decision Making (MCDM) has covered a variety of topics. The intent in this coverage has been both for background and review purposes. It is hoped that in doing so, an appreciation has been gained for MCDM and it various methods and approaches.

Clearly, the context in which a MCDM method is used, improves the efficiency of decision-making with multiple criteria and usually conflicting criteria. Similarly, MCDM provides methods, which are relevant to cope with various criteria in building design. Particularly, the existing criteria in the problems related to sustainability for building design are similar to problems of MCDM where the criteria from different perspectives including society, economy and ecology are involved into the design process. The MCDM methods can address both quantitative as well as qualitative criteria to analyze conflicts in criteria presented by different decision makers. As long as criteria selection and weights, MCDA methods and aggregation methods are appropriate and suitable to the specific decision problems. In this regard, use of MCDM can become an efficient approach to handle the decision-making process for sustainable building design and renovation. The application of the MCDM methods and variations between MADM and MODM for development of a *Holistic Multi-methodology for Building Renovation – HMSR* is elaborated further in section 6.

Almost certainly, no one can distinguish between the MCDM methods, in the way to select the foremost out of them. It is essential that a few different MCDM methods are applied to get the validity in MCDM methods is verified. It is believed that the results obtained by the aggregation methods are more rational and more aggregation methods will aid in the decision-making related to sustainability in the future.

Described with more detail in subsequent chapter, MCDM methods are widely used in sustainability sector. It observed that Pairwise comparison, AHP and TOPSIS are the most popular comprehensive method due to their mechanism, understandability in theory, and the simplicity in application in multi-criteria decision-making problems. With respect to it, the thesis in section 6 provides more detail and proper citations to these methods in order to apply them for development of the HMSR.

CHAPTER IV

DEVELOPMENT OF A HOLISTIC MULTI-METHODOLOGY FOR BUILDING RENOVATION

CHAPTER'S SYNOPSIS

"A review of the barriers for building renovation in Chapter 1 considered building renovation as a complex problem area by addressing cultural changes (attached to the society and stakeholders) and technological/physical changes (attached to the renovation strategies in order to meet sustainability in it full sense). It therefore configured the concept of Holism for this context. This consideration revealed a lack of methodologies, which can promote sustainability objectives and assist various stakeholders during the design stage of building renovation/retrofitting projects. The purpose of this chapter firstly concerns features and properties of an appropriate systematic building design process (section 5). Subsequently, it will develop a Holistic Multi-methodology for Sustainable Renovation, which initially aims to deal with the complexity of retrofitting problems. It then provides a framework through which to involve the different stakeholders in the design process to improve group learning and group decision-making, and as such, it makes the building renovation design process more robust and efficient. The outcome is a proposal for a multi-methodology framework, which is developed by introducing, evaluating and mixing methods from Soft Systems Methodologies – SSM (see chapter 2) with Multiple Criteria Decision Making – MCDM (see chapter 3). The potential of applying the proposed methodology in renovation projects is demonstrated through a case study."

5. Rise of complexity in the new age movement and its effects on updating the process of designing the buildings

5.1. Complexity in building design process

The buildings which are formed around us seem bespoke, which means they are ordered or reserved in advance. This leads to the lack of clarity and organization of these buildings, because their design has often taxed their designer's cognitive capacity well beyond the limit (Alexander, 1970). In building design, as it functions in a complicated network of independencies (i.e. various sustainability solutions), it is difficult to outsmart consequences of the design decisions, and so it is difficult to figure out a solution (a building model), which confronts the design objectives, even if the objectives are clearly specified. It is necessary the wicked[1] nature of design problems (Churchman, 1967) could unveil itself, right from the beginning of the design process since different design objectives might throw down each other. A building is always full of settlements, the result of juggling and trying to make compatible the diverse objectives of its creation (Williamson et al., 2003). As part of design process, the role of the designer is to emphasize the disparate design objectives. Considering of where building design process meets the sustainability solutions enables building designers to learn and later to apply the various possible objectives. Up to now there is a significant spectrum of methods accessible for appraisement of sustainability concept (Haapio et al., 2008; Cole, 2005). Many of these existing assessment methodologies and tools (Gohardani et al., 2012) have been developed for the design of the new buildings, but can be applied for renovation projects as well, and some are particularly intended or adapted for building renovation context (this will be elaborated further in section 7.2). Furthermore, the figure and application of the evaluation tools in the building area has orderly been propounded (Poston, 2011). Sustainability has recently been being studied and addressed through more holistic perspectives such as the research which has been done by International Living Future Institute (2014) and called Living Building Challenge; or it also has been developed into a decision-making support frameworks such as SPeAR by Arup Group Limited [Arup] (2012) or Chris Butters' sustainability framework from Norwegian Architects for Sustainable Development (2014), in order to represent and evaluate sustainability in the form of a holistic Value Map.

[1] The phrase wicked problems (Churchman 1967) was originally used to demonstrate problems that are difficult to solve, because they address complex social interdependencies. The two attributes of a wicked problem are including a) difficulty of formulating their solutions due to the complexity of socio-cultural interactions and interdependencies that leads to the inability to foretell long-term effects of decisions since the recognition of the source of the problem is highly complicated; b) the definition of objectives regarding to these problems due to various circumstances is provisional, and it entails different features, ideas and interests.

The design objectives can be roughly segregated into *design requirements* which are, to a certain degree, unchanging factors and are defined apart from an individual design process and *design intentions* which are both depending on the individual design process and are defined in connection with a specific design context. Some sort of conflict turns up when client's demands can negatively touch building qualities. The architect's concerns might vary substantially from those clients in respect to many building characteristics. Furthermore, regardless of the disharmonies between the client and the architect, there are design intentions, which fundamentally are in antagonism (Williamson et al., 2003). Hence, a conflict can also occur between the design requirements (i.e. site constraints or building codes) and the design intentions (i.e. client intentions or architectural qualities). It hence leads to discovering a superbly formulated complexity in design, which is far more important than defining accurate design objectives, considering a broad design context. The task of the architect is both to set up the goals (formulate the problem) and to find means to obtain the goals (finding solutions). In real-world practice, the problem is not 'given' to architects, but needs to be constructed related to the various circumstances. Often the design problems are anywise defined: there are no design constraints or clearly formulated design intentions. The guidelines for formulating the design objectives should be possibly ecumenical and generic when there are no constraints defined. Usually, architects follow a current stylistic trend or their own artistic preferences towards concretization of the design objectives. It continues when architects decide on the design priority; be it a noteworthy shape, efficiency in site's utilization or corresponding building materials. Obviously, the building of the design objectives is a part of the process and hence the design process has to be a creative task of 'exaction' of an order. Oftentimes, it happens that a designer encounters the situations, which overstep his or her ordinary means of conceptualization. In such a situation, the designer has to construct a new vision of setting the problem – a new frame, which can be called a 'frame experiment', which he tries to inflict in the situation (Schön, 1982). Since the definition of design objectives for different cases and circumstances is itself problematic and glancing (based on different visions and situations), one might conclude that there are no absolute criteria of adjudicating a design. The quality of a design depends forcefully on the predominantly defined design context: a building design cannot be considered as the best solution, either in an absolute sense or in the sense of a set of unique conditions, but only as the most preferred in those circumstances (Brawne, 1992). Accordingly, a solution for design can merely be either 'acceptable' or 'sufficient', relatively to the design circumstances.

5.2. Design process requirements in order to deal with the complexity in building design

A design can often be ameliorated: if more time and consideration are put into the design process; if the complex network of choices/solutions is considered exceedingly; and if the positive and the negative interactions are studied more attentively. Thus, the design process depends on the resources available in particular circumstances (micro and macro levels). Even a design that is far from being perfect can be accepted when the resources are used up. The solution in building design emerges from a process of replacing poor solutions with better ones based on the patterns existing in building design process in spite of its complexity. The adaptive character identifies a solution filtration and takes into account the fact that a building design transforms progressively, towards the design objectives. The iterative character embraces in a cyclical purging of the challenges. It enforces the probative and circular nature of the design process, which frequently re-characterizes the initial design objectives. This process is coordinated by an architect, but it involves many actors who influence the final model by their own judgment about the solution. Later also, the design is assessed by the architect, by the client or group of consultants, by the local community (including owners of the neighboring properties) and finally, by anyone who passes the constructed building. Therefore, there is not one best solution out of this process but the assessments of proposed solutions. That means finding a solution even for strictly defined design objectives is not a linear, straightforward process. The designer should move in a complex network of design choices relevant to its environment, being only partly able to foretaste the consequences of his or her choices to the eventual design. In order to deal with this level of complexity, it is then required to identify, consider, draw and re-construct the design objectives to be adapted into the three design domains which here can be referred as society, economy and ecology. It ultimately requires evaluation of the impacts and effectiveness of these objectives simultaneously through an evolutionary procedure consisting of iterative cycles.

5.3. Systematic approaches in building design

The modern philosophy of systems thinking and theory underlines our broader goals and it shows us to pursue multiple goals (in micro and macro scales) at the same time (Bertalanffy, 1968; Noorani, 2009). Systems thinking through complex systems design based on its properties about development of open systems that integrate diverse components via dynamic networks which uses a top-down process whereas the global functionality emerges and elements identify, interact, adapt, iterate and evolve over time is a suitable methodology to develop practices for addressing complexity in building design process. In order to find the most optimized values derived by the designer in early design stages, it can be considered as an appropriate roadmap to consider the state of 'wicked problems' either whereas different design objectives might throw down each other or where there is not only an accurate answer to design (means solutions can only be 'acceptable' or 'sufficient', relatively to the design circumstances). Using systemic approaches through an adaptive procedure consisting of the iterative cycles is able to capture and address the complexity of the concepts towards considering cause-effect relationships of decisions where the new actions and decisions needs to be taken. Hereafter, the designer will be on the way primarily to integrate various disciplines of knowledge such as social issues beside financial barriers to create seamless frame of understanding of everything.

There is a lack of re-considering and re-thinking of traditional design processes or methodologies and updating them into the modern ones in order to be able to deal with rise of the new paradigms and increasing the complexity in new age movement. The society in our world today, has become more responsive, more adaptive and dynamic, and in cyber-physical perspective is creating the internet of things. Therefore, further development of this world does not follow our traditional design and engineering processes but results in a more organic model. The systematic approaches through an adaptive procedure consisting of the iterative cycles should be essentially considered for building design process. It can be underlined that the job of building designer in new age movement has to turn more into the orchestration of ecosystems and environments in order to achieve their overall functionality by seeking an equilibrium between the different objectives comprehensively.

5.4. Summary

There is a lack of re-considering and re-thinking of traditional design processes or methodologies and updating them into the modern ones in order to be able to deal with rise of the new paradigms and increasing the complexity in new age movement. The society in our world today, has become more responsive, more adaptive and dynamic, and in cyber-physical perspective is creating the internet of things. Therefore, further development of this world does not follow our traditional design and engineering processes but results in a more organic model.

This section provided a consideration about the essence of complexity in the building design process. The systematic approaches through an adaptive procedure consisting of the iterative cycles were deemed suitable for building design process. It can be underlined that the job of building designer in new age movement has to turn more into the orchestration of ecosystems and environments in order to achieve their overall functionality by seeking an equilibrium between the different objectives comprehensively.

6. Development of a holistic multi-methodology for building renovation

6.1. Towards a holistic methodology in sustainable retrofitting

Current barriers in building renovation context have been discussed in section 1.3 and further was structured through concept of Holism including *cultural* (or Transformational) changes and *technological/physical* (or Incremental) changes (see section 1.4). It was described that there is an identified need to investigate and develop an appropriate holistic methodology, which can deal with both cultural and technological/physical aspects, simultaneously. The methodology should be able to address the wicked nature of renovation problems and improve the awareness and learning about sustainability, sustainable retrofitting and sustainable living among the stakeholders. In addition, it should be able to identify, manage and evaluate the building objectives concentrating on selection of the multiple criteria, which form the basis for generation of alternative renovation scenarios/packages. However, a logical question arises: what type of design methodology is most suitable and how can it be developed to deal with the complexity of such problems (?)

6.2. Building renovation through a decision-making framework

Building renovation can be regarded as a problem-solving activity terminated by a solution deemed satisfactory. It is a type of action with a purpose or for a specific purpose. Therefore, it is a process that can be more or less rational, and based on explicit or tacit knowledge. From one perspective, the process can be regarded as a cognitive process resulting in the selection of a most appropriate renovation scenario, selected out of the set of *m* common standard scenarios, which usually is the case for experienced architects or design engineers or consultant companies. In order to evaluate the *m* number of standard scenarios, *n* number of criteria/objectives (for a holistic list of objectives/criteria see chapter 5) will be shortlisted. Next, the pre-generated *m* number of standard scenarios is compared to the *n* number of criteria with the aim to select the most satisfactory scenario for the renovation project (see option "A" in Figure 6.1).

The improvement of existing buildings involves two major steps: current condition assessment and future upgrade strategies (Juan et. al, 2010). Most of the methods focus on the first step of the improvement process, understanding or predicting energy usage but no generation of possible renovation scenarios. While the latter is about proposing of the future upgrade renovation strategies. In this process perspective, it is not a question of assessing standard renovation scenarios/packages but a process of developing scenarios for the individual renovation project bottom-up. In this case, *i* number of renovation actions will be identified and combined in order to make a ranking of the *j* number of building renovation scenarios. To this end, some objectives such as energy efficiency, water efficiency, cost etc. will be shortlisted and to some extent are enhanced by combination of the most fitted renovation actions (e.g. assuming two objectives as object 1 and object 2 as shown in option "B" in Figure 6.1). The goal can be to find a representative set of Pareto optimal solutions (Pareto, 1896), and/or quantify the trade-offs in satisfying the different objectives, and/or finding a single solution that satisfies the subjective preferences of a human decision maker. Using prospect of decision making for building renovation, both of the two options (A and B) demonstrated in Figure 6.1 are regularly being researched and used in practice. In order to proceed with the options, the research can find the roots in decision-making era where a decision is made by explicitly evaluation of multiple conflicting criteria [sustainability objectives/criteria] over various renovation approaches.

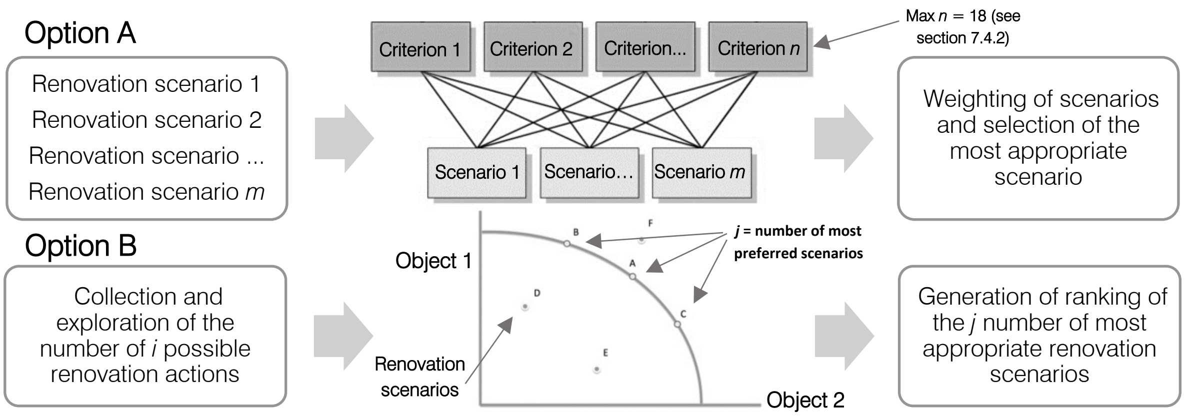


Figure 6.1. Building renovation throughout multiple decision-making frameworks

Hereafter and depends on working with either option A or B, different types of MCDM methods can be utilized (see chapter 3). MCDM basically facilitates the process of resolving the trade-off between criteria (typically based on the preferences of a decision maker) when a solution performs well in all criteria. As described in chapter 3, MCDM can be categorized into MODM and MADM. MODM can be used for decision problems in which the decision space is continuous (option "B" in Figure 6.1) while MADM (option "A" in Figure 6.1) can be used for problems with discrete decision spaces (Triantaphyllou et al., 1998). Taha et al. (2013) discuss that the decision problem in MADM is characterized by the evaluation of a set of alternatives against a set of criteria rather than, as in MODM, the existence of multiple and competitive objectives that should be optimized against a set of feasible and available constraints. The Analytic Hierarchy Process (AHP) by Saaty (1980) is one of the most popular methods in MADM area. Similarly, for MODM area, Genetic Algorithms (GA) is regarded as an effective analytic tool and stochastic search technique to solve large and complicated problems using ideas from natural genetics and evolutionary principles (Juan et al, 2010).

6.2.1. Sustainable Retrofitting Framework – Option "A" using MADM methods

The option "A" shown in Figure 6.1, is related to processes which uses MADM decision-making methods, and hence the trade-offs among the criteria are estimated and addressed (Phdungsilp et al., 2004) based on the interdependent relations among the selected criteria and renovation scenarios (Volvačiovas et al, 2013). For this reason, all the quantifiable criteria including quantitative and qualitative should also be converted to quantitative criteria using for instance "1-9" scaling system proposed by Saaty (1980), or "1-5" Likret scale (1932).

6.2.2. Sustainable Retrofitting Framework – Option "B" using MODM methods

The option "B" shown in Figure 6.1, is related to processes where decision-making includes considerations of all possible renovation actions and their trade-offs in order to generate an optimal solution. The criteria are selected, assessed and optimized by proposing a combination of the most appropriate renovation actions. It is similar to optimization problems in other domains (Ascione et al., 2015). For option "B", a Decision Support System (DSS) needs to be developed in order to assess the building conditions and to recommend an optimal set of sustainable renovation strategies upon consideration of the trade-offs between selected criteria (Juan et al, 2010). DSS have been a major research area in the Information Systems (IS) field. Petkov et al (2007) classified DSS field into (a) computer based automation of problem solving heuristics; (b) computer based model development and manipulation; (c) problem formulation in organizations. All of the three approaches can be considered useful for identifying a solution in option "B". The difference between the option "A" and "B" here is related to where the ranking of the renovation scenarios is made. Combining problem-solving algorithms from MODM with the principles of evolution, GA demonstrates great operations for combinatorial renovation solution optimization (Juan et al, 2010; Lee et al., 2007). However, it seems that all of the existing sustainability criteria cannot be addressed within a DSS, due to the soft nature of some of them (i.e. sociality, identity, spacial etc.). For this reason, and in order to address overall sustainability criteria within a successful renovation scenario, the DSS must be developed into a comprehensive design process in which the process is equipped by use of different methods to cope with them all.

6.3. Introducing three levels of Integrated Design Process Implementation and Evaluation

The discussions of options "A" and "B" in Figure 6.1 have led to the formulation of two different integrated design frameworks (see Figures 6.2 and 6.3). The main reason for development of such a framework is primarily to facilitate understanding of the design process implementation through identification of the different activities, which need to be carried out. Moreover, this also deals with simplification of the existing complexity due to involvement of various types of stakeholders, sustainability criteria and potential renovation technologies in design process. Consequently, the level of complexity for decision-making increases when trade-offs between design criteria and stakeholders priorities need to be addressed; the frameworks seeks to establish a platform for facilitating decision-making under these circumstances.

Figures 6.2 and 6.3 hold information about the relevant activities for each proposed three level of decision-making. The framework in Figure 6.2 has been developed by the principles discussed as option "A" using MADM, and Figure 6.3 by the principles discussed as option "B" using MODM during previous section. Based on the types of the activities that need to be carried out for each level as well as how a decision is processed, they have been named as I) *Exploration*, II) *Assessment* and III) *Scientific Decision-making*.

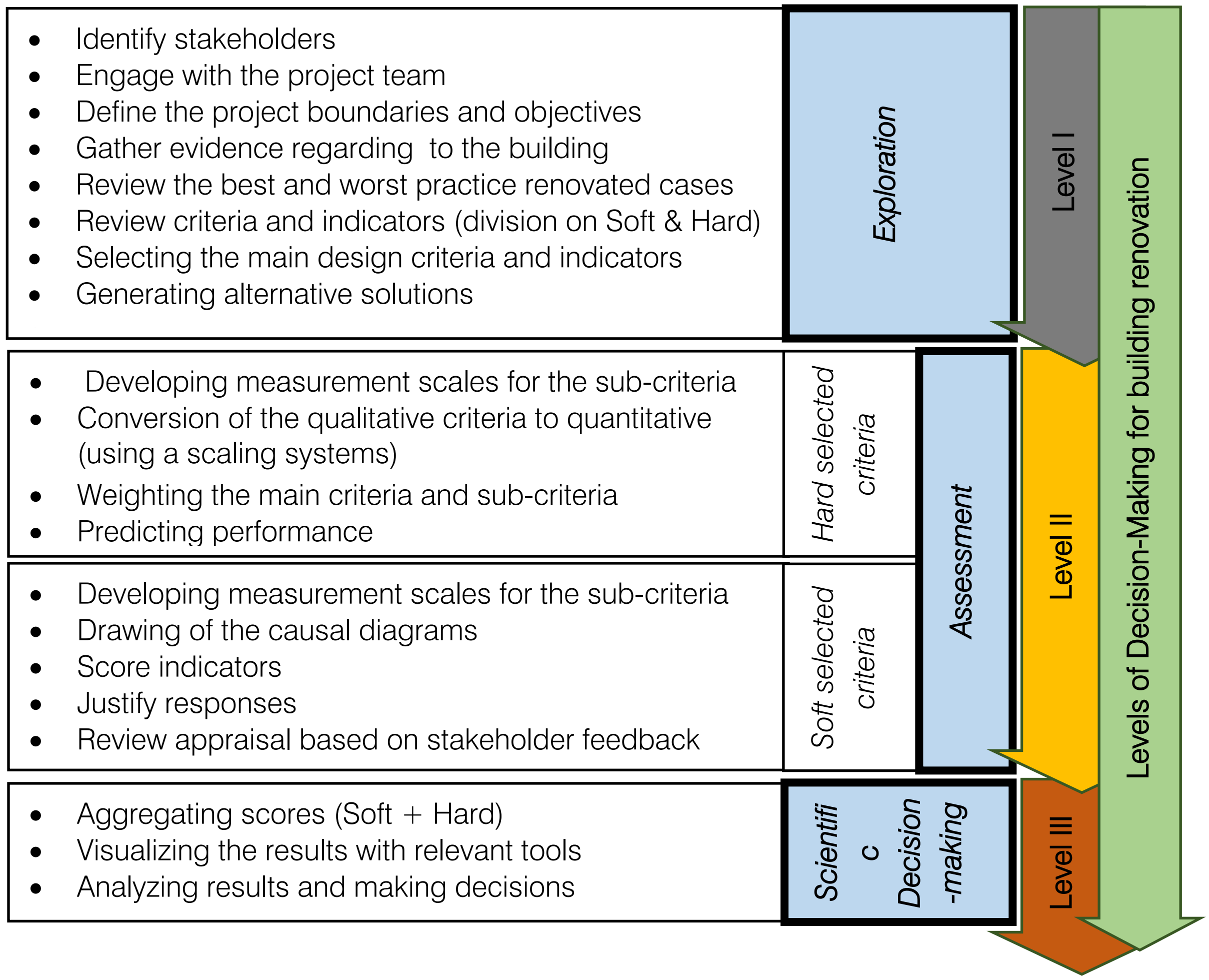


Figure 6.2. Sustainable Retrofitting Framework – Option “A” using MADM methods

Level I - The *Exploration* stage targets the identification and addressing the conditions and details regarding to the buildings and the stakeholders who are involved in the process. The decision that is made at the end of this level is often relevant for renovation of the detached and small buildings i.e., detached residential buildings. It is usually the case for experienced consultant companies that their work scope specifically relates renovation of the similar types of buildings. It sounds logical since the buildings that located in a same region, have 1) similar functions (i.e. dwelling), 2) similar types including shapes and materials, as well as 3) customers with similar range of budgets, ultimately need to be renovated via application of the similar renovation scenarios. Renovation scenarios for these projects are generated while buildings are being explored. For this reason, there are methods such as the Danish - Total Value Model (Schunck, 2011) and/or RENO-EVALUE (Jensen et al., 2015) and/or STBA[1] (2012) that has been developed, specifically in order to finalize the decision for selection of the alternative renovations solutions at level 1, and can be applied for better decision-making.

[1] http://responsible-retrofit.org/wheel/

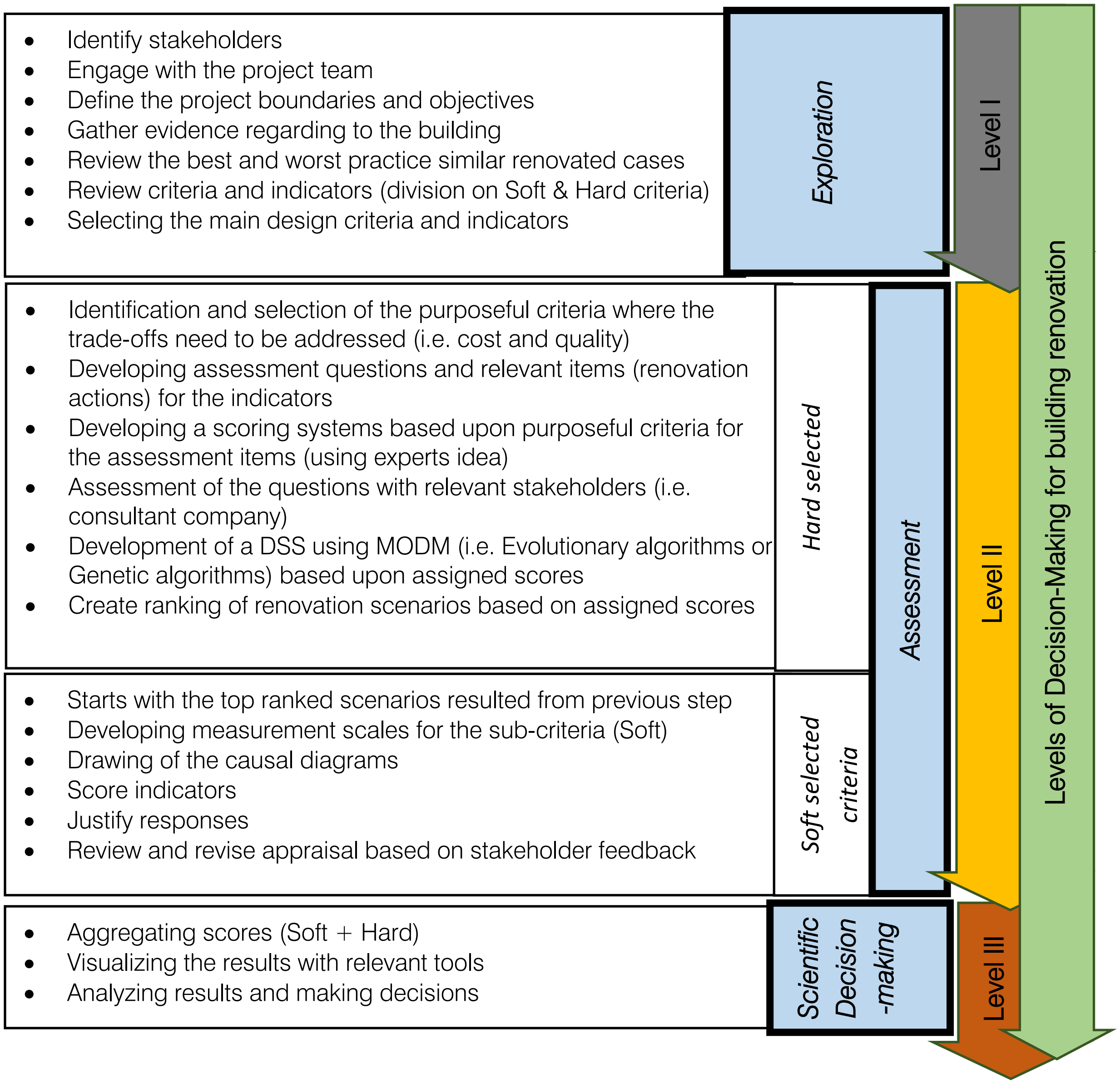


Figure 6.3. Sustainable Retrofitting Framework – Option "B" using MODM methods

Level II - Next, the Assessment stage intends to address the trade-offs or correlations between the sustainability criteria and renovation scenarios, using MCDM methods (Figure 6.1 - option "A" or "B"). The milestone here is about where the soft and hard (quantifiable) criteria have been separated early in the Exploration stage and subsequently can be assessed and addressed in Assessment level, scientifically. It is called "scientifically", due to the terms defined as scientific design in (Cross, 2001). It should be underlined that the MCDM methods here are able to apply on hard/quantifiable criteria. Next, the soft criteria are addressed upon the outcomes of hard/quantifiable criteria regarding to either pre-designed renovation scenarios (option "A" – Figure 6.2) or generated ones using DSS (option "B" – Figure 6.3) and finally the decision is made using brainstorming between the stakeholders.

Level III - The major difference between level 2 and 3 is process of fully scientific decision-making. This level has been named Scientific Decision-makings since it is considered to aggregate and validate the scores regarding to the both hard and soft criteria using MADM methods.

Comparing the frameworks which have been developed in this section, for option "A" the scenarios are generated during the level 1 where a problem is being explored; in the contrary for option "B", the scenarios are developed in level 2 (the *Assessment*) concentrating on addressing the trade-offs between criteria. It is worth noting that, the decision-making at level 3 using option "B" (Figure 6.3) is introduced as a fully scientific approach for building renovation.

6.4. Understanding of 'methodology' and 'design methodology'

The word 'methodology' was originally used to describe 'the science of method', which technically makes the concept of 'a methodology' meaningless. However, Checkland (2000) distinguishes this traditional meaning of 'a methodology' towards a new one including different sets of principles. He addresses 'methodology' as *a body of methods used in a particular activity* (Checkland, 2000: p 26). Moreover, he claims that this latter definition makes the crucial distinction between 'methodology' and 'method'. As the structure of the word indicates, 'methodology' in this situation leads to selection of some certain 'methods', in the form of the specific approach adopted for the specific situation. According to Checkland (2000), most recently developed methodologies follow this latter definition.

There is now a huge diversity of methodologies within the broad field of Decision-making and Management Science, and Engineering Design, all having differing characteristics and stemming from various paradigms based on different philosophical assumptions. Depending on the type of the problem that they are dealing with, including "objective" or "subjective", "soft" or "hard", and "quantitative" or "qualitative", the methodologies can be categorized in two types including Soft Systems Methodologies and Hard Systems Methodologies (Checkland, 2000). "*Soft value management skills are used more in the early project stages when the project is not fully defined. This usually involves reaching consensus with many different stakeholders. As the design develops towards resolved design solutions, so hard value management skills and methods increase in importance"* (Dallas, 2006: p 122).

Researchers such as Cross (2001) strived to investigate and address the methodologies and their differences between *design* and *science* contexts. In this consideration, he identified "Operation Research" as a Scientific Design concept and "Systems theory and thinking" as a Design Science concept (Cross, 2006). Simon's (1969) positivist concept leads to a view of design as 'rational problem solving', and Schön's (1992) constructivist concept leads to a view of design as 'reflective practice'. Cross (2006: p 102) argues that these two concepts might appear to be in conflict, but Dorst's (1997) use of the two paradigms in analyzing design activity, leads him to the appreciation that the different paradigms have complementary strengths for gaining an overview of the whole range of activities within the design domain (Schön, 1988). Whilst this plenitude can enhance practice, it also poses problems for practitioners who often tend to restrict themselves to one paradigm or even one methodology (Mingers, 2014). Similar to Dorst's concept mentioned above, Jackson (2003) states that different methodologies are making different assumptions about the problem at hand and are hence complementary to one another; it is therefore necessary to make a choice as to which methodologies are appropriate for a particular intervention. Mingers et al. (1997:

p 2) contribute to the discussion by stating that to deal with the richness of the real world, it is desirable to go beyond using a single (or, on occasions, more than one) methodology. They argue that it is possible to combine several methodologies - in whole or in part – which stem from different paradigms.

The multifaceted problem for building renovation (which was elaborated in section 1.3) is diverse and complex in character and, it therefore seems obvious that it cannot be served by a single methodology. Consequently, it is my intention to develop a multi-methodology as a way to strengthen multiple perspectives on this complex problem and thereby overcome the shortcomings of traditional approaches. The following section of the thesis will focus on exploring existing methodologies and methods; subsequently to mix them, and ultimately to develop a Holistic Multi-methodology for Sustainable Renovation (hereafter referred as HMSR), which aims to deal with different aspects of the concept of *Holism* for implementation in the building renovation context.

6.5. Developing the HMSR (Holistic Multi-methodology for Sustainable Renovation)

6.5.1. Appropriateness of Soft Systems Methodology (SSM)

Chapter 2 of the present thesis has provided an overview over Engineering Design methods based on systems theory and thinking including SSM and HSM. In this section, by referring to the discussion in chapter 2, I will provide a summary particularly about SSM. As described before, SSM was developed by Peter Checkland in 1970s at Department of Systems, University of Lancaster. Checkland et al. (1990) distinguishes between “hard” and “soft” systems thinking within an attempt to use system concepts to solve problems. Simonsen (1994) defines Hard Systems Thinking within a) Systems Engineering (as the traditional research strategy or design approach for engineers and technologists) and b) Systems Analysis (as the systematic appraisal of the costs and other implications of meeting a defined requirement in various ways). In this perspective, the author (Simonsen, 1994: p 2) discusses that *Hard Systems Thinking has the starting point in 'structured' problems and the assumption that the objectives of the systems concerned are well defined and consistent*; unlike *Soft Systems Thinking* [which] *has the starting point in 'unstructured' problems within social activity systems in which there is felt to be an ill-defined problem situation*. Checkland (1981) refers to Hard Systems Thinking as the 'optimization paradigm' while Soft Systems Thinking is referred to as the 'learning paradigm'. As such, the SSM approach stems from the 'systems movement', which Checkland (1981) considers as an effort to give holistic approaches in socio-technical problems. It is a method that in a systematic way attempts to establish and frame a debate regarding actions for complex and messy situations (Simonsen, 1994). SSM is primary applied in the analysis of complex situations where there are divergent views about the definition of the problem i.e., where nonlinear relationships, feedback loops, hierarchies and emergent properties have to be taken into account. The soft system’s method postulates understanding of a system, by iterative learning process. The methodology provides a well-defined action research approach to help address wicked problems. The concept of SSM has been explained in detail by Checkland (2000) in a ‘seven stages model’ (in 1981), which was subsequently developed through a ‘two main stream’ approach (in 1988) and finally concluded by a ‘four main activity’ method (in 1990).

The final version of the SSM (which is named ‘the four main activity’ method), and, according to Checkland (2000), encourages group learning and is ideal as a group decision-making approach to deal with messy problems. It is strengthened by active participants and stakeholders, and encourages joint ownership of the problem solving process. Neves et al. (2009) in their study about application of SSM in energy efficiency discussed that it played a central role in suggesting questions for eliciting a 'cloud of objectives' that each potential evaluator of energy efficiency initiatives may pursue. Further, Rose (1997) recommended SSM where an organization is seeking to achieve changes in workplace culture and transformation into a learning organization. In this perspective, using SSM for building renovation context could be a way to develop an integrated design process, which deals with the complexity, captures it and communicates it among the key players/decision makers/stakeholders, including non-expert decision makers and occupants. In general, application of SSM in a renovation context is suggested as a way to deal with the *culture* and society, because, it promotes an appropriate way of problem structuring, group decision-making and group learning, and hence it encourages discovering of the knowledge and improvement of the learning about sustainability goals among the stakeholders towards supporting the design decision making in building renovation process.

6.5.2. Appropriateness of Multiple Criteria Decision Making Method (MCDM)

Chapter 3 of the present thesis has provided an overview of MCDM and its various methods. In present section, I will provide a summary ahead of using them in development of the HMSR. As described before, MCDM investigates and assesses multiple criteria throughout complex decision analysis (Belton et al., 2002; Figueira et al., 2005). These methods can address both quantitative as well as qualitative criteria to analyze conflicts in criteria presented by different decision makers (Pohekar et al., 2004). Parnell et al. (2013) discuss it as *a philosophy and a social-technical process to create value for decision makers and stakeholders facing difficult decisions involving multiple stakeholders, multiple (possibly conflicting) objectives, complex alternatives, important uncertainties, and significant consequences*. MCDM can provide a technical-scientific decision-making support approach to justify its choices clearly and consistently, especially for addressing issues in connection with the sustainability area (Cavallaro, 2009). Conflicting criteria are typical in evaluating options i.e., cost is usually one of the main criteria, and some measure of quality is typically another criterion, easily in conflict with the cost (Gal et al., 1999).

Application of MCDM methods in building renovation could be a potential way to deal with evaluation of multiple conflicting criteria in decision-making processes when selecting the most appropriate renovation scenarios/packages. In addition, it corresponds to resolve the trade-off between criteria (typically based on the preferences of a decision maker) when a solution performs well in all criteria.

6.5.3. Mixing SSM with MCDM

The potential of using methodologies such as SSM or MCDM can also be considered from their vast application in the other disciplines. Above all, the availability of the various tools and software in making and implementation of decisions when using SSM or MCDM is another reason that increases their appeal. Neves et al. (2009: p 11) applied SSM to structure a Multi-Criteria Decision Analysis (MCDA) model for appraising energy efficiency initiatives and concluded that: *"SSM is a viable alternative to using mapping-based problem structuring methods to help unveiling a set of objectives* *for structuring a multi-criteria decision analysis model".* The most important weakness of SSM is the lack of support, when using it during the last phases where a decision is made. Similarly, the weaknesses of MCDM was identified during the problem exploration and problem structuring stages due to the lack of adequate brainstorming (Jayaratna, 1994). However, Petkov et al. (1997) underline that these weaknesses should not be considered as a cause for rejection of these techniques. On the contrary, on the basis of Critical Systems Thinking (Flood et al., 1996) and Critical Realism (Bhaskar et al., 2008; Mingars, 2014), one can find a common foundation for the complementarity use of MCDM techniques with SSM approaches. The authors (Petkov et al., 1997) conclude that there is a considerable scope for new and fruitful combined application of MCDM method with different strands of systems thinking, which could ultimately enrich both approaches. It can be adopted from Petkov et al. (2007: p 13) that, it is useful to explore the possibilities to combine separate techniques from SSM with MCDM in order to both reflect the conflicting nature of the criteria, when dealing with increased complexity and multiple stakeholders. It further guides decision makers in complex situations and harness their potential to support learning about the problem and more effective decision support.

In this perspective, I propose to apply a mix of SSM and MCDM methods for the building renovation context to address problem formulated in section 1.3. Issues related *culture* can be addressed through attention to regular communication, collaboration, brainstorming, group learning and group decision-making among the stakeholders to promote learning and participation in a top down procedure by using SSM. Issues related to *technological/physical*, can be addressed by using MCDM. As a result of these interventions, the stakeholders can concentrate on building a common appreciation about the most essential issues corresponding to the social and technical aspects of the issues at hand. Moreover, it propels better informed management decision related to the particular situation.

There are a range of different methods available in SSM and MCDM that are capable of dealing with either *appreciation* and/or *analysis* and/or *assessment* and/or *taking action* (Mingers et al., 1997) while facing a problem. In addition, the framework for implementation and evaluation of factors affecting the retrofitting context serves different perspectives and stakeholders as demonstrated in Figure 1.2. As such, when mixing SSM with MCDM, it is essential to consider which methods are the most applicable. For this reason, the research has used Habermas' (1984) three worlds including *social*, *personal* and *technical* worlds for the evaluation of the capabilities of the methods, which are in line with the terms *Transformational* and *Incremental* changes discussed in section 1.4. Table 6.1 in the following represents the mapping of the various selected methods (most popular methods) from SSM and MCDM as well as their capabilities in relation to the three worlds of *social*, *technical*, *personal* for building renovation purposes. It serves to clarify the correct application of these methods, when using them in development of the HMSR in the next step. A short description and required citation relevant to the identified methods in Table 6.1 will be provided in Table 6.2 (further information can also be find in section 3.2.3.4.).

Table 6.1. Mapping of popular methods from SSM and MCDM discussed in relation to the three worlds of Habermas (1984) for dealing with the concept of *Holism* in building renovation

	APPRECIATION		ANALYSIS		ASSESSMENT		ACTION	
Social world	A, B, C, D	-	A, E, F, G	H	F, G	I, J, K	-	J, K
Personal world	A, B, C, D	-	C, D, E	H	C, D, E	I, J, K	D, E	J, K
Technical world	A, B, C, D	-	C, F, G	H	F, G	I, J, K	-	J, K
	SSM	*MCDM*	*SSM*	*MCDM*	*SSM*	*MCDM*	*SSM*	*MCDM*
A) Rich picture B) CATWOE C) Root definition D) Conceptual models E) PQR F) POT G) SAST H) Delphi method I) Pairwise comparison J) AHP K) TOPSIS								

Table 6.2. The list of proposed Methods and their purpose of usage in the developed HMSR

Method		Purpose	References
SSM	Rich picture	Understanding of the organizational context; Identification of the stakeholders and Key Players	Mingers et al., 1997; Checkland, 2000; Neves et al., 2009
	CATWOE	Customer, Actors, Transformation, Weltanschauung, Owner, Environmental constraints (CATWOE) - Mnemonic for a checklist for problem or goal definition	Checkland, 2000; Neves et al., 2009
	Root definition	Identification of key transformation	Mingers et al., 1997; Checkland, 2000
	Conceptual models	Recognition of key transformation	Mingers et al., 1997; Checkland, 2000; Neves et al., 2009
	PQR	Do P by Q in order to contribute to achieving R, which answers the three questions: What to do (P), How to do it (Q) and Why do it (R)	Checkland, 2000
	POT (Personal, Organizational, Technical)	The three most typical perspectives in addressing complex problems: T is the Technical perspective; O is the Organizational or Societal perspective; and P is the Personal or Individual perspective	Mitroff et al., 1993; Mingers *et al*,. 1997; Vo et al., 2001
	SAST (Strategic Assumptions Surfacing and Testing)	Method for approaching ill-structured problems	Mason et al., 1981; Petkov et al., 2007
MCDM	Delphi method	Estimation of the likelihood and outcome of future events doing by a group of experts	Linstow et al., 2002; Wang et al., 2009; Parnell et al., 2013

	Pairwise comparison	Comparison of alternatives in pairs to judge which of each entity is preferred	Jaccard et al., 1984; Wang et al., 2009; Parnell et al., 2013
	AHP (Analytic Hierarchy Process)	Organizing and analysing complex decisions	Saaty 1980; Wang et al., 2009; Parnell *et al,.* 2013; Petkov et al., 2007
	TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution)	Selection of alternatives that is closest to ideal solution and farthest from negative ideal solution	Hwang et al., 1981; Wang et al., 2009; Parnell et al., 2013

6.5.4. The step-by-step HMSR development

In order to establish the applicability of the methodologies as part of a multi-methodology, I have studied the underlying assumptions behind each methodology with reference to Mingers et al. (1997), Vo et al. (2001), Jackson (2003) and Petkov et al. (2007). For the SSM part, the framework for the development of the HMSR, has been applied from "four main activity approach"; it can be described as a four main activities process of analysis, which uses the concept of a human activity system as a means of getting from "finding out" about a situation to "taking action" and improving the situation (Checkland, 2000).

In addition, following the two typical decision-making frameworks which were developed in section 6.3 based on application of the two different types of MCDM (MADM or MODM), in the present section, HMSR uses the second framework (see Figure 6.3) as the main body of application of MCDM in renovation process. Accordingly, the "four main activity approach" from (Checkland, 2000) have been matched on the "three levels of the decision-making" which were represented in Figure 6.3. Next, the methods from SSM and MCDM based on their capabilities, which were represented in Table 6.1, have been assigned to these stages.

In addition, I have provided information for a standard renovation process (see Figure 2.16 and Table 2.2) from the study done by BPIE (2013) as well as Boeri et al. (2015) in chapter 2 of the present thesis. By merging the standard renovation process from BPIE (2013) beside use of "four main activity approach" from SSM together with the framework about three levels of integrated design process implementation and evaluation (in Figure 6.3) and introducing use of a DSS (Decision Support System) to deal with the "hard", it is possible to address *Holism* (see section 1.3) for renovation from where a problem is primarily explored and formulated to make the most appropriate decision about which scenario to pursue is made at the end of the process. The results have been combined in Table 6.4 and configures/constitute the HMSR with a listing of activities relevant at each decision level (activities 1 to 23).

Table 6.3. Mixing SSM with MCDM methods for sustainable building renovation [together with matching the three levels of integrated design process implementation and evaluation for sustainable renovation (from Figure 6.3) with the framework of the SSM (from Checkland, 2000)]

Decision-making at Level 1	Stage 1	Finding out about a problem situation, including culturally/politically
		Proposed methods: Root definition, Rich picture, CATWOE, Conceptual models, PQR (What, How, Why), and Delphi method
	Stage 2	Formulating relevant purposeful activity models
		Proposed methods: PQR (What, How, Why)
Decision-making at Level 2	Stage 3	Debating the situation, using the models, seeking from that debate both a) changes which would improve the situation and are regarded as both desirable and (culturally) feasible b) the accommodations between conflicting interests which will enable action to improve to be taken
		Proposed methods: POT or SAST + Pairwise comparison and/or AHP
Level 3	Stage 4	Taking action in the situation to bring about improvement
		Proposed methods: AHP and/or TOPSIS

When applying the HMSR, the relevant stakeholders are first identified and their demands or their relevant topics are explored; the design objects are set up; then, there will be a separation on "soft" and "hard" (quantifiable) criteria; next, the criteria are assessed and finally the decision on which scenario to pursue is made. By following the methods which were introduced for performing each step (see Table 6.4) and based on the mechanism of the methods, the mentioned activities can be carried out through the performing two rounds of iteration in the process. For more clarification on how and where the proposed methods are applicable, a real renovation project is described in the following section, including a discussion about the potentials of applying the methods from HMSR.

Table 6.4. The step by step HMSR

Levels of decision-making		Relevant activity	Methods from SSM and MCDM	No. of Act
Decision-making at Level 1		Project start-up - using the "Characteristic Diagram" from (see section 7.4.1)		1
		Identify stakeholders	Rich picture + CATWOE analysis	2
		Engage with the project team		3
		Define the project boundaries and objectives	Root definition + CATWOE analysis + Conceptual models	4
		Gather evidence regarding the building		5
		Review the best and worst practices in similar renovated cases		6
		Review criteria and indicators (division on Soft & Hard criteria) - using the "Value Map" from (7.4.2)	PQR + Delphi study	7
		Selecting the main design criteria and indicators		8
Level 1 : It would be possible to develop and evaluate renovation scenarios using certain simulation and analytical software at the end of this decision level. This would reflect a common/traditional process. At this level, the process could be supplemented by using for instance the Danish Total Value Model (Schunck, 2011) and/or RENO-EVALUE (Jensen et al., 2015)				
Decision-making at Level 2	HARD CRITERIA	Identification and selection of the purposeful criteria where the trade-offs need to be addressed (i.e. cost and quality)	Development of a Decision Support System (DSS) by use of MODM (Nägeli et al., 2017; Yin et al., 2011; Juan et al., 2010)	9
		Developing assessment questions and relevant items (renovation actions) for the indicators.		10
		Developing a scoring system based upon purposeful criteria for the assessment items (using experts' proposals)		11
		Assessment of the questions with relevant stakeholders		12
		Development of a DSS using MODM (i.e. Evolutionary algorithms or Genetic algorithms) based upon assigned scores		13
		Create ranking of renovation scenarios based on assigned scores		14
	SOFT CRITERIA	Starts with the top ranked scenarios resulted from previous step	POT or SAST	15
		Developing measurement scales for the sub-criteria (Soft)		16
		Drawing of causal diagrams		17
		Score indicators	Pairwise comparison or AHP	18
		Justify responses		19
		Review and revise appraisal based on stakeholder feedback		20
Level 2 : It is possible to make a decision at the end of this decision level using for instance brainstorming between the involved stakeholders and hence the renovation scenario is selected.				
Decision-making at Level 3		Aggregating scores - Soft criteria + Hard criteria	AHP and/or TOPSIS	21
		Visualizing the results with relevant tools		22
		Analyzing the results (i.e. using sensitivity analysis) and making the decision on the selection of the right renovation scenario		23
Level 3 : The decision which is made at this level, is scientifically and rationally sound.				
Note: The symbol ↻ refers to the fact that the design process is not linear, but iterative in character. As such, several iterations of the activities are likely to the performed throughout the process. It results from the application of the introduced methods.				

6.5.5. Analysis of a case study

In order to demonstrate how the HMSR could be applied in practice, I introduce a case study in Aarhus, Denmark. The case is included as an example of how a renovation project is carried out today, and how applying the HMSR could have supported the process. This is done with reference to the activities and methodologies put forward in Table 6.4 and based on the my previous experiences with implementing the activities and methodologies in previous cases.

The included case is a social housing block from the late 1960's, which is currently undergoing renovation. At the moment of writing the thesis, the tender for the project has been settled, but the renovation project not yet completed.

The insights communicated in the present thesis are based on information meetings and a research by design-study conducted in one of bidding teams. As such, the insights convey the process as experienced from this specific view point. The research through design-study, has been conducted as part of the Danish research project RE-VALUE (see section 1.10)

6.5.5.1. Demonstrating the application of the HMSR in the renovation case

In the initial phase of the project, the client (the housing association) engaged client consultants to perform initial investigations, *"gather evidence regarding the building"* and develop a building program as the basis for the tender. In this initial phase, the client consultants have engaged in a user process and initiated dialogue with relevant stakeholders, hereunder the municipality and funding institutions. This process can be described as "*identification of stakeholders"* and *"Engaging with the project team"* in accordance with Table 6.4. The stakeholders entered the project with different priorities, spanning *"hard"* criteria related to e.g. finance and thermal capabilities, as well of more *"soft"* criteria related to the general image and safety of the area as well cultural-heritage concerns to name but a few. Due to the socio-economic status of the area, the soft criteria have carried considerable weight throughout the process, which has added to the complexity of the renovation task at hand. Together, the project stakeholders involved at this initial stage have *"defined the project boundaries and objectives"*.

Applying *Root definition*, *CATWOE analysis* and development of a *Conceptual Model*, could have supported the task of identifying key stakeholders and investigate the renovation case from different perspectives. This would offer a framework for capturing and dealing with the complexity of the project and create a shared language for discussing this complexity in a holistic manner.

Back to the studied case; as part of the initial process, a group of representatives of the housing association, consultants, municipality and users went on study trips in Denmark and abroad with the aim to *"review best practices in similar renovated cases"*. Based on this initial process *"criteria and indicators"* were reviewed, selected and communicated in the building program, which founded the basis for the following tender and competition phases. In the specific case, the building program included actual principle scenarios for the renovation, developed by the client consultants prior to the tender and competition phases, to communicate principles to the users, who had to vote for or against the renovations before any further actions were taken. Referring back to the HMSR in Table 6.4, this process of formulating criteria could have been supported by using the *PQR* method from SSM, and *Delphi method* from MCDM, as these methods offer a knowledge-based approach to prioritizing and selecting criteria and sub-criteria. By applying the PQR (Do P by Q in order to contribute to achieving R, which answers the three questions: What to do “P”, How to do it “Q” and Why do it “R”) method, P can be referred to building components, Q can be referred to alternative renovation solutions and R can be referred to sustainability objectives. By applying the *Delphi* method first round iteration on previous activities towards a consensus on selections is carried out as well.

Returning to the studied case, the task of the bidding teams was to interpret the criteria put forward in the building program and develop specific design scenarios, which were ultimately narrowed down to one proposal in each team. During start-up meetings within the team, consisting of a contractor, an architectural consultancy company and an engineering consultancy company, the *“criteria and indicators”* put forward by the client were discussed. The project group met up once a week to discuss and evaluate scenarios for realizing these objectives. Within each sub-group, e.g. the architecture group, several iterations would be carried out during the course of the week, leading up to these weekly joint meetings. During the weekly meetings a dialogue-based evaluation of the scenarios was carried out. In a number of cases the contractor would calculate cost consequences of alternative scenarios after the meeting by use of spreadsheets and continuous dialogue between architects and engineers would serve to secure integrated solutions. At two occasions, the project group had presentations/dialogue meetings with the client, where the proposed design solution was discussed relative to the originally stated criteria. Based on these activities, the scenarios were gradually narrowed down to one proposed scenario, which was delivered to the client and subsequently evaluated by an assessment committee.

If we relate the process in the case study to Table 6.4, we see that the process can be described with reference to decision-making level 1. In the following, I use the framework of the case study to elaborate upon how moving through the decision levels 2-3 could have further influenced and supported the process (see Figure 6.4).

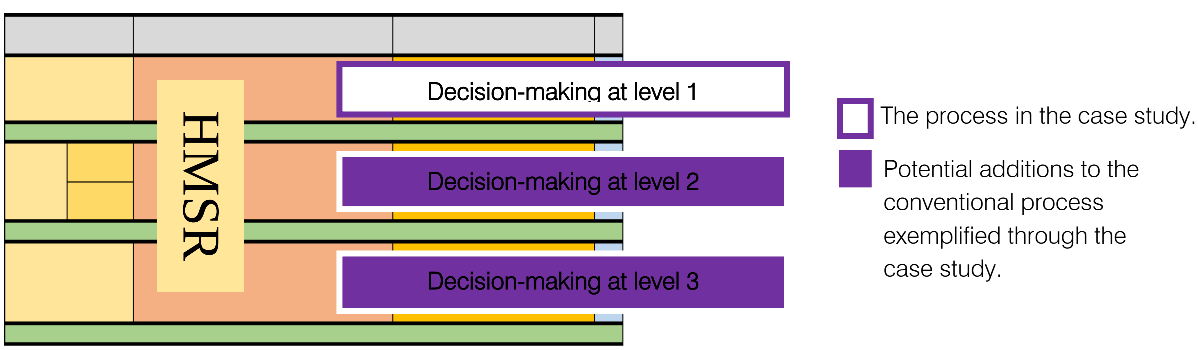


Figure 6.4. Principle diagram illustrating the use of the case study to exemplify how applying the HMSR could potentially influence the renovation process.

Applying the HMSR [moving forward to decision-making at level 2], using a DSS (Näegeli et al., 2017; Yin et al., 2011) could support the process of generating renovation scenarios focusing on “hard” criteria. It improves the quality of the decision as it provides the stakeholders a detailed overview of the possible solutions and how they perform and therefore encourages stakeholders to accommodate holistic renovation solutions. There is a potential to optimize the current process of developing and testing scenarios and, subsequently, reduce the number of meetings needed to evaluate them. Further, by applying the *POT* method (P for Personal, O for Organizational and T for Technical) from SSM, and *AHP* from MCDM, the process of evaluating the final scenarios (i.e. the top ten scenarios generated by application of the DSS) is supported by use of weighted criteria.

Here the weighting progress using *AHP* methods benefits from *POT* method. Performance rating of sustainable value oriented criteria are constructed as quantitative and qualitative values. The quantitative values are used for criteria that can be quantified using numbers (i.e. Energy consumption) which is addressed using a DSS. Qualitative values are used to characterize how well a building scheme is rated against particular criteria in situations where the rating is based on qualitative judgment (i.e. spatial quality, sociality, aesthetic etc.), and thus not normally subject to quantification. Keeney (1992) states that the values must be identified and defined precisely; then, they can be articulated through this meaning qualitatively by stating objectives, and, if desirable, they can be embellished with quantitative value judgments. To this end, the criteria are weighted using *AHP* through setting up the *POT* methods by running a workshop. Application of i.e., *POT* ascertains the second round of iteration on previous activities as well. When the O (Organizational) and P (Personal) perspectives are "swept into" the T (Technical) perspective, gaps between the perspectives are discovered. "*The gaps occur because different perspectives use different languages to talk about the same problem and thus it is difficult for one perspective to communicate with the other perspectives"* (Vo et al., 2001: p 3). Added to this, application of methods such as *POT or SAST* enables stakeholders to hear each other's voices and the common present challenges in renovation context (e.g. the re-bound effect) can be highlighted and emphasized, which potentially help to increase the level of awareness, group learning, and finally group decision-making. This helps to deal with the aspect of *culture,* which was formulated in section 1.3. After this step, and by going through the level 3 of the HMSR, the selection of the most appropriate renovation scenario, based on aggregation of the gained scores from selected "soft" and "hard" criteria for retrofitting, can be finalized. My suggestion is application of two different MCDM methods (i.e. *AHP* and *TOPSIS*) including a *sensitivity analysis* to determine how different value of an independent objective/criterion impact a particular dependent objective/criterion under a given set of assumptions.

In summary about the case study:

It used to reveal how the HMSR could potentially help overcome this complexity by suggesting a mix of activities and methodologies from SSM and MCDM in a unified multi-methodology. Further, the case demonstrated how activities at design-making level 2-3 can add value to the process by providing a systematic methodological framework for developing and evaluating design scenarios. The suggested activates and methods for exploring design scenarios through the use of e.g. generic algorithms were expected to support the current "manual", dialogue-based process of translating criteria into scenarios, through time reductions and the ability to evaluate multiple criteria simultaneously. In total, application of SSM methods to be used from the beginning serves to structure the renovation problem and using MODM (the DSS) and MADM methods helps to generate and select the most appropriate scenario for the renovation project.

As such, the case serves to demonstrate the potential of the HMSR as a systematic methodology for handling the complexity of the renovation domain and there through add value for stakeholders, not least the end-users of the building, by promoting a holistic approach to building renovation.

Several features of HMSR distinguish it from the work of others. Application of MCDM beside SSM in the architectural domain can be considered as the novelty in this study, and the intention should be to promote such methodologies in order to deal with the interdisciplinarity and transdisciplinary characteristics of the problems in AEC sector.

6.6. Summary

This section initially explored the decision-making process in renovation context using either MADM or MODM methodologies.

Thereafter, it addressed the notion of ‘methodology’ and ‘design methodology’. In this consideration, ‘methodology’ was indicated as a body of methods used in a particular activity. I tried to distinguish between soft Systems Methodologies (SSM) and Hard Systems Methodologies (HSM). Soft value management skills were addressed so as to be used more in the early project stages when the project is not fully defined to involve different stakeholders. As the design develops towards resolved design solutions, so hard value management skills and methods increase in importance.

Methodologies and their differences between design and science contexts were also appreciated. In this consideration, “Operation Research” was found as a Scientific Design concept and “Systems theory and thinking” as a Design Science concept.

Further, following the previous chapter of the thesis (chapter 2 and 3), SSM, MCDM, and usefulness of the mix of these two were discussed. Based on the characteristics of the renovation problem, consequently this section produced a multi-methodology, using a mix of SSM and MCDM methods entitled HMSR. The HMSR was structured in three levels including 23 steps. It can serve as a means to structure retrofitting problems in accordance with the sustainable paradigm to support the decision-making and help to develop and select the most appropriate retrofitting alternative.

Further, the HMSR is considered to be able to address issues related to both cultural changes (subjects to essence of various stakeholders, and above all, behavioral barriers to improve the building occupants’ learning about the sustainability and the sustainable living) and technological/physical changes (subjects to physical and/or technological changes to the building to promote sustainability in a holistic sense) simultaneously.

A case study has been introduced as a means to demonstrate how the HMSR could be applied in practice. The case exemplified the complexity of renovation processes due to i.e. involvement of a large number of stakeholders, with different priorities spanning both “soft” and “hard” criteria.

CHAPTER V

SUSTAINABILITY FOCUSED DECISION-MAKING IN BUILDING RENOVATION

CHAPTER'S SYNOPSIS

"Following the existing barriers in renovation context and the discussion in section 1.1 and section 1.2 the purpose of this chapter is to develop a sustainability framework to audit, develop and assess building renovation performance, and support decision-making during the project's lifecycle. It represents the results of research aiming at addressing sustainability of the entire renovation effort including new categories, criteria, and indicators. This is to answer the question concerning the holistic sustainability objectives within building renovation context. In doing so, appropriate data about sustainability objectives will be collected and structured, and subsequently verified using a Delphi study. The developed sustainability framework can be applied during different project stages and to assist in the consideration of the sustainability issues through support of decision-making and communication with relevant stakeholders."

7. Sustainability focused Decision-making in Building Renovation

7.1. A critical review of state-of-the-art evaluation methods and methodologies in building retrofitting

As discussed in earlier chapters, renovation processes make up complex, highly interdisciplinary systems, which involve stakeholders across a broad spectrum of disciplines and potentially affect the everyday lives of a large number of people (Beim et al., 2015). Subsequently, a deep renovation is not 'merely' about optimizing the technical performance of a building, but prescribes a holistic approach, in which measures are considered for their inter-dependence rather than as separate elements in a traditional reductionist line of thought. A number of sustainable assessment methodologies have been developed to assist the decision-making processes and ensure targeted results. Building Research Establishment Environmental Assessment Method[1] (BREEAM) and Leadership in Energy Environment Design[2] (LEED), have been able to establish an international recognition. However, more recent methodologies, such as Deutsche Gesellschaft für Nachhaltiges Bauen[3] (DGNB), are also increasingly recognized (AktivHusDanmark, 2015). Figure 7.1 demonstrates the overall assessment schemes for all three methods, thus highlighting their definition of the balance for sustainability.

Many of these assessment methodologies are claimed to have a holistic approach. However, it is the hypothesis of these analyses that the models themselves represent a stance on sustainability as they assign weight to different 'sustainability indicators'. As such, the same design may be assessed differently according to the chosen tool (Tagliabue, 2016). The study has been done as the part of RE-VALUE project in this section and the results has been presented in Jensen et al. (2017a). It presents the results of a literature review of existing assessment methodologies. The aim is to compare which sustainability indicators each methodology attach importance to, and to provide a synthesis of the findings, which can improve our understanding of the positioning of each methodology relative to each other.

The evaluation of existing sustainability assessment methodologies is performed as a systematic literature review of 7 selected methodologies. The overall aim of the review is to identify to which sustainability indicators each methodology assigns weight. The methodologies have been included in this section for their relevance to retrofitting in a Danish context. They do not necessarily target retrofitting initiatives, but encompass such projects as part of their scheme.

[1] http://www.breeam.org

[2] http://www.usgbc.org

[3] http://www.dgnb.de/en/

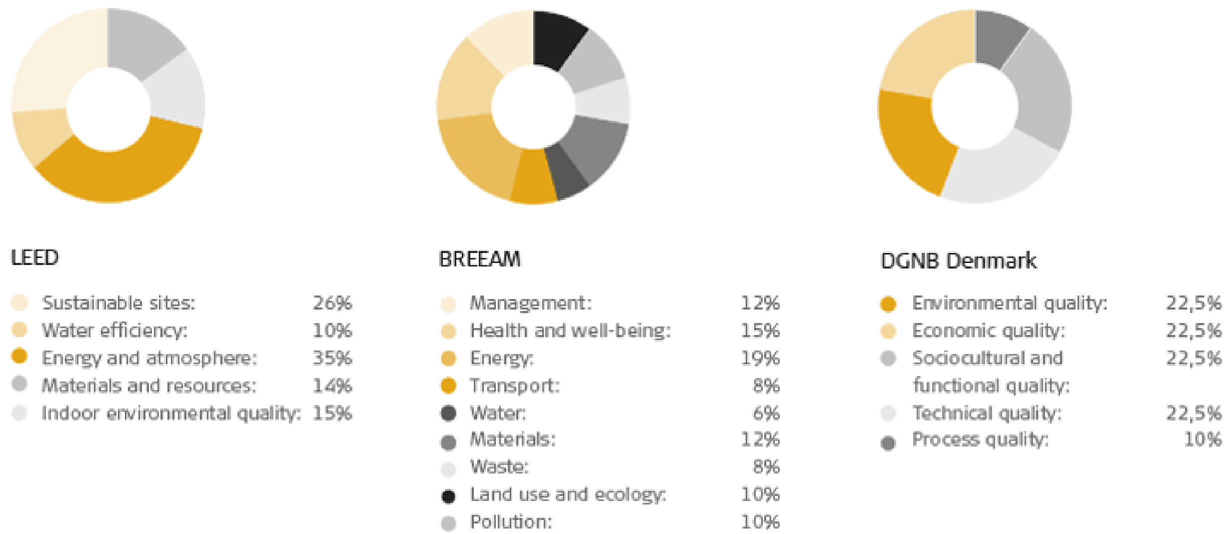


Figure 7.1. Overall assessment schemes for all BREEAM, LEED and DGNB-DK[4] (source: AktivHusDanmark, 2015)

In order to provide a set of 'lenses' through which to map the sustainability indicators in a similar way, the study leans on the three pillars of sustainability, emanating from the 1987 Brundtland Report: social, environmental and financial sustainability (World Commission on Environment and Development, 1987), adding a fourth parameter addressing process-oriented indicators. The findings of the mapping are communicated through diagrams, which depict the indicators relative to these 'lenses' and a timeline which indicates where in the renovation project the given methodology can be applied. The evaluated sustainability assessment methodologies are presented in Table 7.1.

Table 7.1. Short description for the evaluated sustainability assessment methodologies in this section (source: Jensen et al., 2017a)

Name	Description
DGNB-DK	The DGNB-DK tool is a Danish version of the DGNB tool, developed by Green Building Council Denmark in 2012. The purpose is to secure quantifiable standards, which makes it possible to certify buildings based on a "scoring system". The methodology is not targeted renovations, but has been applied to such projects (DK-GBC, 2016). The model has a relatively even distribution of social, economic, environmental and process-related sustainability indicators. It addresses the concept of spatial quality in the subsection devoted to "social quality", e.g. attention to daylight factor, plan layout and to 'aesthetics' through evaluation of whether the project has been put out to tender in an architectural competition and through attention to building integrated art (Beim et al., 2015).
SAVE	SAVE was developed in Denmark in the late 1980's and is now administered by Kulturstyrelsen (The Danish Agency for Culture) (Beim et al., 2015; Kulturarvsstyrelsen, 2011). From 1992-2007 it served as the basis for development of 90 "Municipality-atlasses" in Denmark. The purpose of the methodology is to assess the level of preservation value in buildings or urban environments.

[4] http://www.dk-gbc.dk/

	(Kulturarvsstyrelsen, 2011). The methodology has a clear focus on culture-historical aspects. It includes weighting of economic aspects, but only a limited focus on the environmental value (Beim et al., 2015; Kulturarvsstyrelsen, 2011). The evaluation only focuses on the existing building, and is not considering potential renovation initiatives, including the potential implications on the perceived spatial quality.
Evaluering af kvalitet I boligbyggerier (Evaluation of quality in housing)	The methodology was developed by the Danish Building Research Institute (SBi) in 2000 for the Ministry of Housing and Urban Affairs. The methodology focuses on residential buildings and aims to provide a holistic tool for evaluating the condition and quality of the building across disciplines, focusing on both qualitative and quantitative indicators (SBi, 2000) and (Beim et al., 2015). Each of the 6 themes are evaluated in relation to 4 different scales in the building and by means of different methodologies, which are described as part of the concept. The methodology has a relatively even distribution of indicators across the three pillars. There is well-articulated attention to the more qualitative aspects related to 'spatial quality', however, focuses on the existing building rather than new initiatives (SBi, 2000).
Totalværdi-modellen (total value model)	The model was developed in 2012 by a partnership of local authorities and consultancy companies (Plan C). The model focuses on process management in the initial stages of an interdisciplinary renovation project, rather than the comparison of specific design solutions. As such, the model does not contain an absolute weighting system. Rather, it provides a digital framework with templates. In the model there is a relatively even focus on each of the three sustainability "pillars", which potentially helps to point out and articulate indicators as a sort of "check list" including both quantitative and qualitative considerations. However, it is up to the stakeholders to set up objectives for assessment of design solutions in later phases. The term "architectural quality" is introduced, but not further elaborated (Schunck, 2011). Beim and Madsen point out that the model has a limited focus on cultural aspects, such as building culture and aesthetic qualities (Beim et al., 2015).
RENO-EVALUE	RENO-EVALUE is developed by Centre for Facility Management (CMF) (Jensen et al., 2015). It provides a tool for clarifying sustainability objectives in a renovation process, comparing alternative project proposals and for evaluating the level of sustainability after completion (Jensen et al., 2015). The main purpose is to provide a process tool, which can identify each stakeholder's priorities and help establish common criteria for success in the early phases of large-scale renovation projects (Jensen et al., 2013). The weighting is based on the stakeholders' subjective evaluation. As with the Total Value Model, the model focuses on process-related issues in an interdisciplinary project. The implications on the perceived spatial quality is assessed under the subsection "product" through attention to e.g. indoor climate and comfort. However, the qualitative aspects of "Architecture and aesthetics" are not further elaborated.
Arkitektur, energi, renovering (architecture, energy, renovation)	The concept was developed in 2013 by SBi in collaboration with Henning Larsen Architects. The aim was to create a design guide for architects and engineers, for the early design phase. The guide is based on the understanding that a holistic approach to renovation in terms of energy, daylight and indoor climate should also provide added functional, architectural and/or financial value. The guide is divided into three typologies: single-family houses, multi-story dwellings and offices, and provides simple tools, suggestions for strategies and cases, which exemplify added

	value (Marsh et al, 2013). In general, there is an even distribution of indicators. When zooming in on the architectural indicator, the recommendations appear to be less explicit, e.g. the strategy “improved spatiality” (Marsh et al., 2013) and (Hvejsel et al., 2015).
AktivHus (Active House)	AktivHus is a national initiative from 2015, based on the international ActiveHouse principles (AktivhusDanmark, 2015). The methodology is intended as a design strategy and certification tool. The methodology targets new buildings as well as retrofitting projects. There is a visible focus on environmental indicators. Social aspects of sustainability are here reduced to attention to indoor climate. The methodology does not consider economic aspects. Beim et al. (2015) points out that the methodology does not consider cultural aspects - in this research study addressed under social sustainability - or more process-related aspects of a retrofitting intiative (Beim et al., 2015). If evaluating the methodology in terms of attention to spatial quality, this is ‘only’ addressed as a matter of quantifiable indicators related to indoor climate.

For instance, Figure 7.2 demonstrates the assessment of the DGNB-DK and how its indicators were analyzed through different categories, including Social, Environmental, Economic, and Process.

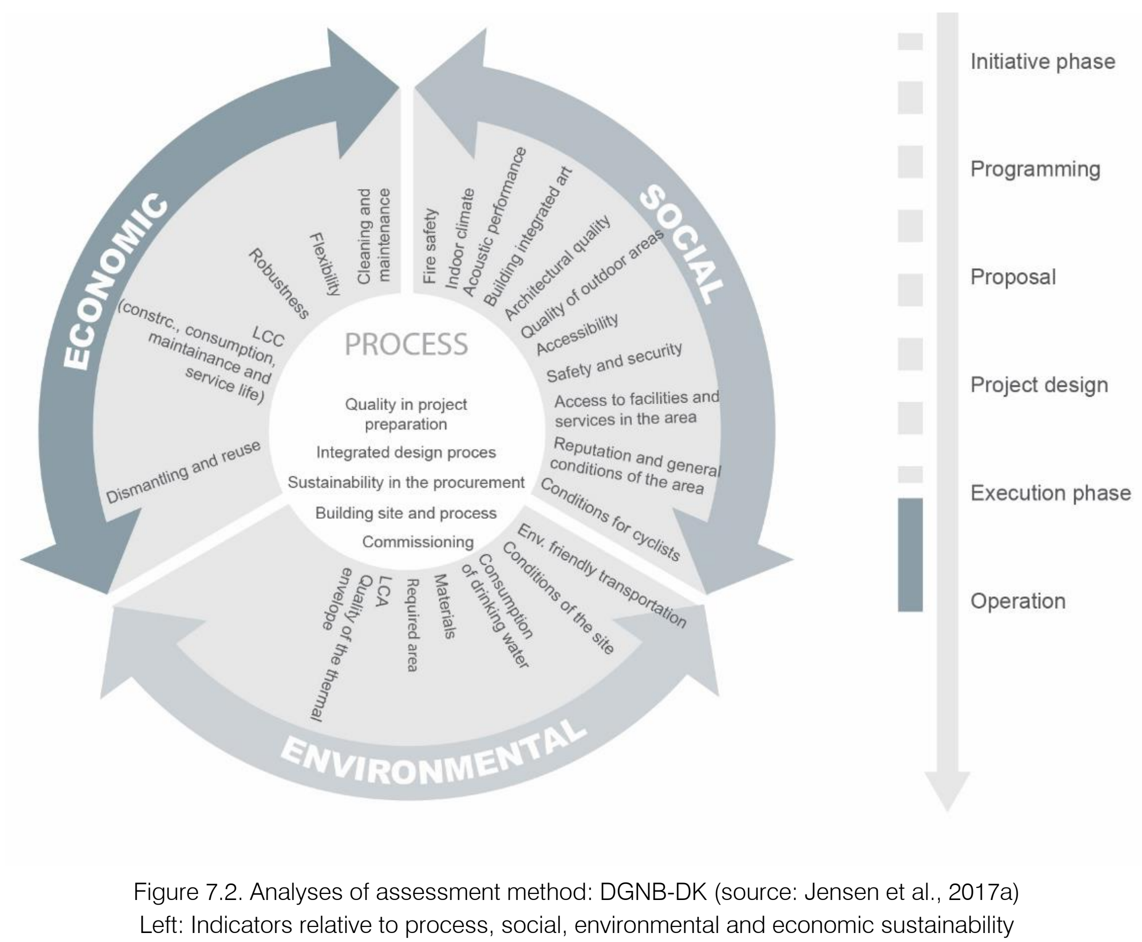


Figure 7.2. Analyses of assessment method: DGNB-DK (source: Jensen et al., 2017a)
Left: Indicators relative to process, social, environmental and economic sustainability
Right: Timeline

A review of the 7 mentioned assessment methodologies were done similar to Figure 7.2. The circle diagrams for each assessment methodology serve to illustrate that the methodologies address different sustainability indicators. For instance, AktivHus puts emphasis on environmental indicators and indoor climate, whereas the SAVE-methodology emphasizes culture-historical indicators. The RENO-EVALUE methodology has a strong weighting of building process indicators, just to mention a few differences. As such, the diagrams serve to indicate that 'holism' is a relative term. Despite the fact that many of the methodologies are characterised as holistic by the developers (e.g. AktivHusDanmark, 2015 and Schunck, 2011), not all methodologies address social, economic and environmental sustainability as well as process-related aspects equally. This supports the initial hypothesis that the models themselves represent a stance on sustainability, which may affect the decision-making process and ultimately the outcome of the renovation project.

In Figure 7.3 the methodologies are positioned relative to each other. Along the "y-axis" a scale spanning from discipline specific tools with a delimited focus is introduced, e.g. preservation value or energy reduction, to holistic tools in the understanding that they consider social, economic and environmental and process-related aspects evenly. Along the "x-axis", a scale spanning from "design guide/process oriented" to "certification system" is introduced, which serves to illustrate that the methodologies are targeted different stages of a renovation process. E.g., the TotalValueModel has a strong focus on project management in the initial phases of a renovation process, whereas DGNB serves as an elaborate certification tool, which can be viewed as less operable on the initial phases of a project.

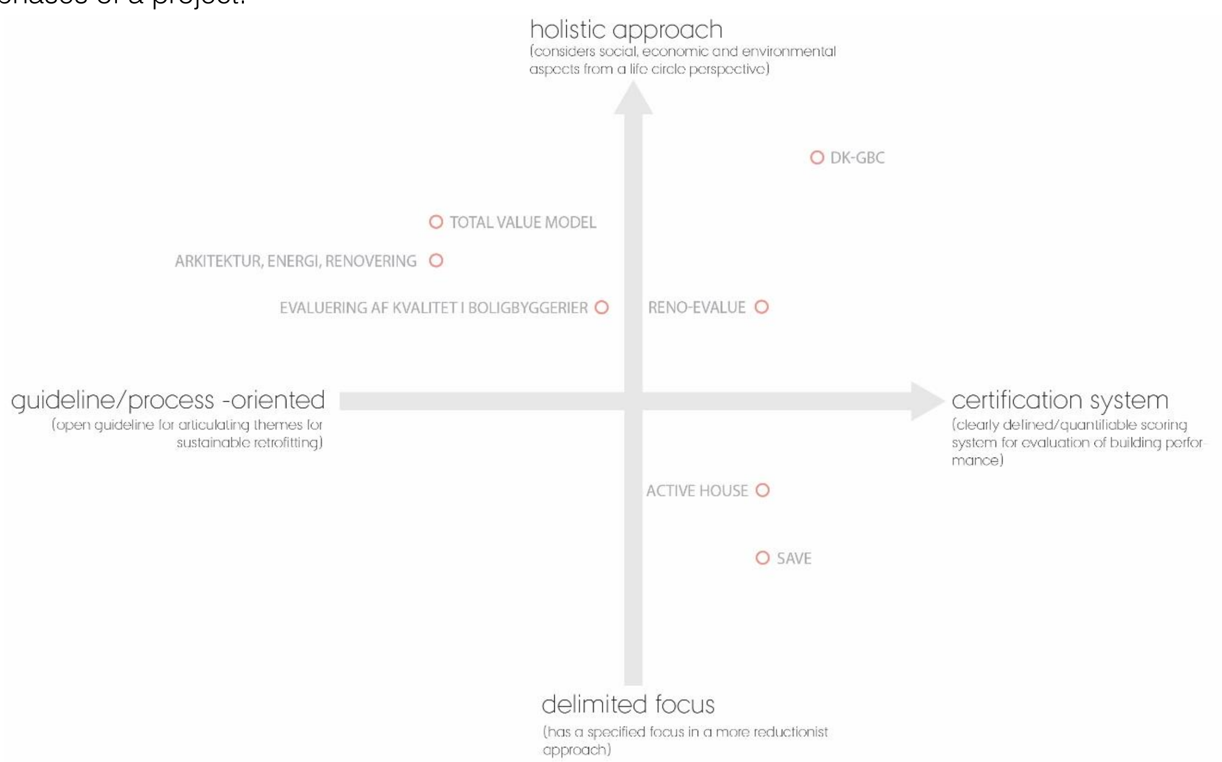


Figure 7.3. Graphical positioning of the studied methodologies for sustainable retrofitting (source: Jensen et al., 2017a)

7.2. Rationalization of developing the decision-making support framework for sustainable retrofitting

The present chapter investigates the problem of knowledge management in building renovation corresponding to sustainability development paradigm. It deals with the overall objective of sustainability to develop a holistic sustainability decision-making framework for building renovation purpose to support project development and to communicate the outcomes with the relevant stakeholders.

Up to now, there is a significant spectrum of methods accessible for appraisement of sustainability concept (Haapio et al., 2008; Cole, 2005; Crawley et al., 1999). They have been expanded beside demands from the surroundings, primarily corresponding to environment as the main category so far, where the most recent tools attempted to evaluate environment, economy and social relations in an equal circumstances (Jensen et al., 2015). Many of the existing assessment methodologies and tools (Gohardani et al., 2012) have been developed for the design of the new buildings, but can be applied renovation projects as well, and some are particularly intended or adapted for building renovation context. BREEAM (by British Research Establishment), LEED (by US Green Building Council), ATHENA[5] (by Sustainable Material Institute in Canada), BEAT (by Danish Building Research Institute), DGNB (by German Sustainable Building Council) and EcoEffect (by Royal Institute of Technology in Sweden) are some examples of these methods. Furthermore, the figure and application of the evaluation tools in the building area has orderly been propounded (Poston, 2011). Sustainability has recently been being studied and addressed through more holistic perspectives such as the research which has been done by International Living Future Institute (2014) and called Living Building Challenge; or it also has been developed into a decision-making support frameworks such as SPeAR by Arup Group Limited [Arup] (2012) or Chris Butters' sustainability framework from Norwegian Architects for Sustainable Development (2014), in order to represent and evaluate sustainability in the form of a holistic Value Map. As part of these recently holistic approaches (Poston et al., 2010), the building's users have to be involved in the process (Yu et al., 2011; Sweeney et al., 2013), especially from early design stages in order to get the ultimate goal of sustainability in building renovation (Degan et al., 2015). People use buildings in unexpected ways. A deep and advanced renovated building with high-energy standards may have an extreme energy consumption from day first if the building occupants misunderstand of their essential roles as a part of highly efficient system. As such, the learning, education and inspiration of the building occupants can also add values to the project and needs to be considered and included in the evaluation of the sustainability.

The study which was done as the part RE-VALUE project and represented in previous section (see section 7.1) served to illustrate that the methodologies indeed attach importance to different sustainability indicators, which underlines that 'Holism' in sustainability is a relative term. Despite the fact that many of the methodologies are characterized as holistic by the developers e.g. (AktivHusDanmark, 2015; Schunck, 2011), not all methodologies address social, economic and environmental sustainability as well as process-related issues equally. As such, the models themselves represent a stance on sustainability, which may affect the decision-making process and

[5] http://www.athenasmi.org/

ultimately the outcome of the renovation project. As discussed earlier in section 1.2, the concept of sustainability is a dynamic process and therefor, many of the existing assessment methods are not applicable for different contexts (design of new buildings or renovation of the existing buildings), locals and regions. Alyami et al. (2012) represents some of the factors that hinder the applicability of the existing assessment methodologies including:

- Climatic conditions,
- Geographical characteristics,
- Potential for renewable energy gain,
- Resource consumption (such as water and energy),
- Construction materials and techniques used,
- Building stocks,
- Government policy and regulation,
- Appreciation of historic value,
- Population growth,
- Public awareness,
- etc.

Furthermore, most of the methods and tools that mentioned above have a narrow environmental or energy focus (Jensen et al., 2015). In other words, the selection of indicators is often unsystematic in those methods. Important factors (specifically in connection to the society) are left out, and different kinds of indicators are sometimes jumbled together (Butters, 2014). Brophy (2014) states that assessment methods have -in the past- been seen as a driver for sustainability, however, both the methods and the context in which they operate, are changing rapidly. This is significant because it leads to misapprehend the correct intention of the sustainability objectives. By using the existing methods, users do not comprehend an overall picture of what the sustainability goals are, what is essential to be addressed, or what objectives are close at hand. In this perspective, the present chapter primarily (see section 7.3) gives information about the methodology adopted in this research; and later in section 7.4 and 7.5, it provides details about the findings and a brief discussion including the development and application of the decision-making framework for the building renovation.

7.3. Methodology for the development of the decision-making support framework for sustainable retrofitting

A knowledge society is based on the need for knowledge distribution, access to information and the capability to convert information into knowledge (Afgan, 2010). Knowledge management is one of the crucial requirements of a knowledge society (Afgan, 2006). In building renovation context, the issue of knowledge management, as stated in precedent sections is a challenge that should not be downgraded. It is a complex system because it cannot be fully evaluated without comprehension of the interconnections and interactions between its technical objectives and society as well as the influences of its development impact on its environment and world (its neighbors and city in a bigger scale) as a whole. There are essential stages regarding to the problem of knowledge management in building renovation context in order to develop a new sustainability decision-making support framework which needs to be performed through a consensus-based process. They have been listed in Alyami et al. (2012) based on Cooper (1999).

Following these steps in a rational order, the overall methodology applied in present research project has been elicited from Neves et al. (2009). The authors (Neves et al., 2009) employed SSM (Checkland, 2000) beside Value Focused Thinking - VFT (Kenny, 1992) approach, in order to refine and structure the list of objectives according to the various perspective regarding to the main evaluators identified in energy efficiency sector. They concluded (Neves et al., 2009), although there is no guarantee that the same problem analyzed by another team or even by the same team in a different occasion would lead to the same results, the exhaustive learning catalyzed by the SSM study, and then with the VFT approach, combined with the ex-post interviews with some experts, explicitly provided confidence about the completeness of the model. In this regard, the present research project has adopted a qualitative multi-method research approach through 7 stages which has been illustrated in Figure 7.4.

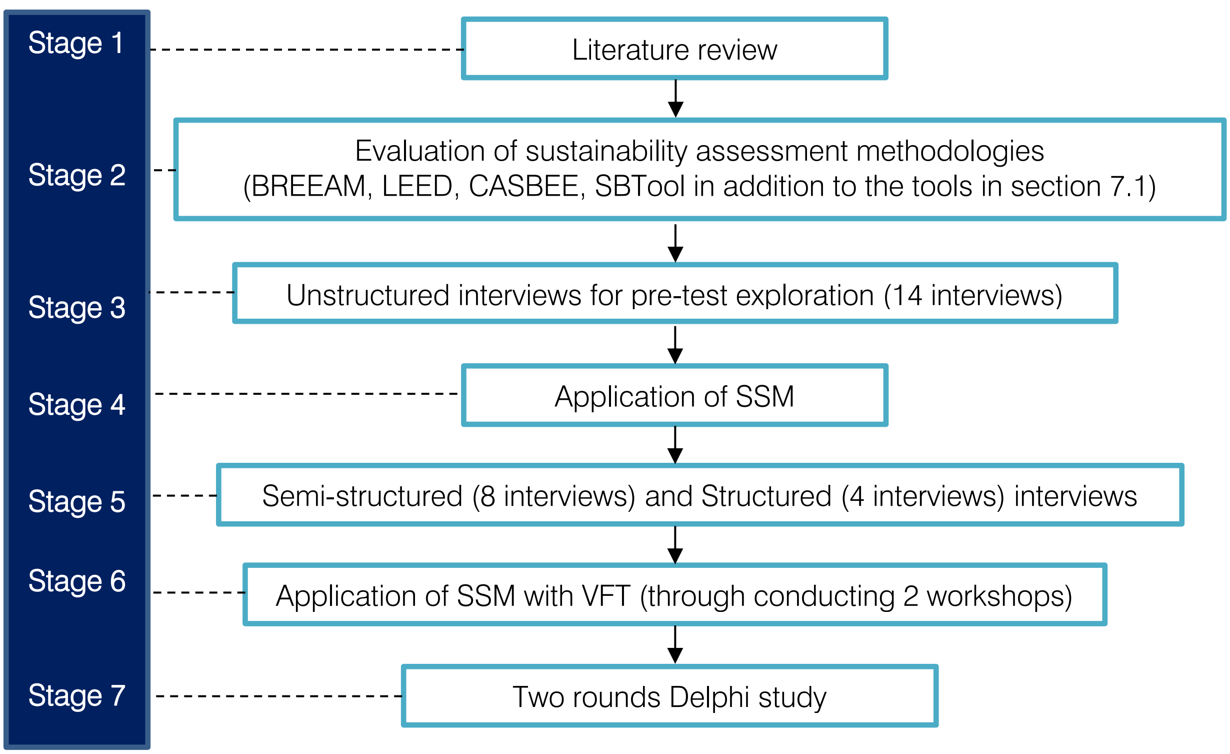


Figure 7.4. The methodology adopted for developing and validating the data to construct the sustainability decision-making framework

The research methodology in this step of the thesis assumed conducting SSM with VFT within consensus-based process. It was done through conducting two workshops and series of academic participant's meetings in the Department of Engineering-Aarhus University and in connection to RE-VALUE research project. The focus group included variety of participants including: architects (from architectural consultant companies – i.e. the AART architects), contractors, experts (in energy efficiency, indoor comfort, construction & management, civil engineering, health and human well-being), decision-makers, professors within different backgrounds (who participate with RE-VALUE project as well as supervise the Ph.D students in Department of Engineering-Aarhus University and Department of Architectures-University of Palermo), Ph.D. students (4 in total who works closely with RE-VALUE project), members of engineering union, and member of government associations (municipality of Aarhus city and Aalborg city in Denmark).

7.3.1. Data collection approaches

In order to ensure that the decision-making framework reflects sustainability best practice, primarily a number of other sustainability assessment methods and literature were reviewed. Added to the methodologies that were described in section 7.1, BREEAM (by British Research Establishment), LEED (by US Green Building Council), DGNB (by German Sustainable Building Council), CASBEE[6] (by Japan Sustainable Building Consortium) and SBTool[7] (by Natural Resource Canada) have been considered as well. The review concentrated on the strength and weaknesses, and also where they have been implemented successfully. These sources were referred to throughout; initially to identify the appropriate categories, then the appropriate criteria and subsequently in drafting the indicators (or sub-criteria). In this consideration, added to the literature studied in the precedent sections (i.e. section 7.2), and in order to recognize and address some specific indicators, the following literature related to *Technical* (Baker, 2009; Burton, 2012; BPI [Building Performance Institute], 2013; CEN [PrEN 15203/15315 Energy performance of buildings], 2006; NIBS [National Institute of Building Sciences], 2014; Bluyssen, 2000), *Architectural* (Acre et al., 2014; Salingaros, 2006; Salingaros, 1995), *Social* (Mofatt et al., 2008), *Environmental* (Baker, 2009; Burton, 2012), *Cultural* (Behzadfar, 2008), *Financial* (Lutzkendorf et al., 2011), *Management* (NIBS, 2014), *Education* (Pilkington et al., 2011), *Regulations* (UN, 2008), and *Cost* (Page et al., 2009; Krstic´ et al., 2012) have been studied.

Subsequently, individual and group interviews (Ali et al., 2009) were utilized in this research project, which is considered as the major path to gather and discuss the data from various stakeholders. To this end, the researchers went into the middle of the field, observed and met the different building occupants. The interview process, though, started by comprising of 14 unstructured interviews (with building occupants). In order to simplify the various demands from the building occupants, the first round SSM was applied. Next, the results were investigated using conversational guide and interview survey with other stakeholders in the field. Therefore, 8 semi-structured and 4 structured interviews among different types of stakeholder (from Academia, Government, and Industry) were carried out. It aimed, instead of collecting general knowledge about the retrofitting in practice, to recognize the areas where further research and development could lead to construct a difference and add value for retrofitting projects. The central aim of these stages was to provide information in order to feed into the complementary round use of (stage 6 in Figure 7.4) SSM.

[6] http://www.ibec.or.jp/CASBEE/english/

[7] http://www.iisbe.org/node/140

7.3.2. Soft Systems Methodology (SSM)

SSM was developed by Peter Checkland in the late 60’s at the University of Lancaster in the UK (Checkland, 2000). Initially it was seen as a modelling tool, but by passing years it has become progressively as a learning and meaning development tool so far (Williams, 2005). It is a systems approach that is used for analysis and problem solving in complex and messy situations. These situations are "soft problems" such as: How to improve building performance? How to perform a sustainable retrofitting? Checkland et al. (1990) distinguish between 'hard' and 'soft' systems thinking within the attempt to use system concepts to solve problems. Simonsen (1994) describes Hard Systems Thinking within Systems Engineering (as the traditional research strategy or design approach for engineers and technologists) and Systems Analysis (as the systematic appraisal of the costs and other implications of meeting a defined requirement in various ways). The author (Simonsen, 1994: p 2) discusses *Hard Systems Thinking has the starting point in 'structured' problems and the assumption that the objectives of the systems concerned are well defined and consistent;* unlike *Soft Systems Thinking has the starting point in 'unstructured' problems within social activity systems in which there is felt to be an ill-defined problem situation*. SSM exploits “systems thinking” in a cycle of action research, learning and reflection to help understand the various perceptions that exists in the minds of the different people involved in the situation (Maqsood et al., 2001). Checkland (1999) discusses this further where it can be used to analyze any problem or situation, but it is most appropriate where the problem “cannot be formulated as a search for an efficient means of achieving a defined end; a problem in which ends, goals, purposes are themselves problematic”. It was reported as a viable alternative to use mapping-based problem structuring methods to help unveiling a set of objectives for structuring a multi-criteria decision analysis model (Neves et al., 2009). In particular, SSM is able to stimulate, debate and capture the required vision for the future of complex challenges; it is a considered appropriate methodology in appreciation and analysis of Social (social practices, and power relations), Personal (individual beliefs, meanings, emotions), and Material (physical circumstances) worlds (Mingers et al., 1997). There are many documented examples of the successful use of SSM in many different fields, ranging from ecology to business and military logistics.

Developing a new sustainability decision-making support framework in retrofitting context is ultimately a very complex (due to different decision maker), and multi-disciplinary task (within a sustainable perspective). As mentioned in earlier chapters, this issue from many angles is similar to the problems known as messy/wicked problems. The phrase ‘wicked problems’ (Churchman, 1967) was originally used in the context of social planning, where it was used to demonstrate problems that were difficult or impossible to solve, because they address complex social interdependencies. Similarly, the characteristics of the problems in the retrofitting discipline involves many qualitative and quantitative factors and criteria that are provisional case to case. SSM in this situation functions as an interrogative device that enables debate amongst concerned parties (Checkland, 1999); it leads to catch the complexity of the existing issues from different perspectives among various stakeholders and later communicate the possible solutions. Such methods can be exploited to equip a basis for technical design and social intervention. In this perspective, the following model (see Figure 7.5) was used to benefit from SSM in the present research project. It hence has been applied to explore the innovation and knowledge management in aforementioned context.

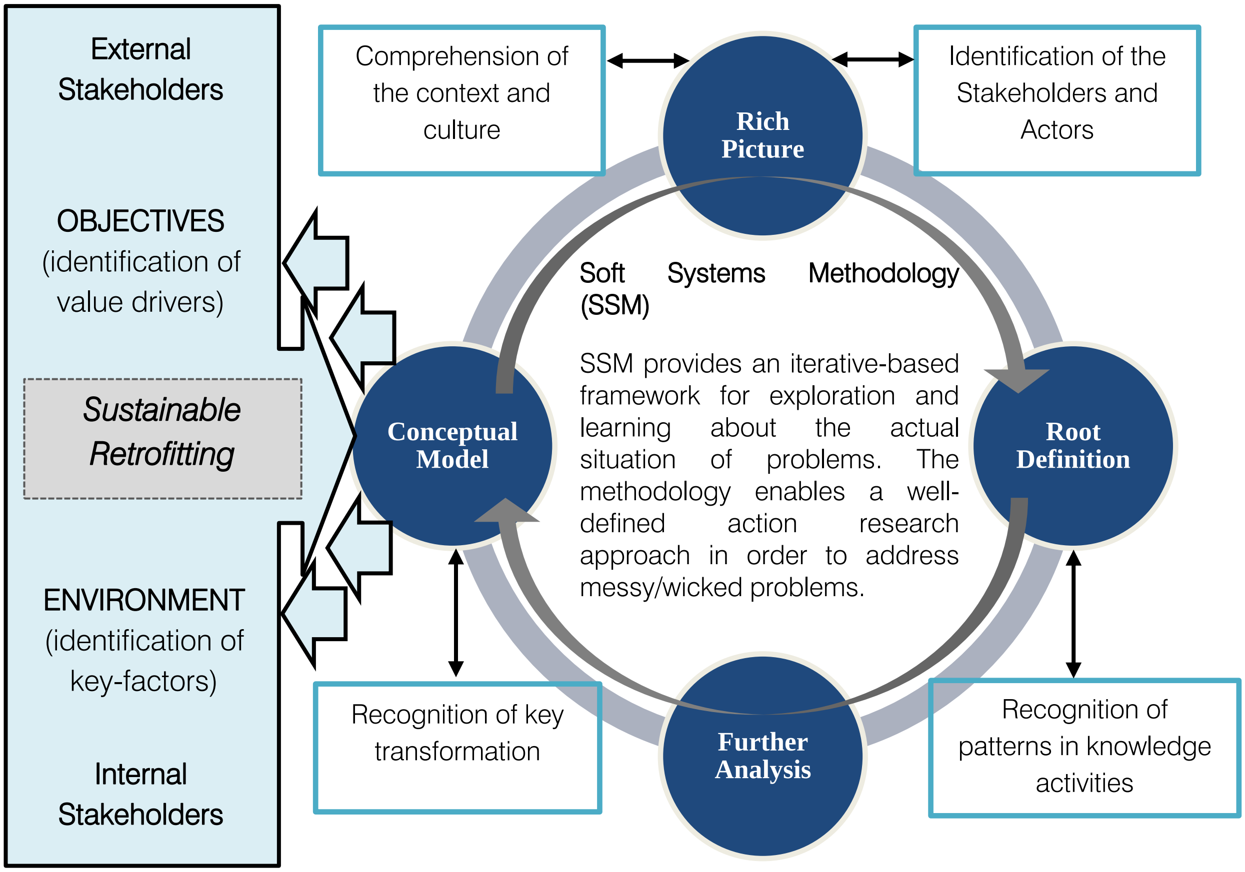


Figure 7.5. Application of SSM to knowledge management in sustainable retrofitting

7.3.3. Value Focused Thinking (VFT)

The basis for the developing sustainable framework is where the right values should be the driving force for the decision-making process (Komiyama et al., 2006). Keeney (1992) discusses that the relative desirability of decision-making's consequences is a concept based on values, and thus the fundamental notion in decision-making should be values, not alternatives. He describes further, the premise is focusing early and deeply on values when facing difficult problems which lead to more desirable consequences. Historically and theoretically, the concept of value is closely related to economics and productivity (Hansen, 2010). However, the complexity of building design, with its variety of stakeholders, calls for a broader understanding of the term (Madsen et al., 2015). Keeney (1992) emphasizes on the role of values to end up much closer to getting all of what required while facing a problem. He states the principle of thinking about values is to discover the reasoning for each objective and how it relates to other objectives. VFT essentially consists of two activities: first deciding what you want and then figuring out how to get it (Keeney, 1992). Once the list of objectives is reasonably complete, it is important to specify clearly what each objective includes. Since the main purpose of the present research is to develop a new decision-making framework to support sustainable retrofitting, the concepts presented in Keeney's VFT (Keeney, 1992) considered appropriate to structure the outcomes from the SSM study. Figure 7.6 illustrates the advantages of the application of VFT in present research study.

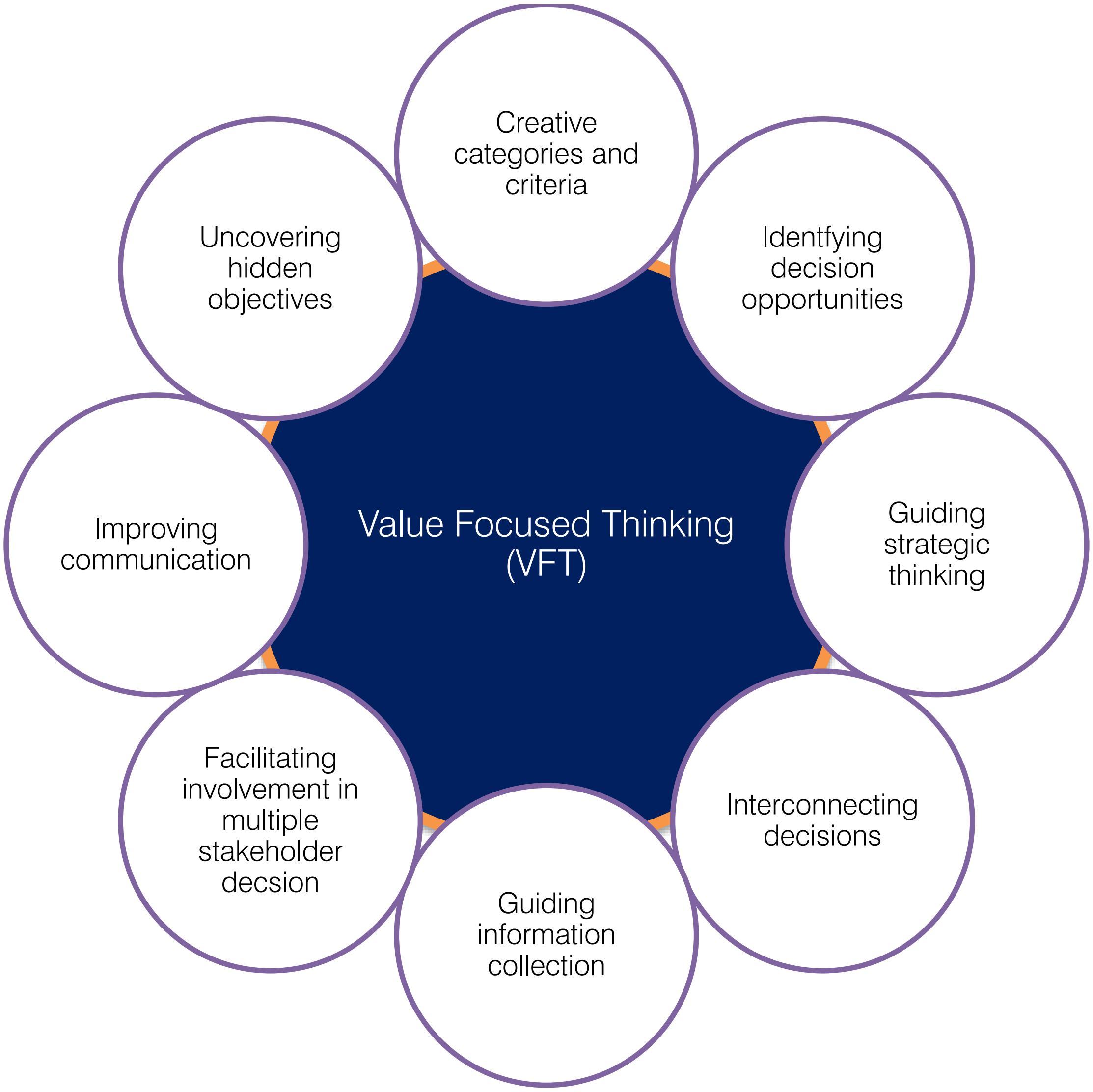


Figure 7.6. Advantages of using VFT to knowledge management in sustainable retrofitting

7.3.4. Applying SSM beside VFT to building renovation

As stated before, building renovation context is a both highly multi and inter-disciplinary field and it involves a considerable number of stakeholders. Therefore, it covers domains, which are identified in different ontological outsets; some sub-domains are focusing on quantifiable aspects, such as energy consumption and construction cost, whereas other domains are more concerned with qualitative aspects related to e.g. society (Estkowski, 2013). In addition, it should be in accordance with sustainable development paradigm. To this end, the research based on the model developed in Figure 7.5, primarily developed a Rich Picture (see Figure 7.7) among different stakeholders in the workshops about RE-VALUE project. It also exploited CATWOE analysis and Root Definition (see Table 7.2) as well as developed the Conceptual Model (see Figure 7.8).

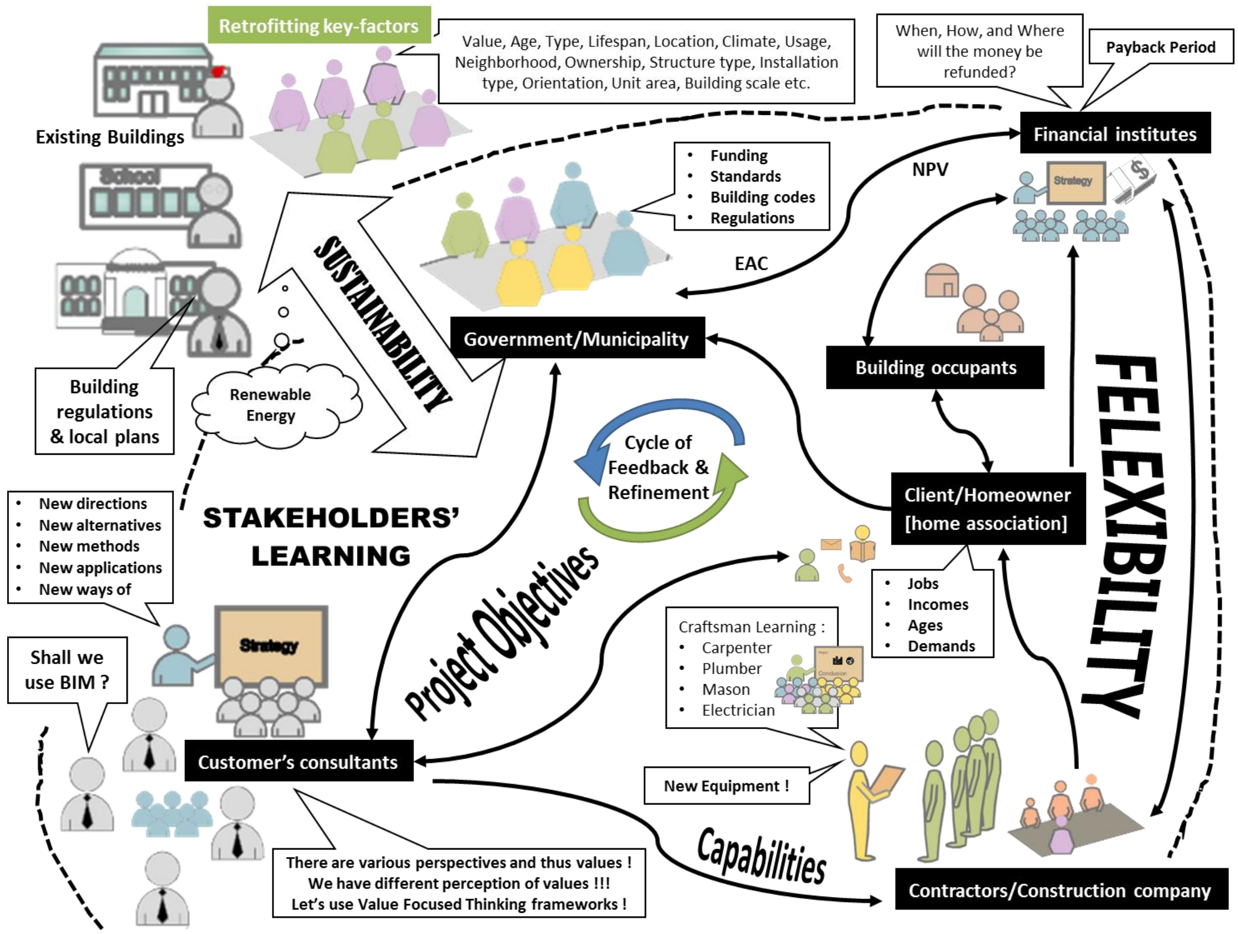


Figure 7.7. Rich picture – The stakeholders and process of the building renovation

The benefits of doing a sustainable retrofit are significant and it is not quite apparent in the minds of the different relevant stakeholders in the renovation process. This was identified while the Rich Picture was being developed that demonstrates the structure, processes and particularly the system of dialogues, requirements and perceptions of the stakeholders about the building renovation process. The thorough utilization of SSM (see Figure 7.7, Figure 7.8 and Table 7.2) in the retrofitting context formalized the knowledge of the renovation process explicitly, highlighted problematic areas, and explored the requirements. It provided recommendations where the sustainability values can be identified and added in this context.

Table 7.2. Root Definition and CATWOE analysis for building renovation context

ROOT DEFINITION	CATWOE analysis
A system owned by project manager who together with Architect and Design Engineer, use knowledge, skills and experience to prepare and assess possible retrofitting alternatives through sustainable value oriented criteria that delivers the most appropriate solution for the retrofitting project. This is undertaken	Customer: The client and the community. Actors: Client/Homeowner, Customer's consultants, Government/Municipality, Financial institutes, and Contractors/Construction company Transformation: To use knowledge, skills and experience to proper and assess applicable retrofitting alternatives through the sustainable value oriented perspectives that delivers the most appropriate solutions in existing building stock.

where all the different stakeholders specifically the consultant company have a well understanding of the process, objectives/goals, issues and challenges. The community expectation and behavior for the design and construction of the project must be taken into the consideration.	**Weltanschauung (why bother?):** To assess the feasibility of making a sustainable retrofitting we need a good/well understanding of the process, objectives/goals, and issues. **Owner:** Design team including Architect, Design Engineer and Engineering Manager **Environment:** Historical value of the existing building, Climatic zoon, Location etc.

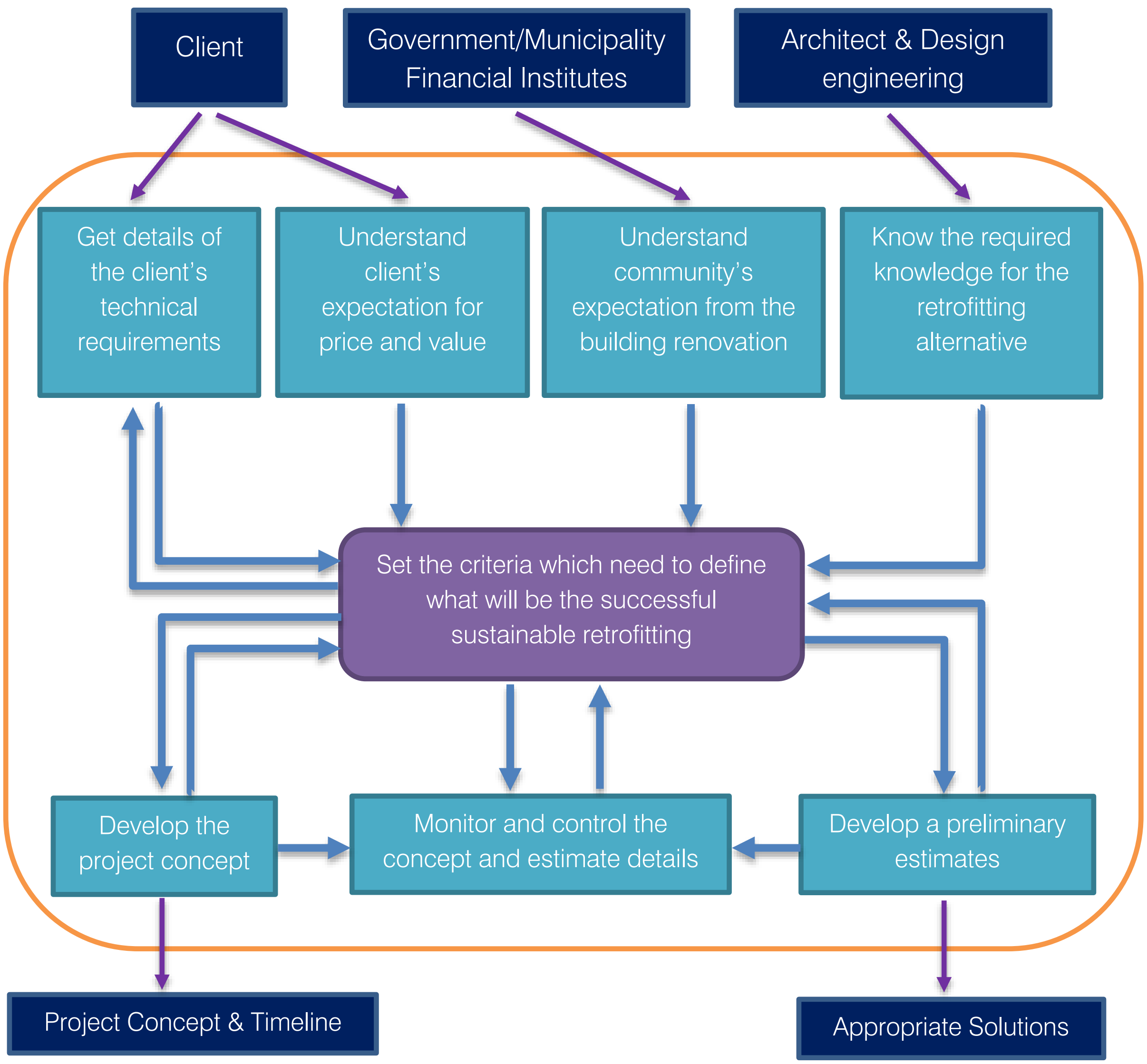


Figure 7.8. Conceptual Model - Building renovation context

Present research endeavored to investigate the common patterns among the decisions made by different stakeholders within building renovation circumstances that highly influence the other key members' decisions with different priorities. In this intervention, SSM played an important role proposing questions[8] to extract the list of value drivers in regard with the involved stakeholders. Hereafter, the guidelines proposed by Keeney (1992) as the framework of VFT were utilized to modify and structure the value drivers (see Figure 7.9), turn them into the sustainability objectives, and ultimately expand their relevant indicators. It was performed using two essential frameworks, which is known as the hierarchy of fundamental objectives and the network of means-ends objectives. By developing the first one, it initially recognizes the values to use in the decision process while the second one leads to construct the alternatives to judge. This research project primarily focused on the primitive structure in order to identify the sustainability objectives. However, in order to distinguish the objectives and their sub-objectives, it was considered vital to identify the means objectives and end objectives. The list of objectives were hence analyzed to identify which of them are end-objectives and which are means that lead to that end. It concluded the framework of fundamental objectives and sub-objectives. Later, they have been renamed as the criteria and indicators so as to develop the new sustainability decision-making framework which were represented in Table 7.3 and Table 7.4. The methods of SSM and VFT were though applied in sequence. Attaching the context of knowledge management including application of SSM with VFT to the scenario of building renovation augmented a new vigor, insight and framework in order to be comprehended by different stakeholders specially the design team.

It worth noting that, application of SSM in building renovation mapped a research path to address one of the most popular barriers, which is occurred in this area (the building renovation). It is called "Rebound effect" in which the post-retrofit energy consumption is higher than predicted, due to changes in occupant behavior following the installation of a measure (Booth et al., 2013). The question that arises inevitably is how to involve different stakeholders and on the top of that building occupants (Eriksen et al., 2013) [and keep them involved] in the design process so as to promote and improve their learning about the sustainability, the sustainable retrofitting and the sustainable DIY (do-it-yourself). This issue was addressed in chapter 4 of the present thesis by development of a HMSR for development of the holistic renovation scenarios.

[8] The list of the guidelines was used from Neves et al. (2009: p 10 - table number 5).

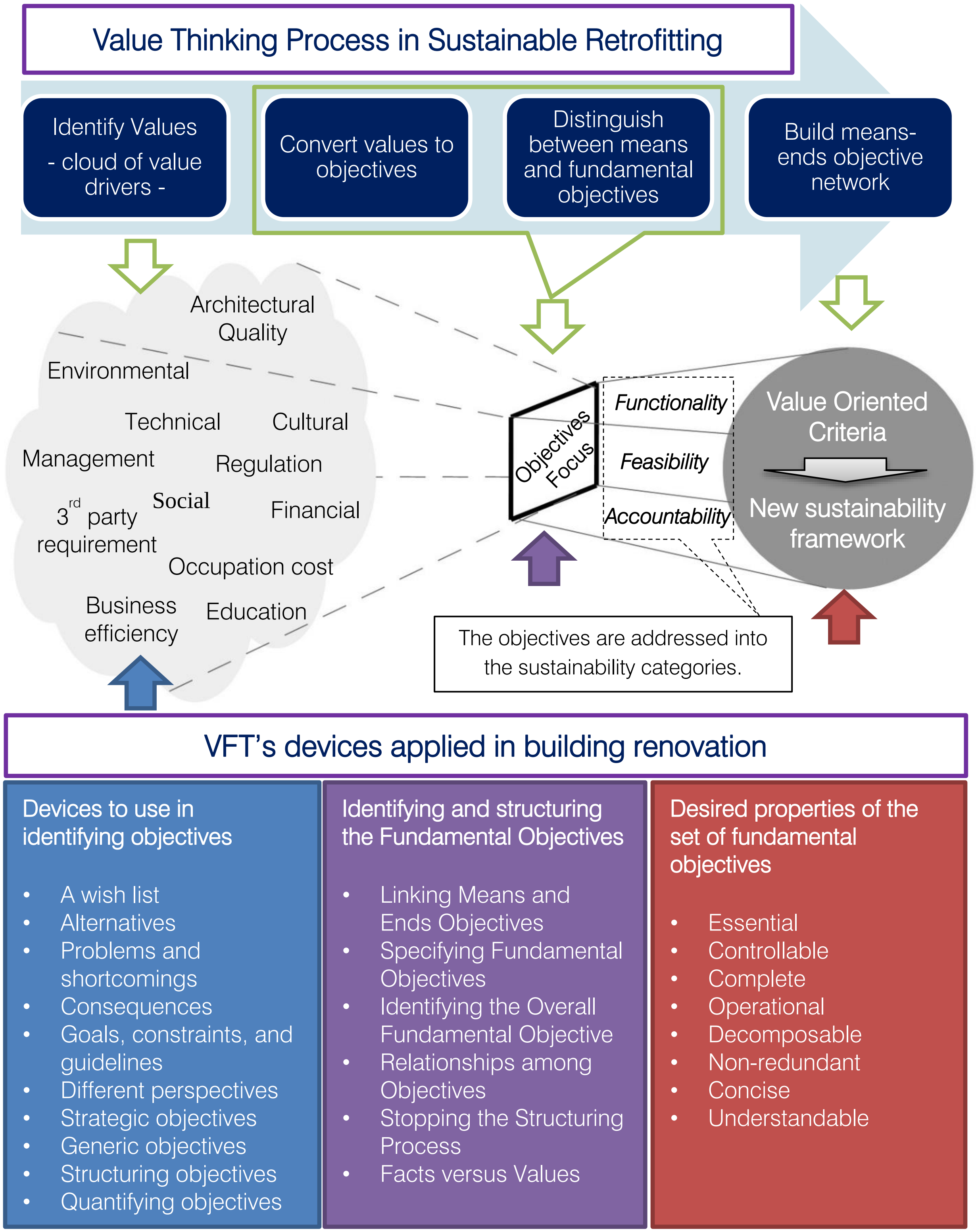


Figure 7.9. Application of VFT to knowledge management in sustainable retrofitting

7.4. Findings

The sustainability decision-making support framework developed in this chapter should be able to represent if a building renovation has been successful at meeting an expected level of performance (in accordance with sustainability in its totality) in a number of declared criteria. The sustainability matrix was created in response to the collected data within stages 1 to 7 of the applied research methodology (see Figure 7.4). The outcomes concluded that the decision-making framework should bear the following characteristics:

- The framework must be able to be applied from the pre-retrofit or start-up stages in renovation design process.
- It should be comprehensive enough along with sustainability pillars in order to address the building renovation performance from different aspects – environmental, social, and economical with respect to local, cultural and urban context.
- The sustainability framework should creatively be developed in order to be comprehended as simple as possible.
- The categories, criteria, and indicators of the developed framework should acknowledge the context of building renovation.
- The new criteria and indicators need to be established based on expert knowledge and a consensus-based process.
- The values about architectural quality must be included into the framework.
- The stakeholder's learning about the sustainability, the sustainable retrofitting and the sustainable living should be considered as a value and be included into the framework.
- The value of an efficient collaborative process should be a part of the framework.

7.4.1. Key factors in building renovation

The outcomes of stages 1 to 6 of the applied research methodology (see Figure 7.4) identified and listed 30 key-factors which particularly must be considered for any retrofitting case during pre-retrofit survey and project set-up (see Table 7.3). The result of the utilization of this stage in practice, indicates if there is potential for building renovation before taking any action. The intent concerns the overall exploration of the building as well as involvement of the building occupants and understanding both their demands of the renovation and their behavior or special habits while living in the building.

Table 7.3. List of the key factors for retrofitting projects during project set-up and pre-retrofit survey

Value	Building type	Tenancy
Climate	Building story	Buy and Sell
Location	Unit area	Occupant's daily stay
Site	Structure	Occupant's monthly stay
Neighborhood	Shape	Occupant's yearly stay
Building function	Ventilation	Occupant's consumption habits
Ownership	Material	Occupant's demands
Orientation	Installations	Occupant's income
Age	Retrofitted yet	Occupant's job
Lifespan	Balcony & Chimney	Additional consideration

A brief description about the existing key factors in building renovation context:

Value
Does the property have historical or cultural value?

Climate
What is the dominant climate or related climatic zone of the area? (e.g. cold and dry)

Location
Does the building located in rural area or urban sector?

Site
What are the specific characteristic of the site the property situated? (e.g. proximity to crowded spaces)

Neighborhood
What is the neighborhood status of the building? Does the building working or connected with other buildings?

Building function
What is the function of the property? (e.g. residential, commercial, hospital etc.)

Ownership
What is the status of the building's ownership and occupants? (e.g. the owner is government and the flat has been rented as a 100 years inhabitancy schema)

Orientation
What is the orientation status of the building?

Age
What is the age of the property?

Lifespan
Has the building been planned (from construction to demolition) for a certain period? (e.g. municipalities outreach plans)

Building type
What is the type of the building? (e.g. multi-story building, single flat building etc.)

Building story
What is the scale of the building? (e.g. the number of the floors and units in a multi-story and unit apartment)

Unit area
What is the area of the units? (e.g. the size of the units in a multi-unit apartment)

Structure
What is the structure and envelope type of the property? (e.g. metal and brick)

Shape
What are special things about the shape of the building? (e.g. a curvy shape)

Ventilation
What is the ventilation system of the building?

Material
What are the types and specialty of the existing material?

Installations
What is the installation (heating, cooling and electrical systems) type of the building? Have they divided privately between the units or they are common between the units? (e.g. central heating system in a multi-story building)

Retrofitted yet
Has the property been renovated so far? When?

Balcony and Chimney
Is there balcony or chimney in the building?

Tenancy
How late is the property under rent? (e.g. the property has been rented for 2 years till January/2017)

Buy and Sell
Is the owner going to sell the property? When? (e.g. owner is going to renovate the building in order to immediate sell)

Occupant's daily stay
How many hours are the occupants staying at unit/flat? (e.g. day and night except 7 am to 2 pm)

Occupant's monthly stay
How many hours are the occupants staying at unit/flat? (e.g. day and night except 7 am to 2 pm)

Occupant's yearly stay
How many month are the occupants staying at unit/flat? (e.g. all of a year except July)

Occupant's consumption habits

What is the occupant's energy consumption habits? (e.g. opening the windows from 5 pm to 7 pm during the day)

Occupant's demands

What is the occupant's demands of retrofitting? (e.g. no changes in the building but insulation)

Occupant's income

How much is the occupant's income level?

Occupant's job

What jobs type are the occupants doing?

Additional consideration

In some special cases there is possibility of adding question to this list (e.g. is the building suffering from special fungus, insects etc.?)

7.4.2. Categories and criteria

The three newly defined categories and totally 18 main sustainable value oriented criteria were addressed through the application of the research methodology stages 1 to 7 (see Figure 7.4). On the top of that, SSM was considered dramatically effective, in order to analyze and uncover a "cloud of objectives/criteria" regarding different sustainability perspectives and relevant stakeholders' priorities in building renovation process. The outcomes of this step led to create three new categories in order to illustrate sustainability in the way that is more comprehensive and recognizable to the different stakeholders. The new categories were defined as,

- "Functionality" which refers to technical, environment and used resources (environment),
- "Feasibility" which encompasses financial, process, management, education and institutional indicators (economy), and
- "Accountability" which embraces municipal, architectural, cultural, human and community indicators (society).

However, the cloud of objectives still lacked structure. For this reason, several VFT's devices (see Figure 7.9) were employed to expand and refine the list of criteria achieved at the end of the second round SSM workshop. The central aim of the consolidated categories and criteria was to provide first round Delphi panel experts (from Academia, Government, and Industry) on checking and validating the outcomes. The panel of 16 experts, therefore as the point of departure, was activated to brainstorm and perform deliberative consideration, based on 'open ended solicitation of ideas' taking place in October 2015. It investigates the list of applicable criteria for the building renovation purpose in connection to 3 newly driven categories. In this stage, the goal was to examine the essential and relevance of the requirement specification and framework outline. As well, the initial draft of the possible indicators for each criteria was addressed. As the result of this contribution, each category was illustrated by 6 sustainable value oriented criteria (see Table 7.4).

Table 7.4. List of three different categories and their related sustainable value oriented criteria

FUNCTIONALITY	ACCOUNTABILITY	FEASIBILITY
Indoor comfort	Aesthetic	Investment cost
Energy efficiency	Integrity	Operation & maintenance cost
Material & waste	Identity	Financial structures
Water efficiency	Security	Flexibility & Management
Pollution	Sociality	Innovation
Quality of services	Spatial	Stakeholders engagement & education

Further considering and evaluation of the identified criteria in this section, has led to develop the list of more detailed Indicators (or sub-criteria), following the approach in next section (see section 7.4.3). A brief description about each sustainability value oriented criteria for building renovation context:

Indoor comfort

It is the condition of mind that expresses satisfaction with the Air quality, Lighting (including daylight), Thermal comfort, Moisture comfort, Acoustic and in most cases assessed as a subjective evaluation process after the retrofitting components are added during the early design stages. Maintaining this standard of indoor comfort for occupants of buildings or other enclosures is one of the important goals of retrofitting focusing on Passive and Active design approaches such as HVAC (heating, ventilation, and air conditioning) systems (Bluyssen et al., 2002).

Energy efficiency

It (described as the second-law efficiency or rational efficiency as well) calculates the efficiency of a procedure taking the second law of thermodynamics into account. Energy converts from one form to another during a procedure. In the contrary, energy computes for the irreversibility of a procedure by increasing the entropy (Wang et al., 2009). The energy efficiency of a building is the extent to which the energy consumption per square meter of floor area of the building measures up to established energy consumption benchmarks for that particular type of building under defined climatic conditions (UN, 2008). Building energy consumption benchmarks are representative values for common building types against which a building's actual performance can be compared. Benchmarks are applied mainly to heating, cooling, air-conditioning, ventilation etc. The benchmarks used vary with the country and type of building. For a building to work properly, the energy efficiency of the building is depends on other parameters then only energy consumption including other sources of energy generation in the building (use of renewable energies), energy saving equipment of the generated energy from renewable sources, and finally the ways of monitoring the energy equipment and energy consumptions. More about energy generation, it refers to how much useful energy we can get from a renewable energy sources (solar, wind, water). The efficiency is the ratio and comparison of the input energy generated via renewable energy sources on the fossil energy sources, which is used to evaluate retrofitting scenarios. Efficiency in this regards is one of the ''twin pillars'' of a sustainable energy policy.

Material & waste

The focus here is about material and waste management in retrofitting context. It is encompasses how compatible, recyclable and thus sustainable are the used materials for choose of renovation approaches. Furthermore, waste management refers to use of recycling storages and treatment related to construction waste, solid waste, and urban waste, in general.

Water efficiency

This been designed to deal with consumption of the water, storing, and recycling of the used water in buildings.

Pollution

This criterion addresses the presence in or introduction into the environment of a substance or thing that has harmful or poisonous effects. For renovation context, it refers to CO2, NOx, water pollution, noise and effects of refrigerant to include the chlorofluorocarbons (CFCs).

Quality of services

A retrofit system's durability is its expected lifetime, or the acceptable period of use in service. In general, the system tire's life follows the bathtub curve, to boot. After execution, it does not seem a small probability of failure. Later, it continues to work for a long duration relative to its expected service life. After a period, the failure probability will rise. In contrast to payback period, longer service life is preferable to homeowners to select the most appropriate renovation scenario.

Aesthetic

Typically, the aesthetic characteristics are regarded as subjective, vague and difficult to express. Such factors have to be considered at the design stage, and of course they can be. Following Alexander (2004), Salingaros (2006), Salingaros (1995), aesthetics is a domain in which assessments are relative: many can tell which of two buildings is more beautiful or harmonious, but few could justify their judgments in quantitative terms. Obviously, the evaluation of visual qualities will always be to some extent subjective. It is important to be considered since usually when customers seeking for more beauties in their buildings relevant to their arbitrary building materials and equipment it requires spending more money.

Although the visual building characteristics are generally regarded as subjective, there are approaches attempting to measure the quality of a building's form in inter-subjective terms. For instance, Salingaros (2006) endeavors to formulate the aesthetic qualities of a building in mathematical terms. His key concept of building's 'life' is defined as a multiplication of the building's temperature' and its 'harmony'. Harmony is something opposite to randomness. While 'H' corresponds to a conventional meaning of architectural harmony, 'T' is a new concept. All the components of 'temperature' and 'harmony' are specified in detail in Salingaros' model, and the specification.

Integrity

It encompasses the integrity of the used land by building renovation regarding more scales than just its neighbors, otherwise in district areas or urban regions. The environment and landscape are affected directly by the land occupied by these buildings. It is quality of being organized with urban and infrastructure standards along with outreach plans. It represents one of the most critical factors for the intervention site, especially where the human activities are relevant factors of environmental pressure.

Identity

It represents the conception, qualities, beliefs, and expressions that make the building different concerning the history, culture and civilization of the location which building situated.

Security & safety

It is the degree of resistance to, or protection from, harm. In retrofitting context, it is described as balancing the project's sustainable goals with its security goals including protecting the building and its occupants from natural and man-caused disasters. According to NIBS [National Institute of Building Sciences] (2014), hazard mitigation refers to measures that can reduce or eliminate the vulnerability of the built environment to hazards, whether natural or man-made. However, the users may have a different, lived perception of the security of the area yet. The fundamental goal of hazard mitigation is to minimize loss of life, property, and function due to disasters. Designing to resist any hazard(s) should always begin with a comprehensive risk assessment. This process includes identification of the hazards present in the location and an assessment of their potential impacts and effects on the built environment based on existing or anticipated vulnerabilities and potential losses. When hazard mitigation is implemented in a risk-informed manner, every dollar spent on mitigation actions results in an average of four dollars' worth of disaster losses being avoided.

NIBS (2014) states that the most security and safety measures involve a balance of operational, technical, and physical safety methods. In addition to the operational/technical/physical taxonomy, it is useful to characterize risk reduction strategies as either structural or non-structural. Structural mitigation measures focus on those building components that carry gravity, wind, seismic and other loads, such as columns, beams, foundations, and braces. Examples of structural mitigation measures include building material and technique selection (e.g., use of ductile framing and shear walls), building code compliance, and site selection (e.g., soil considerations). In contrast, non-structural strategies focus on risks arising from damage to non-load-bearing building components, including architectural elements such as partitions, decorative ornamentation, and cladding; mechanical, electrical, and plumbing (MEP) components such as HVAC, life safety, and utility systems; and/or furniture, fixtures and equipment (FF&E) such as desks, shelves, and other material contents. Non-structural mitigation actions include efforts to secure these elements to the structure or otherwise keep them in position and to minimize damage and functional disruption. These measures may be prescriptive, engineered, or non-engineered in nature.

Sociality

It (or social acceptability) represents the overview of opinions concerning to the process of retrofitting by the local population regarding the hypothesized realization of the projects under review from the customer point of view. It is exceedingly significant due to the opinion of the population and of pressure groups can extremely affect the amount of time required to continue with and fulfill a sustainable retrofitting through bigger scales.

Spatial

It refers to the sensorial qualities that a space emits. Spatial quality is an immediate form of physical perception, and is recognized through emotional sensibility. It dramatically increases occupants' receptiveness of energy renovation in a building block scale.

Investment cost

In a sustainable retrofitting, investment cost is a summation of all fees concerning: the procurement and buy of mechanical equipment (Building elements or HVAC systems), technological installations, construction, engineering services, drilling and other incidental construction work. It estimates the cost of a replaceable and new requirements or equipment, in other words. Labor costs and costs for the equipment maintenance are not included in investment costs (Wang et al., 2009).

Operation & maintenance cost

Maintenance and operation costs are a part of the building's life cycle costs, i.e. whole life cycle costs. Life cycle cost elements according to ISO 15686:5-2008[9] are shown in Figure 7.10.

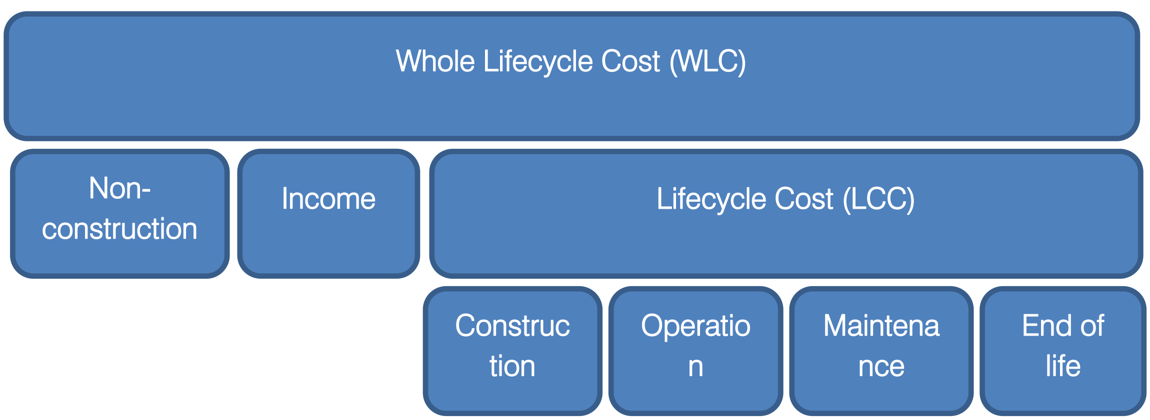


Figure 7.10. Whole Lifecycle Cost (source: ISO 15686:5-2008)

Krstić et al. (2012) based on : ISO 15686:5-2008 describe that maintenance costs cover the cost of labor and material, as well as other related costs that are incurred to keep the building or its parts in the state in which it can perform its required functions. Maintenance implies the conduct of corrective, responsive and preventive maintenance activities on constructed assets, or on some parts of these assets. Operation costs include running costs

[9] https://www.iso.org/obp/ui/#iso:std:39843:en

and costs of managing the facility or built environment, including administrative support services (e.g. rent, rates, insurances, energy and other environmental/regulatory inspection costs, local taxes and charges).

Financial structures

Net Present Value (NPV), also entitled as net present worth (NPW), is designated as the generic present value of a time series of incoming and outgoing cash flows. Incoming and outgoing cash flows can also be defined as benefit and cost cash flows, respectively. It is a standard method for using the time value of money to appraise long-term retrofitting projects. Used for capital budgeting, and extensively all over economics, it considers the over-plus or shortfall of cash flows, in present value terms, once financing charges are met. NPV is necessarily measured in early decision making stages upon developing a retrofitting system (Page et al., 2009).

Flexibility & Management

It must considered one of the most important criteria derived in Value Map. It refers to the absolute range of goodwill, compassion, ease and co-operation between stakeholders that tries to facilitate all process from customer's decision to municipalities/government bodies, banks/mortgages institutes/state agents and contractors in order to settle financial (Lutzkendorf et al., 2011) issues. It can be considered as the value of an efficient collaborative process.

Innovation

It refers to any new technology, design, construction, operation, maintenance or demolition method or process that can be shown to improve the sustainability performance of a building and is of demonstrable benefit to the wider industry.

Stakeholders engagement & education

This relates to building occupants and their behavior to promote and improve their learning about the sustainability, the sustainable retrofitting and the sustainable DIY (do-it-yourself).

7.4.3. Indicators (or sub-criteria)

The criteria developed in previous step, are attached to a certain number of indicators (Segnestam, 2002). The indicators (or sub-criteria) are the details that sit behind each criteria. Table 7.5 in the following represents the results of the data, which were collected from literature review, investigation on existing assessments methodologies, interviews and group discussions and two rounds Delphi study. The further studies included consideration of some renovation cases in different stages in Denmark. In fact, the outcomes from the first round of the Delphi study (see section 7.4.2), were reconsidered and expanded further in Aarhus University-Denmark. As such, based on the observations and consideration of the 5 renovating cases (all in Denmark), the addressed criteria were further reviewed and validated in the second round of the Delphi study with 19 participants (from Academia, Government, and Industry) taking place in November 2016. However, the reason was to build a critical consideration of the sustainability framework (which will be argued in section 7.5) and discussion of development of the indicators based on the collected information and to reconsider the outcomes regarding to the renovation cases before generating the last version of the framework. Accordingly, the indicators which were addressed for each criteria were checked and validated by 4 groups of the experts (19 participants with different area of expertise – see section 7.3) during the RE-VALUE research project's workshop.

Table 7.5. Sustainability decision-making support framework's categories, criteria, and indicators[10]

Column A : Category
Column B : Criteria
Column C : Indicators or sub-criteria
Column D : Source of creation

A	B	C		D
Functionality	Indoor comfort	Indoor air quality		1, 2
		Lighting comfort (day and artificial)		2
		Thermal comfort		2
		Acoustic comfort		2
		Moisture comfort		2, 3
	Energy efficiency	Reduction of energy consumption	Heating	1, 2
			Hot Water System	
			Cooling	
			Cold Water System	
			Air-conditioning	
			Ventilation	
			Lighting (interior & exterior)	
			Fans	
			Pumps and Controls	
			Electricity consumption for external lighting	
			Other electrical equipment	
		Energy generation		1, 3
		Energy monitoring		1, 3
		Energy efficient saving		2, 3
	Material & Waste	Material cycle	Environmental impact of the materials	1, 2
			Local materials	1, 2
			Recyclable material	1, 2
			Re-use of structural frame materials	1, 2
			Building fabric component (Insulation)	1, 2
			Responsible source of materials	1, 2
			Use of finishing materials	1, 2
			Material efficiency over its life cycle (LCA)	1, 2

[10] Column D in this table refers to the procedure, which the indicator has been created from. In this regard, '1' refers to the indicator which was extracted from Literature Review; '2' refers to the indicator, which was extracted from considering of the existing assessment methodologies (BREEAM, LEED, CASBEE, and SBTool in addition to the items considered in section 7.1); '3' refers to the indicator which was outlined from the Interviews, and '4' refers to the indicator which was resulted from the Group discussion.

			Use of material that are designed to deal with future climate change	1, 2
			Material with high/low thermal mass (depends on the climatic zone)	1, 2
		Waste	Construction waste management	1, 2
			Solid waste treatment	1, 2
			Waste treatment	1, 2
			Recycling facilities	1, 2
			Recycling storages	1, 2
	Water efficiency	Water consumption		2
		Grey water recycling		2
		Rain water harvesting		2
		Water fixture & conservation strategy		2
		Irrigation system		2
		Water monitoring		2
	Pollution	CO2 emissions		2
		NOx emissions		2
		Impact of Refrigerant		2
		Light pollution (night light)		2
		Water pollution		1, 2
		Noise pollution		2
	Quality of services	Usability		1, 2
		Adaptability for future change		1, 2
		Durability and reliability		1, 2
		Controllability of system		1, 2
		Efficient infrastructure		1, 2
		Maintenance of performance		1, 2
Accountability	Aesthetic	Temperature	Intensity of perceivable details	1, 4
			Density of differentiations	1, 4
			Curvature of lines and forms	1, 4
			Intensity of color hue	1, 4
			Contrast (amongst other color hues)	1, 4
		Harmony	Reflectional symmetries on all scales	1, 4
			Translational and rotational symmetries on all scales	1, 4
			Degree to which distinct forms have similar shapes	1, 4
			Degree to which forms are connected geometrically one to another	1, 4
			Degree to which the colors harmonize	1, 4
	Integrity	Site protection - Cultural Heritage privacy		1, 2
		Site protection - Natural privacy		1, 2
		Site protection - Prevent Criminal threads		1, 2
		Mitigation ecological impact		1, 2
		Enhance site ecology		1, 2
		Land function		1, 2
		Infrastructure		1, 3, 4
		Pathways and accessibility		1, 3, 4
		Neighborhood and lighting policy		1, 3, 4
		Pedestrian & cyclist safety		1, 3, 4

		Building density		1, 3, 4
	Identity	Natural identity (e.g. Desert town, Mountain town, Windward town etc.)		1, 3, 4
		Artificial identity (e.g. University City, Religious city, Touristic city, Industrial city etc.)		1, 3, 4
		Human identity (e.g. Attitudes, Traditions, Customs etc.)		1, 3, 4
	Security	Occupant health		1, 4
		Occupant safety (building scale)		
		Fire Protection		1, 4
		Security for building occupants and assets (building scale)		1, 4
		Natural hazards mitigation		1, 4
	Sociality	View quality - Enclosure and peripheral density (configuration of the block that affects views)		1, 4
		Block physical boundaries (peripheral density and contour)		1, 4
		The height to width ratio (proportion) of internal block spaces (such as courtyards) and the sense of enclosure		1, 4
		Functions in the block, and built and human densities		1, 4
		Physical barriers between public and private spaces		1, 4
		Outdoor private spaces		1, 4
		The facade composition and permeability (changes in facade permeability and composition, such as the size of windows and dwelling entrances)		1, 4
	Spatial	View from the inside (private domain) to the outside (public domain) of dwellings and from outside to inside (visual privacy)		1, 4
		View quality by Lighting Distances between public and private domains		1, 4
		The articulation between space and its boundaries, and between adjacent spaces		1, 4
		The privacy within the dwelling (zoning considering different groups within the family)		1, 4
		Light (access of daylight, layout zoning, and sun orientation of openings)		1, 4
		Color (types and effects in the space)		1, 4
Feasibility	Investment cost	Design		1, 3
		Construction		1, 3
		Procurement	Building equipment (e.g. door, window, materials, furniture etc.)	1, 3
			MEP equipment	
			Structural equipment	
		Replacement	Building equipment (e.g. door, window, material, furniture etc.)	1, 3
			MEP equipment	
			Structural equipment	
		Repair	Building equipment (e.g. door, window, materials, furniture etc.)	1, 3
			MEP equipment	
			Structural equipment	
	Operation & maintenance cost	Statutory periodic inspections		1, 3, 4
		Costs of replacing degraded materials and elements		1, 3, 4
		Costs of periodic works and repairs		1, 3, 4
		Costs of reactive maintenance		1, 3, 4

		Operational costs		1, 3, 4
	Financial structures	Payback period		1, 3, 4
		Net Present Value (NPV)		1, 3, 4
		Affordability of residential rental		1, 2
	Flexibility & Management	Commissioning		2, 4
		Consultation		2, 4
		Collaboration		2, 4
		Construction planning		2, 4
		Construction site impacts		2, 4
		Perform proper building operations and maintenance		2, 4
	Innovation	Building form		1, 4
		Building envelop		1, 4
		Passive design (lighting and ventilation)		1, 4
		Building structure		1, 4
		Interior design		1, 4
		Built area		1, 4
		HVAC system		1, 4
	Stakeholders engagement & education	Environmental strategy/Design & Features	Sustainable urban drainage systems	1, 3, 4
			Air source heat pump	
			Photovoltaic	
			Low-E Glass	
		Operational instructions	General	1, 3, 4
			Electrical	
			Plumbing	
		Sustainable DIY (do-it-yourself)	Fixings	1, 3, 4
			Certified materials	
			Paints & Finishes	
		Energy consumption		1, 3, 4
		Water use		1, 3, 4
		Home information guide alternative formats		1, 3, 4
		Alarm information		1, 3, 4
		Recycling and waste system and collection		1, 3, 4

7.5. Developing sustainability decision-making support framework for building renovation

7.5.1. General features

The new sustainability framework has been developed using the results from previous sections. It has been divided into the two parts (see Figure 7.11). The *External* part (the Characteristic Diagram) which can be used for the collection of the required data on pre-design or start-up phase of the retrofitting projects; and the *Internal* part (that is the main part of the developed framework) works as Value Map (see next section for the application). The main 4 inherent principles of the framework can be described as:

External part (Characteristic Diagram for Building Renovation)

1) The renovation key-factors on external part of the framework must be considered initially before making any decision on retrofitting case

Internal part (Value Map)

2) The Value Map (internal part) is separated into three equal parts and each one belongs to the three newly driven sustainability categories;
3) The value score is outwards and therefore the best renovation alternative corresponds to largest star;
4) The divisions are utilized instead of compass points in order to illustrate values by assigning a visually correct geometrical weighting.

The purpose of developing this framework has been to represents a new simplified sustainability decision-making framework for building renovation to support project development and communicate outcomes with stakeholders. An adjacent counterpoising of the different criteria in the Value Map that some methods try to carry out, should not be performed. It predominantly seems essential that the three pillars of *Functionality*, *Feasibility* and *Accountability* have to be given even portion visually. Doing so represents the relative effect of various possibilities to the users. For each renovation project, the priorities are quite vary from case to case and therefore the counterpoising of the criteria is interdependent consistently. A renovation strategy can clearly be considered far better than another, even without calculation of a value precisely. Precise scores matters less than the process to make the final decisions.

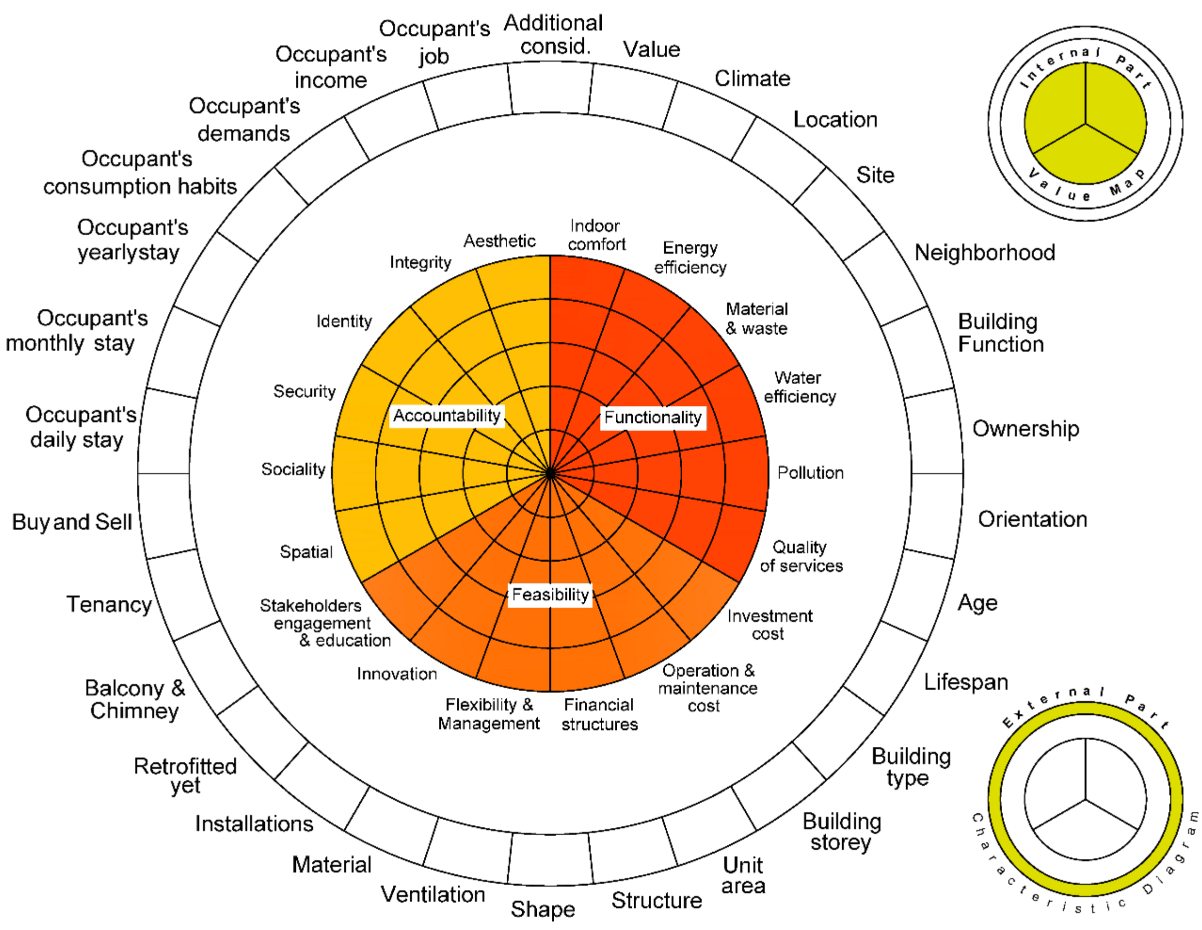


Figure 7.11. Holistic sustainability decision-making support framework for building renovation

7.5.2. The application

The decision-making support framework developed during the research activity is not just to evaluate if one solution (among possible retrofitting options) is preferable than the other, but it also can be utilized in early design stages to characterize essential areas and initiatives to achieve a holistic building renovation. The collected data relating to the key-factors (application of the external part of the framework), provides a basic and general knowledge about the renovation project, and further in a bigger picture, indicates if there is potential for the building to be renovated. The internal part of the developed decision-making framework, functions as a Value Map (see Figure 7.12) which visualizes the main objectives for sustainable retrofitting. It does not offer guidelines for sustainable design, rather it focuses on multi-criteria appraisal, and can be used together with consultant sustainability services. The intent is an optimum of all requirements, not maximization of some. For this reason, a comprehensive data gathering needs to be performed. Literature reviews, site visits, desktop study, review meetings, and participation with relevant stakeholders are the possible ways of data gathering. Further, the data need to be examined to ensure that it has been collected methodologically and statistically sound. The results can be utilized in order to observe, audit and assess the renovation case performance (to be in accordance with sustainability in its totality) and support decision-making during the project's lifecycle.

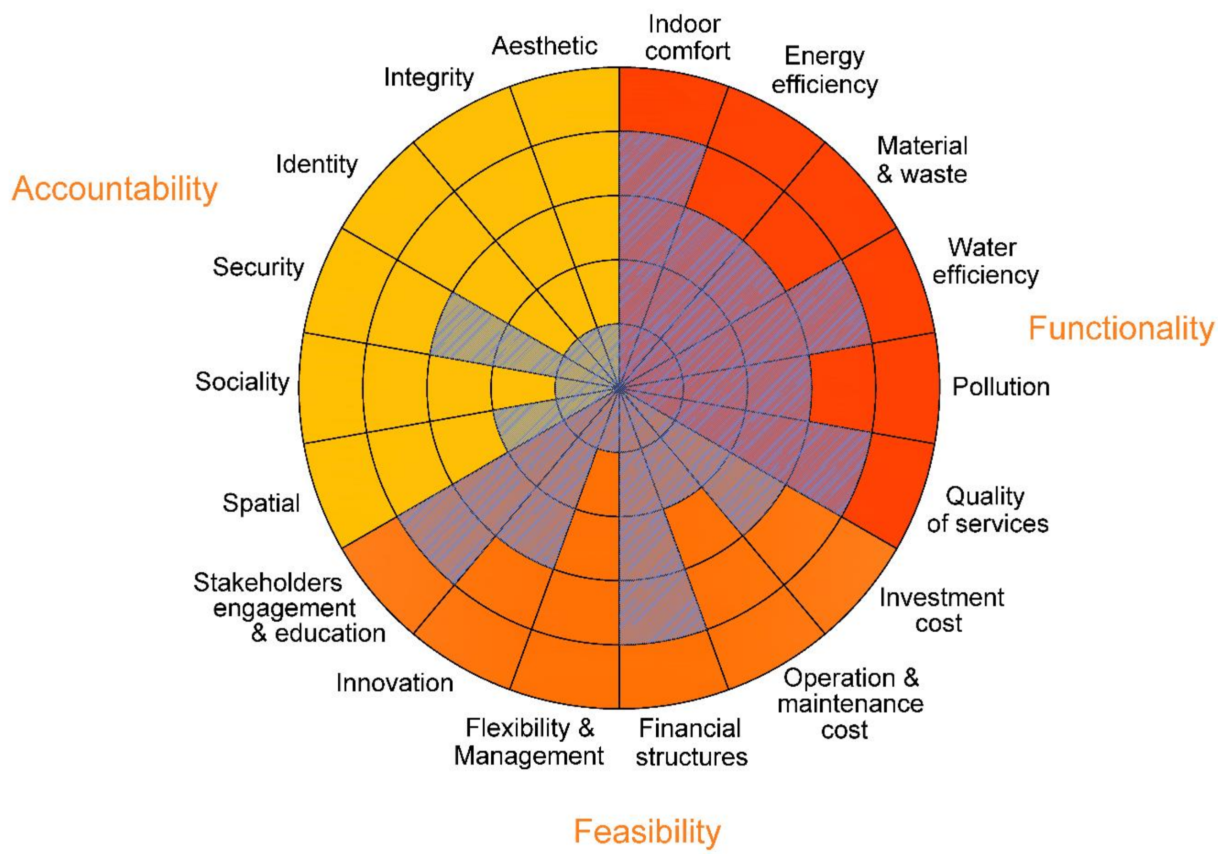


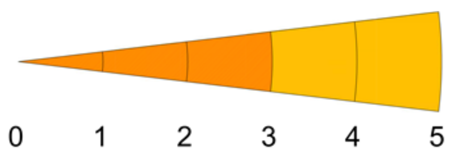
Figure 7.12. Holistic sustainability decision-making support framework for building renovation (Internal part: the Value Map)

It can be utilized to perform a baseline appraisal, investigation on the possible gaps within and on intersections of the key risk areas, or recognize and set up key performance criteria and indicators during early design stage. It can also be utilized to guide decision-making and stakeholder participation. In addition, the pros and cons of each alternative renovation solutions can be compared so as to identify their particular significance, which effect differently from case to case due to related various circumstances. It can also be utilized to undertake assessment after the execution processed or during operation phases that can lead to organizational learning and identification of efficient approaches to latter cases. In addition, it might be used for the regions that do not yet offer rating and certification among existing assessment methodologies, or where a client wants to test readiness for certification (e.g. DGNB-DK) and enhance performance of the building renovation. Hence, it can be underlined that the developed framework can be considered not only as an abstract framework while a project is being developed, but a bound method of the design and planning process as well as assessment and comparison within building renovation context.

7.5.3. The scale of the criteria

The sustainability decision-making support framework's performance rating system (in accordance with sustainability in its totality) for criteria has represented in Table 7.6. It demonstrates a graduated rating system from a range of 1 to 5. In this framework, value 1 indicates sub-standard quality while value 2 means "normal practice" or features expected about recently retrofitted buildings and solutions. Value 3 corresponds a results well above today's practice, and value 4 means application of exceedingly advanced solutions. Value 5 which is the maximum value in this framework refers to what we presently may contemplate as more or less "fully sustainable retrofitting" – for instance a near-zero energy renovated projects (Morelli et al., 2012). There are very few projects in around the world, which may reach this outward ambience at more than two or three scores. In a full assessment of each criteria – in addition to the indicators provided for each criteria (see Table 7.5) - most might require further detailed breakdown including sub-indicators, for instance the different factors regarding to Human Identity. Therefore, for each one of the 18 criteria, indicators can be expanded more in detail and as such, the evaluation can be performed either in a detailed format or/and simple procedure. During the appraisal, those are the indicators that are evaluated using the holistic sustainability decision-making support framework's performance rating. The privileged and insecure cases will be identified for each indicator. Further, the assessment items are deployed from the indicators through running a comprehensive set of essential questions. In order to aid the user while considering the questions, extra information such as some figures and more explanation can be provided. These questions can be utilized by design team to estimate the specific rating that each indicator has to obtain. The assessment items (questions) have to be assessed in turn and assigned a score. A short description have to be provided for the justification of the scores. To this end, scores should be allocated based on topic experts and building renovation contractors. It needs to be critically done where there are especially regulatory requirements that needs to be met. Hereafter, an initial appraisal based on aggregation of the indicators and sub-indicators' scores can be estimated and subsequently the averages of these scores will be assigned to the criteria. Doing so leads to both collect and later assess the required data about the renovation project comprehensively.

Table 7.6. The sustainability decision-making support framework's performance rating system – e.g. of the indicator: Durability

DURABILITY	value	standards	ratio	example
	1	Sub-standard	low	5-10 years
	2	Minimum standard	reasonable	10-15 years
	3	Good practice	moderately	15-20 years
	4	Best practice	high	20-25 years
	5	Exemplary	very high	more than 25 years

7.5.4. Qualities and quantities

Depends on the type of the criteria which were developed in this study, they can be categorized as soft or hard, subjective or objective, and qualitative or quantitative inherently. Factors corresponding to *Functionality* in the Value Map are quantifiable mostly; it can be considered as the main reason why many architects or design engineers often used to narrow their design on sustainability to the a few factors including energy efficiency, lifespan or investment costs, which can be measured in an adequately objective way. Factors regarding to *Accountability* or *Feasibility*, in the other side, are not quantitative but qualitative. In addition, it means they need to be assessed or appraised qualitatively. They have to be met and designed at the drawing board stage. It compulsorily needs to be performed, however the outcomes are to a far larger degree relevant to stakeholders' perceptions. Keeney (1992) states that the values must be identified and defined precisely; it can then be articulated through this meaning qualitatively by stating objectives, and, if desirable, it can be embellished with quantitative value judgments. Wandahl et al. (2006) discuss difficulty of measuring a value grounded in at least two factors, the subjectivity of value, and the difficulty in making the value statements explicit – you cannot measure something you do not know. In this regard, developing such decision-making support framework can overcome the second issue; and corresponding to the first one, evaluation should be post-occupancy, using sociological methods such as the approaches which were being developed in Systems Thinking (Checkland, 1999) and Theory domains and have been used broadly. Nevertheless, a comprehensive pre-evaluation would also relevant. Consequently, for renovation projects to be in accordance with sustainability in its full sense, it seems essential to focus on the interactions and interdependences of quantitative and quantitative aspects corresponding to the objective and subjective values during the project life cycle. As Butters (2014) states, the sustainability is not something that can be delivered. Nor can it be evaluated once and for all. It is a condition that must be considered over time.

7.6. Summary

This section included the development of a new simplified (in terms of application and representation) holistic sustainability decision-making support framework, which applies to the structures of the built environment regarding to building renovation. The procedure for development of the framework has been a consensus-based process. In order to develop, the research employed a multi-dimensional research strategy that involves a variety of approaches including literature review; exploration of some well-known existing assessment methodologies; conducting individual and focus group interviews; and eventually it included the application of SSM with VFT to problem of knowledge management in building renovation, as a complex issue, challenging from case to case and difficult to act upon. The outcomes were validated using two rounds Delphi study.

The framework has been divided into the two parts. The external/outer part (the Characteristic Diagram) which can be used for the collection of the required data on pre-design or start-up phase of the retrofitting projects; and the internal/inner part (that is the main part of the developed framework) works as Value Map.

The developed sustainability Value Map for building renovation consisting of three categories – Functionality, Accountability, and Feasibility – with a total of 18 sustainable value-oriented criteria and 118 sub-criteria. The major part of the criteria in the Functionality category are quantifiable while the qualitative criteria have been listed in other category named Accountability. From other side, Feasibility category contains a mix of quantitative (i.e. cost criteria) and qualitative criteria such as advantages in using an efficient renovation process where it influence the key stakeholders.

The framework can both be utilized as a holistic sustainability framework to audit, develop and assess building renovation performance, and support decision-making during the project's lifecycle. It is a holistic sustainability decision-making framework to support the development of renovation projects and communicate the outcomes with relevant stakeholders. Early in a project, it can be used to identify key performance criteria, and later evaluate/compare the pros and cons of alternative retrofitting solutions either during the design stage or upon the project completion.

According to the procedure of the consensus-based process for the development of an effective sustainability decision-making framework, which was employed in this study, the outcome can also be considered as an outset step intended for the establishment of a sustainability decision support and assessment tool suited to building renovation context.

CHAPTER VI

TOWARDS DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR GENERATION AND EVALUATION OF RENOVATION SCENARIOS IN BUILDING RENOVATION

CHAPTER'S SYNOPSIS

"This chapter provides further investigation of the main components in renovation context. Using empirical information, it expands a Domain Mapping Matrix (DMM) between the recently developed criteria (in chapter 5) and renovation approaches (26 categories including 139 alternatives). The aim is to consider the dependency between renovation approaches while they meet different criteria or sub-criteria, and vice versa, regarding to the selection of the criteria versus application of some possible renovation approaches. Developing a DMM enhances the required insight for the development of an operational system for architecture of decision-makings in aforementioned area. It has a strong effect to deal with existing complexity regarding to the large number of renovation approaches and various sustainability objectives/criteria. Added to this, the DMM can be used for understanding and tracking of the value (or added value) regarding to the other criteria (i.e. spatial quality) while the focus is on optimization of some common criteria i.e., improvement of energy efficiency or reduction of investment cost."

8. Domain Mapping Matrix (DMM) for sustainability renovation criteria and alternative renovation solutions

8.1. '*System architecture*' and modelling of a '*system architecture*' by use of matrix-based approaches

Nowadays, renovation projects and development of the most appropriate renovation scenarios are becoming more and more complex for the reasons discuss earlier chapters. In the development of renovation scenarios, considerations about involvement of various objectives, architectures and modularization of the generated scenarios sounds crucial. For development of an efficient DSS to this end, the decision architecture should be designed systematically. This can be addressed through use of computational design synthesis field principles. The field of computational design synthesis has been an active area of research for almost half a century (Cagan et al., 2005) in other domains such as Mechanical Design. Research advances in this field have increased the sophistication and complexity of the designs that can be synthesized, and advances in the speed and power of computers have increased the efficiency with which those designs can be generated (Cagan et al., 2005). Oberhauser et al. (2015) state that by use computational design synthesis a constrained solution space can be automatically generated and a high number of design candidates can be quickly explored without fixation on common designs. In this regard, the authors (Cagan et al., 2005) discuss that computational design synthesis methods in general need to integrate four main activities: Representation of the attributes of the design space (design alternatives, objectives and constraints are specified); Generation, which uses this representation to propose candidate solutions; Evaluation with regard to final objectives; and feedback from the evaluation called Guidance, which is used to steer the search process in subsequent iterations. In this classification, the representation of the attributes of the design space is considered the most essential step, which is a question of modeling of *systems architecture*. *System architecture* is a term used related to many different topics, and therefore not always define the same meaning. Jankovic et al. (2016) argue the systems architecting process consists of modelling of requirements and constraints, generation of possible architectures and their evaluation with regard to desired performances. Urlich (1995) defines *system architecture* as "(1) the arrangement of functional elements; (2) the mapping from functional elements to physical components; (3) the specification of the interfaces among interacting physical components". For Crawley (2007), the *system architecture* is "the embodiment of concept and the allocation of physical/informational function to elements of form, and definition of interfaces among elements and with the surrounding context". Eppinger et al. (2012) define *system architecture* as "the structure of the system, embodied in its elements, their relationships to each other (and to the system's environment), and the principles guiding its design and evolution – that give rise to its functions and behaviours". Relying on these descriptions, Hamida et al. (2015) state that the functional architecture represents one facet of the *system architecture* and links system design intentions to the physical world. For developing a *system architecture*, Bonjour et al. (2009) argue that matrix-based product modelling methods represent the product architecture, product elements and their relationships, shown as a matrix. They are being increasingly used by (Sharman et al., 2004), since they can support different research goals, for example, product modularization (Bonjour et al., 2009), analysis of technical interactions either within the products or within the project organization (Szykman et al., 2000), design analysis (Suh, 1990), and change propagation analysis.

Bonjour et al. (2009) discuss that *system architecture* modelling relies on different kinds of matrix in order to design a complex system in a systematic and coherent way. Bonjour et al. (2009) based on Malmqvist (2002) distinguished two levels of product analysis that are related to different design goals. First, product-level matrices provide a mapping between a set of properties or other elements and a number of "whole" alternatives. The authors discuss further (Bonjour et al., 2009), the motivation for such methods is to support decision-making about the entire product life cycle or about product platforms of which product-level variants are the "parts." Developing product platforms requires considerations of common and unique modules within a brand and within a platform but also requires seeing each product variant as a whole (Dahmus et al., 2001; Jiao et al., 2007). Second, element-level matrices represent the relationships between the elements/parts/components of a single product in a matrix. According to Bonjour et al. (2009), there are two subtypes of element-level matrices, including:

- Interdomain Matrix or Incidence Matrices (IMs) or Domain Mapping Matrices (DMMs) represent relationships between two domains. These matrices are basically Incidence Matrices (IMs) or Domain Mapping Matrices (DMMs). They can represent a set of design decisions or relationships between what and how.
- Intradomain Matrix or Dependency Structure Matrix (DSM). Intradomain matrices represent relationships between elements of the same domain, for example, between components. These matrices are usually called, design (or dependency) structure matrix (DSM).

Danilovic et al. (2007) state that DMM analysis augments traditional DSM analyses. They (Danilovic et al., 2007) sum up that comparison of DSM and DMM approaches shows that DMM analysis offers several benefits. For example, it can help (1) capture the dynamics of PD (product development), (2) show traceability of constraints across domains, (3) provide transparency between domains, (4) synchronize decisions across domains, (5) cross-verify domain models, (6) integrate a domain with the rest of a project or program, and (7) improve decision making among engineers and managers by providing a basis for communication and learning across domains. To say briefly, the DSM and DMM approaches are complementary to each other with the difference that DSM focuses on one domain while DMM focuses on the interaction between domains. Furthermore, according to Danilovic et al. (2005) the DSMs and DMMs can be combined to provide engineers a situational visibility, in which individuals can understand the need for information exchange, interdependencies and the context of the project. This will lead to transparency within and between domains in a project, between a project and the basic organization, and between projects. This reduces the risk and uncertainty, as individuals understand the whole situation and have a better insight in their responsibility. It is also possible for such matrices to perform analyses such as clustering. As an example DMM can aid in visualizing dependencies between teams within one project towards other projects i.e., how other projects affect or relate to teams that are carried out in the project of interest. Clusters in the matrix can identify the level of interdependencies between teams and the other projects (Danilovic et al., 2005).

8.2. Matrix-based approaches for building renovation context

According to Alexander (1964) and Pimmler (1994), the general approach when developing complex systems is to decompose the product into subsystems, and if the subsystems are still too complex, decompose these into smaller components. Using matrix-based methods, further, can also represent relationships and couplings between or within them. In the following development of this chapter, I consider that *system architecture* for generation of the renovation scenarios is composed of modules and integrative elements that fulfil system functions. Therefore, the *system architecture* is defined by focusing on interactions throughout enabling a matrix methodology to include not just one domain at a time but to allow for the mapping between two domains. The two domains are 'sustainability objectives/criteria' and 'renovation approaches'. This is carried out by developing a DMM based on empirical studies. As such, the DMM which is developed in this chapter demonstrates how renovation approaches can be mapped to the sustainability objectives/criteria and vice versa.

Development of the DMM for building renovation entails three steps including (1) identification of the sustainability objectives/criteria, (2) discovering and structuring the renovation approaches, (3) and finally investigation of the dependencies among its elements. It provides the primary elements for systems architecture of a DSS that can be used to develop holistic scenarios for refurbishment actions. It further aims to enhance the required insight and addresses the issues for developing the DSS. Moreover, developing such a matrix can (1) capture the dynamics between the renovation approaches and the sustainability objectives/criteria, (2) show traceability of constraints across objectives/criteria, (3) provide transparency between the mentioned elements, (4) synchronize decisions across the domains, (5) cross-verify domain models, (6) integrate a domain with the rest of the project, and (7) improve decision making among design team, engineers, and other key stakeholders who are involved in the renovation process by providing a basis for communication and learning across domains. It therefore plays a strong roll to deal with existing complexity regarding to the large number of renovation alternatives and various types of criteria. Above all, it can be used to consider the propagation of the values, as well as tracking of other values (or added value) regarding to the other considered criteria (i.e. spatial quality) while the focus is on optimization/enhancement of some common criteria i.e., improvement of energy efficiency or reduction of the investment cost.

8.3. Application and development of a DSS (Decision Support Systems) for building renovation

Developing systems architecture for a DSS for generation of sustainable building renovation scenarios is an intricate, challenging task. The increasing complexity of decision problems regarding to the fulfilment of sustainability objectives/criteria, the growing number of subjects involved and keen competition between conflicting costs and interests make decisions and decision support difficult. In order to involve all the sources which can add value in renovation projects, in chapter 4, I explored the decision-making processes for building renovation, and there through identifying a need for introducing three different decision-making levels. The levels help stakeholders in the renovation process to discuss their project “on the same level” and make transparent decisions in a rational order. In the two typical decision-making frameworks, which were developed, the decision-making on third level of the second framework including use of Multi Objective Decision Making – MODM (Climaco, 1997) was considered as the integrated design process implementation and evaluation for sustainable renovation and entitled *scientific decision-making*. Following this concept, as part of the developed HMSR (Holistic Multi-methodology for Sustainable Renovation), there is a strong reasoning for development and application of a DSS (Näegeli et al., 2017; Yin et al., 2011; Juan et al., 2010) in the body of the HMSR for generation of the renovation scenarios.

There are a remarkable number of early stage DSS for sustainable building renovation (Nielsen et al., 2016). They are used by owners and designers mostly to plan energy efficiency retrofitting. Nielsen et al. (2016) stated that almost 30% of the DSS (10 out of 43 studied tools) have been developed to generate the design alternatives. Ferreira et al. (2013a,b) concluded that these DSS (which are capable of making design alternatives) are mostly focus on technical performance enhancement of renovation approaches and therefore used by engineers. This means the DSS have just been begotten to deal with certain Hard (or quantifiable) engineering criteria such as energy efficiency, investment costs etc. and this leads to generate sub-optimal solutions. While as mentioned earlier, the existing building stock should benefit from more holistic renovation approaches embarking on sustainability objectives in its full sense. In this perspective, an optimal renovation scenario is achieved higher scores depends on the selected criteria from intervention of both Soft (i.e. spatial quality) and Hard (i.e. energy efficiency) criteria. Consequently, for development of a DSS to generate holistic renovation scenarios, the question arises concerning the holistic sustainability objectives and possible renovation alternatives. Development of a DMM, further, indicates how these two interact on each other. This consideration, therefore, deepen the knowledge about what value is, how value is created, and where the value will be added in building renovation context.

8.4. PQR (What, How, Why) for Sustainable Renovation

PQR methods was described in the ‘section 3.2.3.5’ and the instruction for its application was represented in Figure 3.22. PQR is classified within the SSM method. Checkland (2000) addresses it through, do P by Q in order to contribute to achieving R, which answers the three questions: What to do (P), How to do it (Q) and Why do it (R)? ‘Do P by Q’ is richer, answering the question: how? And also forcing the model builder to be sure that there is a plausible theory as to why Q is an appropriate means of doing P. The application of PQR method for building renovation context addresses three main questions, which the answers of these questions are used as the inputs for development of a DMM in next step. The question corresponding to renovation context are referred to:

- What to do ? The answer of this question is to develop a list of building components, which in fact the renovation approaches will influence them.
- How to do ? The answer of this question is to develop a list of a comprehensive renovation approaches.
- Why to do ? The answer of this question is to develop a list of holistic sustainability objectives/criteria.

8.4.1. Sustainable Value oriented Criteria (PQR → Why to renovate?)

There are a wide array of advantages that can be obtained as an outcome of a holistic and sustainable retrofitting to higher energy performance standards. Many are tangible and possible to quantify, while others are less so and may be difficult to allocate a monetary value. These renovation goals must be identified and targeted early in the design process while renovation scenarios are developed. Regarding the full scope of this discussion, the "Holistic sustainability decision-making support framework for building renovation" by applying Checkland's Soft Systems Methodologies – SSM (2000) beside Keeney's Value Focused Thinking – VFT (1992) was developed in chapter 5. As such, sustainability was defined and represented in its full sense from three categories including Functionality, Accountability and Feasibility (18 sustainable value oriented criteria [118 sub-criteria] have been identified) for holistic/deep building renovation purpose (see Table 7.5).

8.4.2. Building Components for retrofitting purpose (PQR → What to renovate?)

In an existing building there is a list of building components that the possible renovation approaches are applied to them. Table 8.1 in the following represents a list of building components which have been developed for building renovation purpose. For the development of a database of building components, the relevant data have been collected from relevant literature (Boeri et al., 2014; Burton, 2012; Baker, 2009), evaluation of the 10 European renovation research projects (see section 8.4.3.1).

Table 8.1. A List of building components for the renovation purpose

Floors		
	Solid ground floors	
	Suspended ground floors	
		Concrete or ceramic blocks
		Timber or timber product deck
	Intermediate floors	
External walls		
	Solid walls	
	Cavity walls	
		Masonry cavity
		In situ concrete external cladding
		In situ concrete internal cladding
		Framed
Atria and Double Skins		
	Atria	
		External envelop

		Part of the external envelop
		Open-roofed entrance hall
	Double Skins	
		Single glazing
		Double glazing
		Triple glazing
Internal walls		
	Movable/Removable walls	
	Non-movable/Non-removable walls	
Roofs		
	Roofs with accessible attic spaces (double pitched, mono-pitched or flat)	
	Roofs with voids	
	Solid roofs	
	Green roofs	
	Roof ponds	
Windows		
	Single glazing	
	Double glazing	
	Triple glazing	
	Double low-e glazing	
	Double low-e inert gas glazing	
	Double tinted glazing	
	Double reflective glazing	
	Double low-e high performance glazing	
Mechanical services and controls		
	Boilers	
	Heat distribution	
		Water
		Air
	Heat emitters	
		Radiator
		Convector
		Fan coil
		Underfloor heating
		High level radiant panel
		Via the ventilation air
	Cool emitters	
		Radiator
		Convector
		Fan coil
		Underfloor heating
		High level radiant panel
		Via the ventilation air
	Ventilation fans	
	Water circulation pump	

	Refrigeration		
		Absorption chillers	
			Wet cooling towers
			Dry cooling towers
			Using the ground
		Local 'split-unit' heat pumps	
			Wet cooling towers
			Dry cooling towers
			Using the ground
	Lighting installations		
		Residential Buildings	
			Corridors
			Stairs
			Bed rooms
			Living rooms
			Dining rooms
			Kitchen
			Bathrooms
			Toilets
			Elevators
			Parking
			Basement
			Store
		General buildings	
			Corridors
			Stairs
			Reception areas
			Offices general
			Offices + VDU (Visual Display Units)
			Offices + task lighting
			Drawing offices
			Drawing offices + VDU (Visual Display Units)
			Conference rooms
		Airport & transport buildings	
			Reception areas
			Circulation areas
		Libraries	
			Bookstacks
			Reading areas
		Museums and art galleries	
			General
		School & colleges	
			Classrooms
			Lecture theatres
			Laboratories

			Sports halls
	Controls		
		Local control	
		Central control	
	Lighting controls		
		Occupancy detection	
		Daylight detection	
	Building energy management systems		
	Adaptive controls		
	Hybrid and mixed mode systems		
Built area			
	Addition of new buildings		
	Demolition of existing building		
	Building enlargement		
Renewable energy options			
	Solar thermal		
		Solar thermal evacuated tubes	
			Upgrading domestic hot water system for hotels, hospitals, schools
			Contributing to space heating in buildings with low heat demand and integrated storage system
		Solar thermal flat plate: Low temperature applications such as swimming pools	
		Solar thermal cladding collector: Re-cladding in conjunction with external insulation	
	Photovoltaic		
		Re-cladding panels and roof tiles	
		Re-cladding with air-cooled PV panels	
		Opaque PV used as shading devices	
		Semi-transparent PV used for reduced transmission glazing panels in large spaces such as atria	
	Biomass heating: Biomass heating requires space for fuel delivery and storage		
	Ground source heating: Uses a heat pump		
	Ground source cooling: Uses a heat pump		

8.4.3. Alternative renovation solutions (PQR → How to renovate?)

There are a broad range of renovation approaches that can be applied to the building components in Table 8.1 for the renovation of existing buildings, including insulation approaches, replacement of existing windows, integration or replacement of existing equipment, heating/cooling system, building envelope implementation of roof and partially of facades to avoid thermal bridges, total building envelope implementation, volumetric additions, partial replacement of existing windows, partial building envelope implementation, integration of PV and solar collectors on the roof/facades etc. (Boeri et al., 2014). For the development of a database of renovation approaches, the relevant data have been collected from relevant literature (Boeri et al., 2014; Burton, 2012; Baker, 2009), evaluation of the 10 European renovation research projects (further details will be provided in section 8.4.3.1), as well as investigation of the SIGMA database by Molio (further details will be provided in section 8.4.3.3). Moreover, a renovated building project (the Section 3 of Skovgårdsparken located in 8220

Brabrand, Denmark) has been studied (further details will be provided in section 8.4.3.2). The results in total led to expand a list of 26 renovation categories including 139 renovation alternatives (see Table 8.2). It should be noted, however, that they are not necessarily separate components; indeed, integration of actions in any renovation project is very important.

Table 8.2. A comprehensive list of renovation approaches

A		Insulation approaches
	A.a.	External wall thermal insulation [insulation from outside]
	A.b.	External wall thermal insulation [insulation from inside]
	A.c.	Roof [last floor thermal insulation]
	A.d.	Ground floor [first floor thermal insulation]
B		Envelope (exterior finishes)
	B.a.	Wall - Light concrete
	B.b.	Wall - Concrete
	B.c.	Wall - Brick
	B.d.	Wall - Steel
	B.e.	Wall - Wood
	B.f.	Wall - Glass
	B.g.	Wall - Plaster
	B.h.	Roof - Concrete
	B.i.	Roof - Tile
	B.j.	Roof - Cementbased
	B.k.	Roof - Steel
	B.l.	Roof - Roofing Felt
C		Window (replacement)
	C.a.	Plastic
	C.b.	Aluminium
	C.c.	Wood
	C.d.	Wood/Aluminium
D		Doors (replacement)
	D.a.	Interior doors - steel
	D.b.	Interior doors - wood
	D.c.	Exterior doors - Plastic
	D.d.	Exterior doors - Aluminium framework
	D.e.	Exterior doors - Wood
E		Airtightness and Damp proofing approaches
	E.a.	Jointing
	E.b.	Vapor Barrier
F		Waste facilities
	F.a.	Waste management [solid waste storage]
	F.b.	Wastewater technologies [collection and recycling of greywater]
	F.c.	Rainwater and graywater storage - Concrete Well
	F.d.	Rainwater and graywater storage - Plastic Well
G		Building security approaches
	G.a.	Fire protection system

	G.b.	Access Control
	G.c.	Automatic burglar alarm system
	G.d.	Prevent slips, trips, and falls
	G.e.	Electric safety
	G.f.	Locks
H		Building site
	H.a.	Pavement type
	H.b.	Green spaces [improving current greenery condition]
	H.c.	Playground [a specific space belongs to the children's plays in building site]
	H.d.	Rainwater ground storage
	H.e.	Parking [any extra costs]
I		Structural system
	I.a.	Structural system
	I.b.	Structural elements
	I.b.	Foundation
J		HVAC system
	J.a.	Ventilation system
	J.b.	Heat Generation
	J.c.	Thermal energy distribution system
	J.d.	DHW's Heat/cold distribution
	J.e.	Cooling Technologies
K		Renewable Energy Sources
	K.a.	Biomass boilers
	K.b.	Solar photovoltaic system
	K.c.	Solar water heating
	K.d.	Air source heat pump
	K.e.	Geothermal heat pump
	K.f.	Wind turbine
	K.g.	Micro wind turbine
L		Energy storage
	L.a.	Thermal energy storage (TES)
	L.b.	Electrical energy storage systems
M		Electrical system
	M.a.	Electrical installations
	M.b.	Exterior lights
	M.c.	Interior lights
	M.d.	Empty pipes [for wires passing through]
N		Plumbing system
	N.a.	Copper pipes
	N.b.	Galvanized Steel
	N.c.	Pipe insulation
	N.d.	Sewer inside
	N.e.	Sewer pipes
O		Controls

	O.a.	Indoor climate control
	O.b.	Chemical/pollutant control devices
	O.c.	Water use minimization devices
	O.d.	Energy measurement devices
	O.e.	Water measurement devices
	O.f.	Sound controls
	O.g.	Motion sensors
	O.h.	CTS
P		Flooring
	P.a.	Tiles
	P.b.	Laminate
	P.c.	Wood
	P.d.	Linoleum
	P.e.	Surface treatment
	P.f.	Cement sheets
Q		Interior finishes - Ceiling
	Q.a.	Plaster on concrete
	Q.b.	Surface treatment
	Q.c.	Suspended ceiling - Mineral wool
	Q.d.	Suspended ceiling - Plaster
	Q.e.	Suspended ceiling - Aluminum
	Q.f.	Suspended ceiling - Steel
	Q.g.	Surface mounted ceiling - Wood-concrete
	Q.h.	Surface mounted ceiling - Plaster
	Q.i.	Surface mounted ceiling - Wood
R		Interior finishes - Walls
	R.a.	Plaster
	R.b.	Tiles
	R.c.	Wallpaper
	R.d.	Surface treatment
S		Increasing solar Gain
	S.a.	Roof – Skylight windows
	S.b.	Roof - Light-pipes
	S.c.	Fibre Optic Ligthing
	S.d.	Light Wells
T		Avoiding overheating
	T.a.	Reducing external heat gains [use of Solar-shading]
	T.b.	Window treatments
U		Redesign of external and internal spaces
	U.a.	Taking advantage of the geometry
	U.b.	Including unused spaces
	U.c.	Extending the existing building
	U.d.	Adding new functions
	U.e.	Improving the spatial quality
V		Common areas (interior)

	V.a.	Corridors
	V.b.	Basement
W		Individual building elements
	W.a.	Staircases
	W.b.	Chimney
	W.c.	Fireplace
	W.d.	Ducts
X		Sanitary appliances
	X.a.	Unit solution
	X.b.	Wash basins
	X.c.	Shower
	X.d.	Bath tube
	X.e.	Urinal and toilet
Y		Fixed furniture [essential]
	Y.a.	Kitchen cabinet
	Y.b.	Fixed table [Kitchen islands]
	Y.c.	Kitchen sink
	Y.d.	Shelves
	Y.e.	Mail box
	Y.f.	Fixed fixtures
Z		Movable furniture [optional]
	Z.a.	Kitchen table beside chairs
	Z.b.	Dining table beside chairs
	Z.c.	Sofa set beside sofa table
	Z.d.	Bed and siding table
	Z.e.	Refrigerator
	Z.f.	Washing machine
	Z.g.	Dish washing machine
	Z.h.	Stove
	Z.i.	Wine store
	Z.j.	Decorative Lighting
	Z.k.	Photo/painting panels
	Z.l.	Carpet
	Z.m.	Recycle Bin
	Z.n.	Outdoor furniture
	Z.o.	Other

8.4.3.1. Analysis of 10 building renovation research projects in Europe

There are two objectives for analysis of the 10 renovation research projects in this thesis. It is, first, for the development of a comprehensive list of renovation approaches, which was represented in Table 8.2. It helps to deal with massive number of renovation approaches and development of a comprehensive list of renovation approaches which is systematically sound. The analysis is, second, for consideration of the current state of renovation context and where it moving forward in future. It leads to realize about possible gaps regarding their outcomes for the future of the renovation field in practice. This will discuss further in chapter 7. The research projects have been selected due to their scale, history, the involved countries, and their funding that underlines their importance (see Table 8.3).

Table 8.3. Information about the 10 analyzed renovation research projects

Project name	Year	Countries involve	Total cost	EU program
iNSPiRe Development of Systemic Packages for Deep Energy Renovation of Residential and Tertiary Buildings including Envelope and Systems	2012 - 2016	Spain, Germany, Sweden, Austria, Italy, France, United Kingdom, Belgium	EUR 10 841 678,29	FP7
http://cordis.europa.eu/project/rcn/104743_en.html				Links to Project
http://inspirefp7.eu/				
EcoShopping Energy efficient & Cost competitive retrofitting solutions for Shopping buildings	2013 - 2017	Germany, Spain, Austria, Portugal, Croatia, Poland, Italy, Spain, United Kingdom, Turkey, Taiwan, Hungary	EUR 5 929 338,01	FP7
http://cordis.europa.eu/project/rcn/109127_en.html				Links to Project
http://ecoshopping-project.eu/index.html				
HERB Holistic Energy-efficient Retrofitting of residential Buildings	2012 - 2016	Greece, United Kingdom, Italy, Portugal, Germany, Switzerland, Spain, Turkey, Poland, Netherlands	EUR 8 606 892,87	FP7
http://cordis.europa.eu/project/rcn/105487_en.html				Links to Project
http://www.euroretrofit.com/				
REFURB REgional process innovations FOR Building renovation packages opening markets to zero energy renovations	2015 - 2018	Belgium, Netherlands, Denmark, Slovenia, Estonia, Germany	EUR 2 074 875	FP7
http://cordis.europa.eu/project/rcn/194628_en.html				Links to Project
http://go-refurb.eu/about-refurb/				
READY Resource Efficient cities implementing ADvanced smart citY solutions	2014 - 2019	Denmark, Sweden, Lithuania, Austria, France	EUR 33 340 202,60	FP7
http://cordis.europa.eu/project/rcn/197826_en.html				Links to Project
http://www.smartcity-ready.eu/				
3ENCULT Efficient ENergy for EU Cultural Heritage	2010 - 2014	Denmark, Germany, Austria, UK, Spain, Italy, France, Netherlands, Czech Republic, Belgium	EUR 6 704 955,74	FP7
http://cordis.europa.eu/project/rcn/97086_en.html				Links to Project
http://www.3encult.eu/en/project/welcome/default.html				

MORE-CONNECT Development and advanced prefabrication of innovative, multifunctional building envelope elements for MOdular REtrofitting and CONNECTions	2014 - 2018	Netherlands, Latvia, Estonia, Portugal, Denmark, Czech Republic, Switzerland	EUR 5 557 263	H2020
http://cordis.europa.eu/project/rcn/193236_en.html				Links to Project
http://www.more-connect.eu/links/				
BuildHeat Standardized approaches and products for the systemic retrofit of residential Buildings, focusing on HEATing and cooling consumptions attenuation.	2015 - 2019	Italy, Belgium, Germany, Austria, Spain, United Kingdom	EUR 9 136 072,50	H2020
http://cordis.europa.eu/project/rcn/198377_en.html				Links to Project
http://www.buildheat.eu/				
NeZeR Promotion of smart and integrated NZEB renovation measures in the European renovation market.	2014 - 2017	Finland, Netherlands, Sweden, Romania, Spain	Co-funded	H2020
https://ec.europa.eu/energy/intelligent/projects/en/projects/nezer#partners				Links to Project
http://www.nezer-project.eu/2.1f96676d145d7c93741c57.html#.WLVrXDsrJPY				
RePublic_ZEB Refurbishment of the Public building stock towards nZEB	2014 - 2016	Greece, Romania, United Kingdom, Croatia, Hungary, Slovenia, Portugal, Italy, Bulgaria, Spain, Macedonia	Co-funded	H2020
https://ec.europa.eu/energy/intelligent/projects/en/projects/republiczeb				Links to Project
http://www.republiczeb.org/index.jsp				

The analysis have classified above projects in three levels including *moderate* or *ordinary*, *deep* renovation, and *Near Zero Energy Building* (NZEB). The mentioned terms have been extracted from the projects themselves. In this classification, *moderate* is attached to features expected about recently retrofitted buildings and solutions; *NZEB* refers to application of exceedingly advanced solutions which lead to develop renovation scenarios with very high energy performance; and lastly *deep renovation* that refers to implementation of wider range of sustainability criteria for renovation purpose. The identification of the renovation approaches (level of details) in the listed renovation projects in Table 8.3, were particularly investigated through four categories: 1) low numbers of identified renovation actions + low amount of provided technical properties (referred as low); 2) Low numbers of identified renovation actions + high amount of provided technical properties (referred as moderate); 3) High numbers of identified renovation actions + low amount of provided technical properties(referred as high); and 4) High numbers of identified renovation actions + high amount of provided technical properties (referred as very high).

Table 8.4. Analysis of 10 European building renovation research projects

Project Name	Renovation level			Renovation project phase											Building function			Case study evaluation (renovation)	Focus on specific climate zoon	Focus on building elements for renovation	Major considered criteria									Development of a digital tool
	Moderate	Deep	NZEB	Energy auditing and Renovation	Identification of the renovation actions (level of details)				Enhancement of renovation actions	Creation of renovation actions	Generation of renovation scenarios	Site implementation	Validation and Verification	Monitoring	Residential buildings	Public/Commercial/Office buildings	Historical buildings				Energy consumption	Renewable energy	CO2 emission	Water consumption	Indoor comfort	Payback period	Cost	Occupant behaviour	Renovation process	
					Low	Moderat	High	Very high																						
iNSPiRe		+		+		+			+	+	+	+		+	+	+		+	+	+	+	+	+		+		+			
EcoShopping						+										+					+	+			+		+			
HERB		+			n/a	n/a	n/a	n/a	+	+	+	+		+	+			+		+	+	+	+			+	+			+
REFURB		+	+		n/a	n/a	n/a	n/a			+	+	+		+			+			+		+				+	+	+	
READY			+			+				+				+	+	+			+	+	+	+	+	+			+		+	
3ENCULT				+			+		+		+			+			+	+			+				+				+	
MORE-CONNECT		+	+			+				+					+	+	+			+	+				+					+
BuildHeat	+				+				+	+	+				+			+		+	+							+	+	
NeZeR	+	+	+			+			+	+					+			+	+		+	+					+		+	
RePublic_ZEB			+	+				+	+	+	+					+		+	+	+	+	+	+				+		+	

Note: Despite analysis of the renovation approaches in this section, the rest of the investigated and discovered items in Table 8.4 will be used and discussed further in chapter 7.

The highlighted column with grey color in the Table 8.4 demonstrates the level of the details, which the projects have been provided about the various types renovation approaches. For the development of the comprehensive list of renovation approaches, which was represented in Table 8.2, the project that has provided the details referred to 'very high' above have been exploited in present thesis. It hence is 'RePublic_ZEB'. As an example, a list of technologies suitable for the refurbishment of existing buildings from 'RePublic_ZEB' project for context of ITALY will be provided in Appendix 1. In addition, retrofit measures and the energy efficiency levels and referred cost for the same context have been provided in Appendix 2. The provided information in appendices can be used for addressing the parameters, which are usually used by engineers in the renovation process and for further development of the outcomes in section 8.4.3 can be added up to the renovation approaches which have been listed in Table 8.2.

8.4.3.2. Analysis of a case study [Section 3 of Skovgårdsparken[1] located in 8220 Brabrand, Denmark]

There are two main objectives for analysis of the Section 3 of Skovgårdsparken that recently has been renovated (see Figure 8.1). The case is included as an example of how a real renovation project is carried toady and b) what people expect out of a holistic renovation scenario in real practice of this context. It therefore aims to identify an actual holistic renovation scenario, which has been developed and subsequently applied for the mentioned building. Consequently, it has been used to systematically develop a comprehensive list of renovation approaches in three levels, which was represented in Table 8.2. The case has been selected due to a comprehensive renovation scenario (i.e. insulation of walls, renovation of foundation, installation of PV etc.) that has been developed and applied for the renovation purpose.

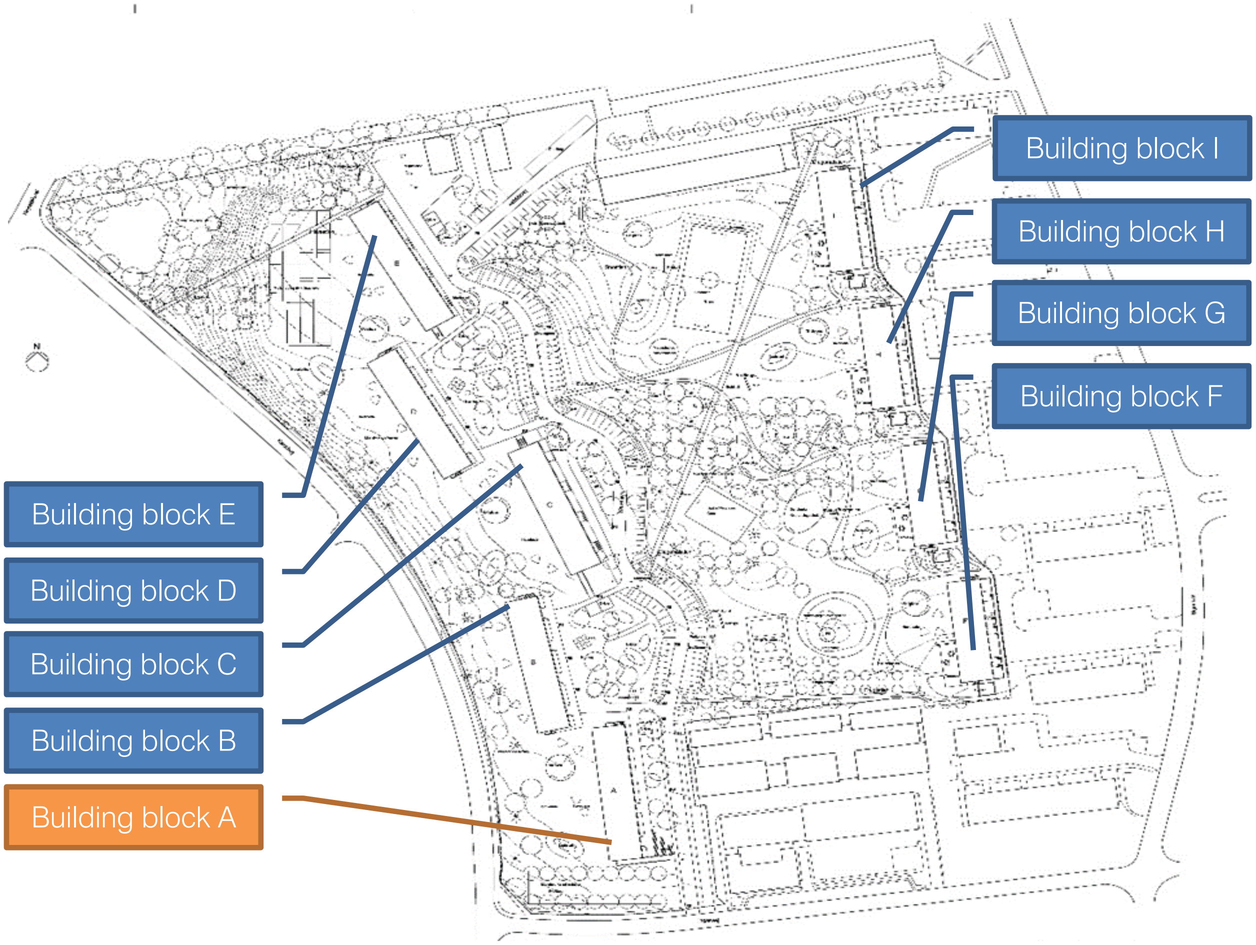


Figure 8.1. Site plan of Section 3 of Skovgårdsparken (social housing project) including nine building blocks (A-I) [Note: a small selection of the as-built drawings for building block 'A' have been provided in Appendix 3]

Section 3 of Skovgårdsparken (see Figure 8.2) is a social housing project (including nine blocks), modernistic in terms of typology, built during 1968/72. The building has been renovated by Brabrand Housing Association (Brabrand Boligforening Gudrunsvej 10A, 8220 Brabrand), which is a project partner in RE-VALUE project (it was introduced in section 1.10). It is located in 8220 Brabrand,

[1] https://www.bbbo.dk/projekter/skovgaardsparken/

Denmark. Skovgårdsparken is one of the oldest sections in Brabrand Boligforening, and over the past few years, 256 of the sections including 432 apartments have undergone a comprehensive energy renovation. Outdoors have been replacing roofs, after-insulation of facade bricks and replacing to closed balconies. Inside, the technical installations have been replaced as well as ventilation on all occasions.

Figure 8.2. Skovgårdsparken after renovation

In outdoor areas, an exciting landscape with green, park-like conditions has been built, where residents have good living areas with opportunities for activity, play and movement. There are a number of sustainable measures in the renovation such as paper wool in the facades, recycling of glass for insulation, a solar collector project, solar cell and geothermal heating and wastewater recycling as well as water collection. In addition, it is the first renovation of this type in Denmark and the largest geothermal plant with energy wells to date (see Figure 8.3). The energy-saving renovation of Skovgårdsparken means that rent has only risen to a minimum, as major energy savings mean that the renovation will eventually serve itself as home. The extensive energy conversion has meant that Skovgårdsparken has reduced energy consumption by 90 percent.

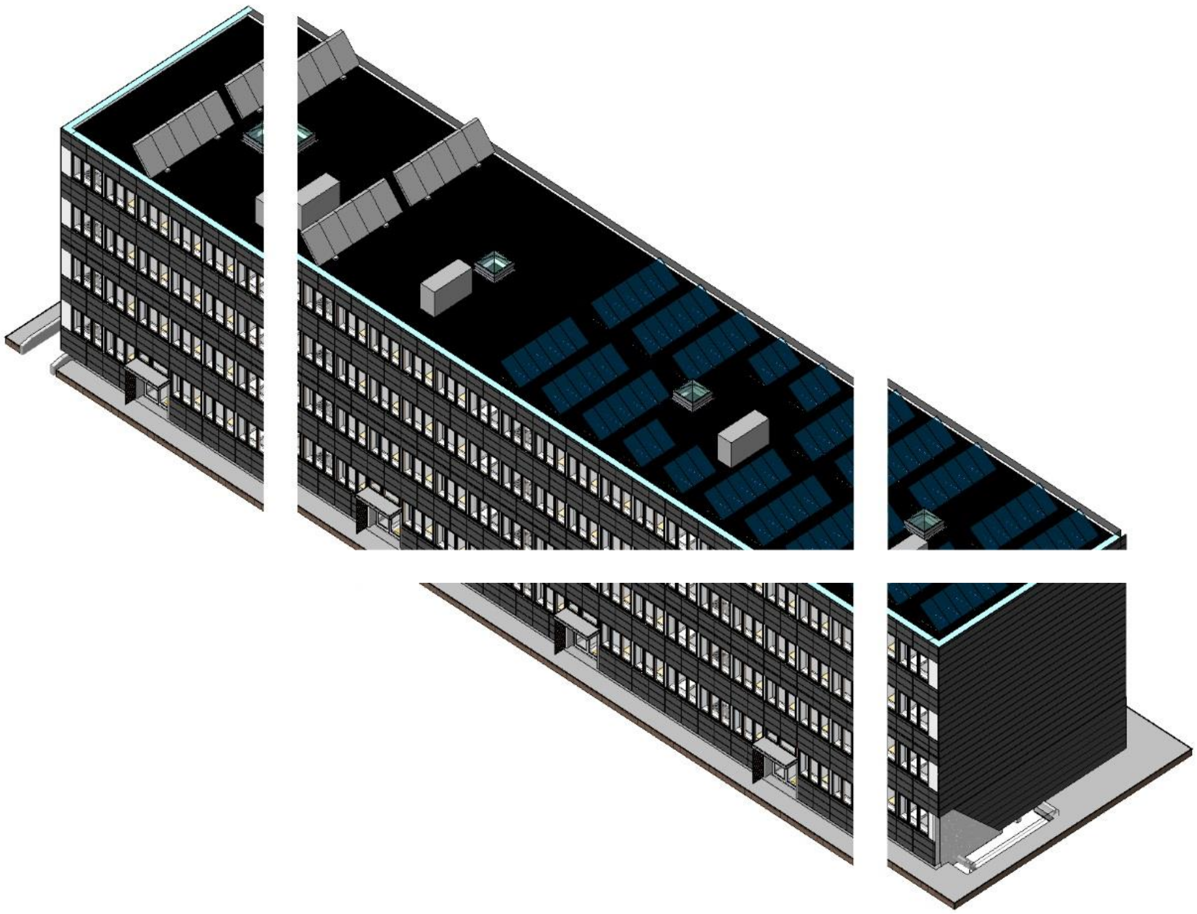


Figure 8.3. 3D view of the building block 'A' including renovation scenario in renovation of the section 3 of Skovgårdsparken project

A team of Architects (Poulsen & Partnere A/S Kystvejen 17, 5.sal - 8000 Århus C), Engineers (Moe & Brødsgaard a/s Åboulevarden 22 - 8000 Århus C) and Landscape designers (Preben Skaarup Graven 3 - 8000 Århus C) beside the contractor (MTHøjgaard a/s Lystrupvej 50, 8240 Risskov Århus) have worked together to develop the renovation scenario for the Skovgårdsparken renovation project. Therefore, the renovation scenario for the entire project has been developed focusing on all the requirements from Architecture, Engineering and Landscape design fields. The above teams have provided more than 1000 drawing and description sheets for renovation purpose of the mentioned nine building blocks. In this thesis, I will provide a small selection of the drawings belongs to only 'building block A' (that means 1 building block out of the 9 – this is due to the similarities between the building blocks) renovation in Appendix 3. However, it must be underlined that for identification of the entire renovation scenario (including all the fields Architecture, Engineering and Landscape) which has been developed and applied to the aforementioned social housing project, I have looked into the entire provided documents from the home association office. The results come together in Table 8.5 including the entire list of renovation alternatives, which have been combined so as to develop a holist renovation scenario for the aforementioned renovation project.

Table 8.5. The entire list of renovation alternatives, which have been used for renovation of Section 3 of Skovgårdsparken (a social housing project)

Renovation category	Renovation alternative	Renovation action used in Skovgårdsparken
Insulation approaches	External wall thermal insulation [insulation from outside]	External insulation 100 mm MINERAL WOOL panels
Insulation approaches	External wall thermal insulation [insulation from outside]	Injection of cellulose fiber panels in wood panels (600x900x)
Insulation approaches	Roof [last floor thermal insulation]	Isover wedge shaped pressure resistant glass wool U=0.10
Envelope (exterior finishes)	Wall - Concrete	8 mm Fiber concrete Cladding on facade
Envelope (exterior finishes)	Wall - Brick	Brick cladding on gables
Envelope (exterior finishes)	Wall - Glass	Closing balconies with glazing + Installations of steel railings for glazing fittings + Reconstruction wall between balcony
Window (replacement)	Plastic	Window sills around windows
Doors (replacement)	Interior doors - wood	Panel door to basement from stairwell (steel)
Doors (replacement)	Exterior doors - Plastic	Balcony doors
Doors (replacement)	Exterior doors - Aluminum framework	Alu glazed entrance door
Doors (replacement)	Exterior doors - Aluminum framework	Steel - alu zink coated exterior basement door
Airtightness and Damp proofing approaches	Jointing	DAFA airstop multi-ceiling tape between junctions of existing concrete elements, vertical
Building security approaches	Fire protection system	Fire protecting new steel structures with Glosrock F
Building security approaches	Fire protection system	Fire separation between windows 15 mm gyproc plaster board
Building security approaches	Prevent slips, trips, and falls	Installation of railing at exterior stairs and basement entrances

Building security approaches	Locks	Installation of new lock system
Structural system	Foundation	Renovation of foundation
HVAC system	Ventilation system	Change of mechanical ventilation fans in bathroom + Change of exhaust hood above stove + Installation of smoke exhaust ventilation in stairwell + Agregates with fixtures, sound silencer, and insulation
HVAC system	Thermal energy distribution system	Necessary valves in new piping system
HVAC system	Thermal energy distribution system	Installation of new radiators
Renewable Energy Sources	Geothermal heat pump	Geothermal plant with energy wells
Renewable Energy Sources	Solar photovoltaic system	Installation of Solar photovoltaic system on roof (480 units)
Renewable Energy Sources	Solar water heating	Installation of Solar photo thermal system on roof
Electrical system	Electrical installations	Installation of electrical panels + Wiring for solar panels + Installation of caple holders + New outleds + Installation of grounding systems
Electrical system	Exterior lights	Incandescent light on site + Incandescent light on site
Electrical system	Interior lights	Removal of light from walls to demolish + Removal of light from outdoor paths and facade + Facades incandescent light
Electrical system	Empty pipes [for wires passing through]	Installation of empty pipes indoor + Installation of empty pipes outdoor
Plumbing system	Galvanized Steel	Galvanized steel pipes for domestic water (Cold, Hot, Circulated) because of PT panels
Plumbing system	Sewer inside	Downpipes from kitchens in stairwell with connection to old and vent in roof
Plumbing system	Sewer inside	Adjusting new sewers to fit the existing
Plumbing system	Sewer inside	Establishing of drain including well and covers
Plumbing system	Sewer inside	Dismantling of electrical systems for plumbing control, pumps and mixing loops
Controls	Water use minimization devices	Installation of water measurements devices
Controls	Motion sensors	Removal of outdoor sensors
Flooring	Tiles	Adjusting and reparation of existing terreazzo floor
Flooring	Laminate	Installation of floor mat
Interior finishes - Ceiling	Surface treatment	Stairwell ceiling - 1 time Matte paint

Interior finishes - Walls	Plaster	Installation of plaster walls around stairwells + Installation of plaster walls around shafts
Interior finishes - Walls	Surface treatment	New walls on balconies -2 times gloss paint + Internal walls stairwells - 2 times gloss paint + Akryl finish
Interior finishes - Walls	Surface treatment	1 time Matte paint + Priming +Fairing + Visible metal - Priming + Akryl Middle paint + 2 times gloss paint finish + Ceiling reparations under repos
Increasing solar Gain	Roof - Light-pipes	Installation of 3 layer Akryl skylight in stairwell
Fixed furniture [optional]	Mail box	Installation of new mailboxes at facade entrance
Fixed furniture [optional]	Other	Installation of phone

8.4.3.3. Danish SIGMA database

For the comprehensive development and specifically organization of the renovation categories (A-Z in Table 8.2), I have used the Danish SIGMA database (see Figure 8.4). The Danish non-profit organization Molio (2016) is behind this database, which is ongoing updated. Molio's aim is to contribute in strengthening competitiveness for companies involved in construction, works and maintenance, for the benefit of industry and society. Investigation of the Danish SIGMA database can further help to extract the relevant price for the listed renovation alternatives.

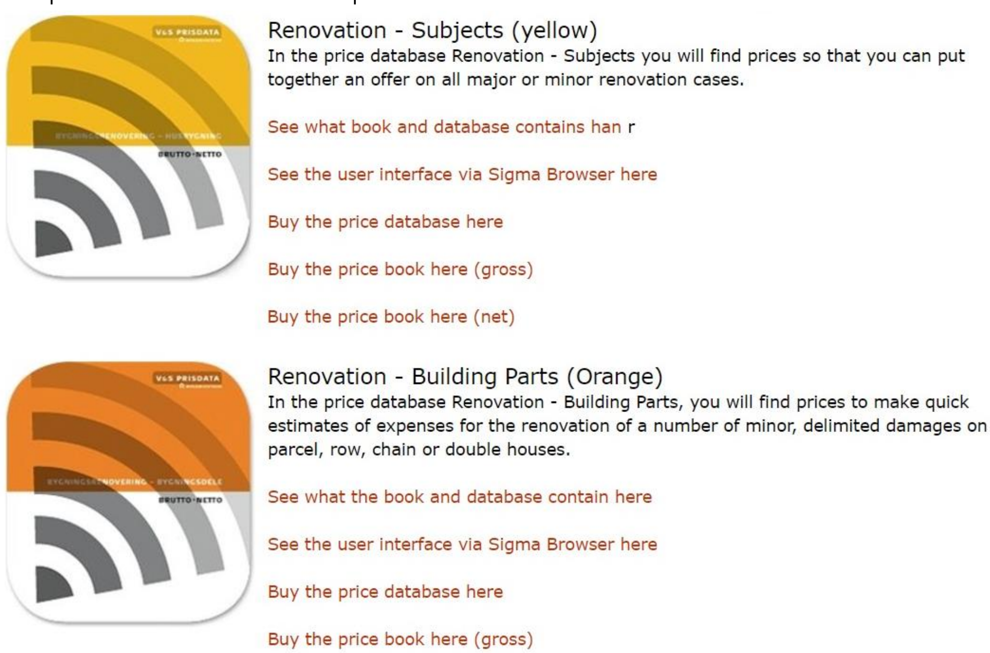


Figure 8.4. Molio's data for data for renovation[2]

8.5. Domain Mapping Matrix (DMM) for building renovation

The DMM developed in this section represents the components in building renovation and their interactions, thereby highlighting the system's architecture (or designed structure). The DMM is

[2] https://molio.dk/molio-prisdata/renovering/

developed between recently developed criteria in chapter 5 (see Figure 8.5) and renovation approaches in section 8.4.3 (see Figure 8.6).

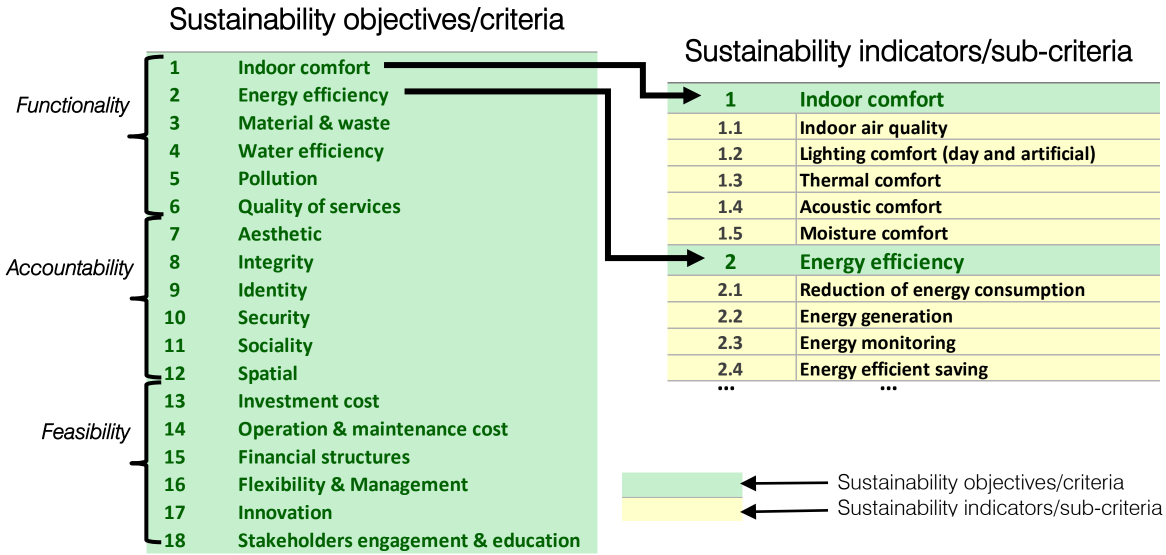


Figure 8.5. Sustainability objectives/criteria for building renovation

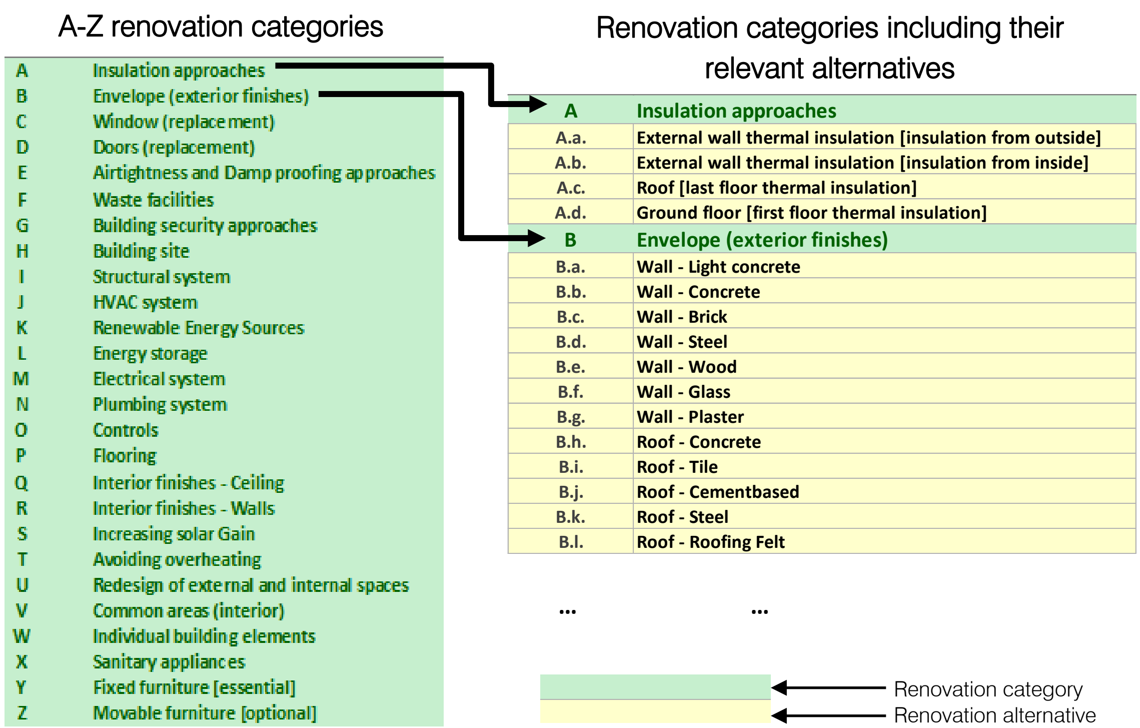


Figure 8.6. Structure of the A-Z renovation categories and their relevant alternatives

The matrix representation of the DMM is a rectangular and binary (i.e. a matrix populated with only zeros and ones) with *m* rows and *n* columns, whereas *m* is the number of renovation alternatives and *n* is the number of sustainability sub-criteria (see Figure 8.7 and Figure 8.8). If there exists a dependency from node *i* to node *j* (equivalent to $a_{i,j}$), then the value of the item $a_{i,j}$ (column *i*, row *j*) is unity (or flagged with a mark such as "X"). Otherwise, the value of the element is zero (or left empty).

$$DSM_{m\times n} = \begin{pmatrix} a_{1,1} & \cdots & a_{1,j} & \cdots & a_{1,n} \\ \vdots & & \vdots & & \vdots \\ a_{i,1} & \cdots & a_{i,j} & \cdots & a_{i,n} \\ \vdots & & \vdots & & \vdots \\ a_{m,1} & \cdots & a_{m,j} & \cdots & a_{m,n} \end{pmatrix}$$

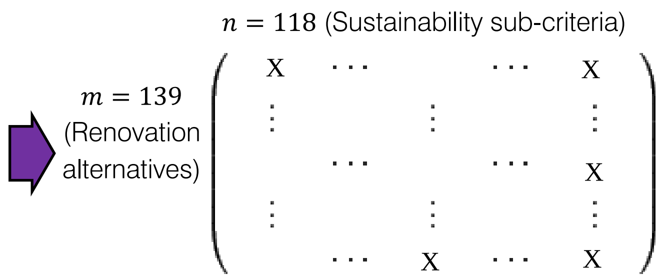


Figure 8.7. The DMM for building renovation with *m* number of renovation alternatives and *n* number of sustainability sub-criteria (the mark “X” has been used if there exists a dependency between elements node *i* to node *j*)

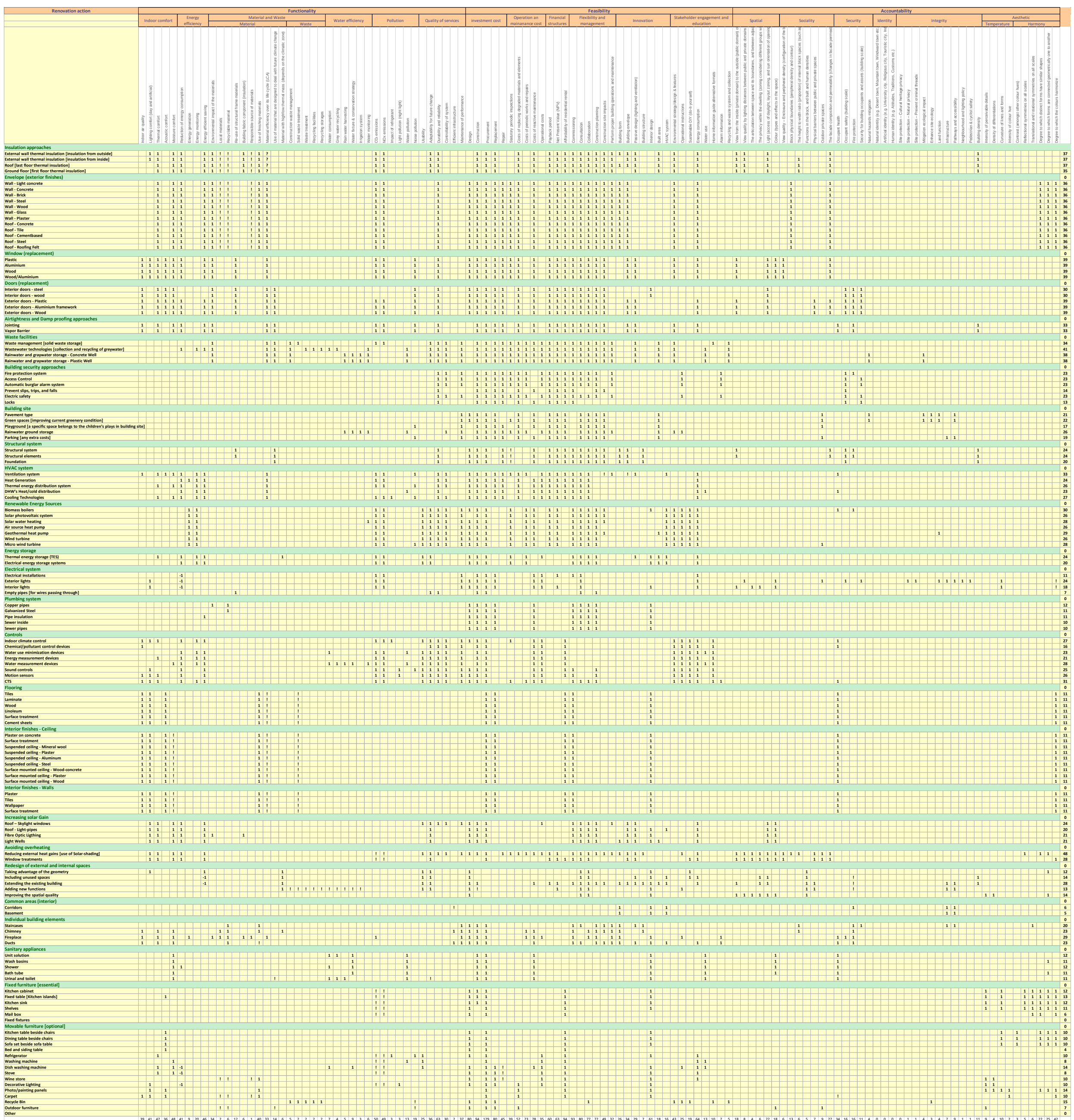


Figure 8.8. The DMM for building renovation (the figure is in high quality and can be zoomed in digital format)

8.5.1. Findings

Developing the DMM in this study indicated the presence or absence of a relationship between pairs of renovation alternatives and sustainability sub-criteria for renovation projects. Having an overview of the number of dependencies from the sustainability criteria (and sub-criteria) into the renovation alternatives (see Figure 8.9) indicates that

- the criteria 'indoor comfort', 'quality of the services', 'energy efficiency' from Functionality category; 'investment cost', 'financial structures', 'flexibility & management' from Feasibility category; and 'aesthetic', 'security and safety', 'spatial quality' from Accountability category are respectively more affected criteria comparing to the others in their own category.
- the criteria 'investment cost', 'financial structures', 'flexibility & management', 'aesthetics', 'indoor comfort', and 'energy efficiency' are respectively the most impressive/affected ones resulted from application of the renovation alternatives. That means in a typical renovation process these criteria have to be targeted and prioritized in early design stages. It is due to the large number of connections between them and the other criteria. Obviously, they make more values as well.
- the sub-criteria 'procurement', 'affordability of residential rental', 'commissioning', 'energy consumption', 'durability and reliability', and 'degree to which the colors harmonize' are respectively the most connected to the renovation alternatives. It demonstrates their importance and ability to gain more scores in a holistic renovation process. In another perspective, this also point out different ways of generating these values/objectives by use of various renovation approaches.

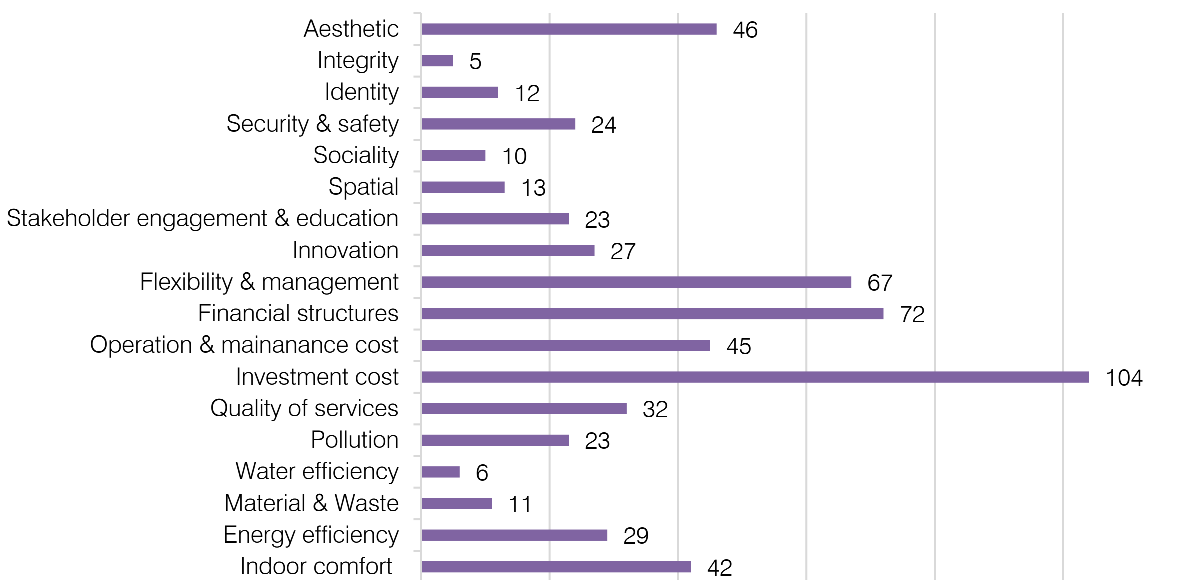


Figure 8.9. The average number of dependencies for renovation sustainability criteria, from the sub-criteria (total 118) into the renovation alternatives (total 139)

Having an overview of the number of dependencies from the renovation alternatives into the sustainability criteria (see Figure 8.10) indicates that

- application of the renovation solution categories 'windows (replacement)', 'avoiding overheating', 'envelope (exterior finishes)', 'insulation approaches', and 'waste facilities' are respectively influencing more sub-criteria. The results suggest how the values (objectives/criteria) are affected comprehensively by use of different renovation strategies. It enables us to track where the value will be created and where the value will be added. For instance, the analysis shows that use of the category 'windows (replacement)' has an average of 38 dependencies with various sub-criteria. That means replacement of the windows as part of the renovation strategy influences sub-criteria under 'indoor comfort', 'energy efficiency', 'material & waste', 'pollution', 'quality of services', 'all related costs', 'aesthetic', 'security & safety', 'sociality' etc. due to existing dependencies among them.
- application of the renovation alternatives 'reducing external heat gains [use of Solar-shading]', 'external insulation', 'window replacements', 'renewable energy technologies', 'wall - exterior finishes', 'roof – exterior finishes', 'indoor climate control', 'fire places', 'structural system', and 'HVAC system' respectively embark on more sub-criteria and therefore they create more values in renovation process. Next, the values (objectives/criteria) that have been created should be investigated and demonstrated to all stakeholders in the process.

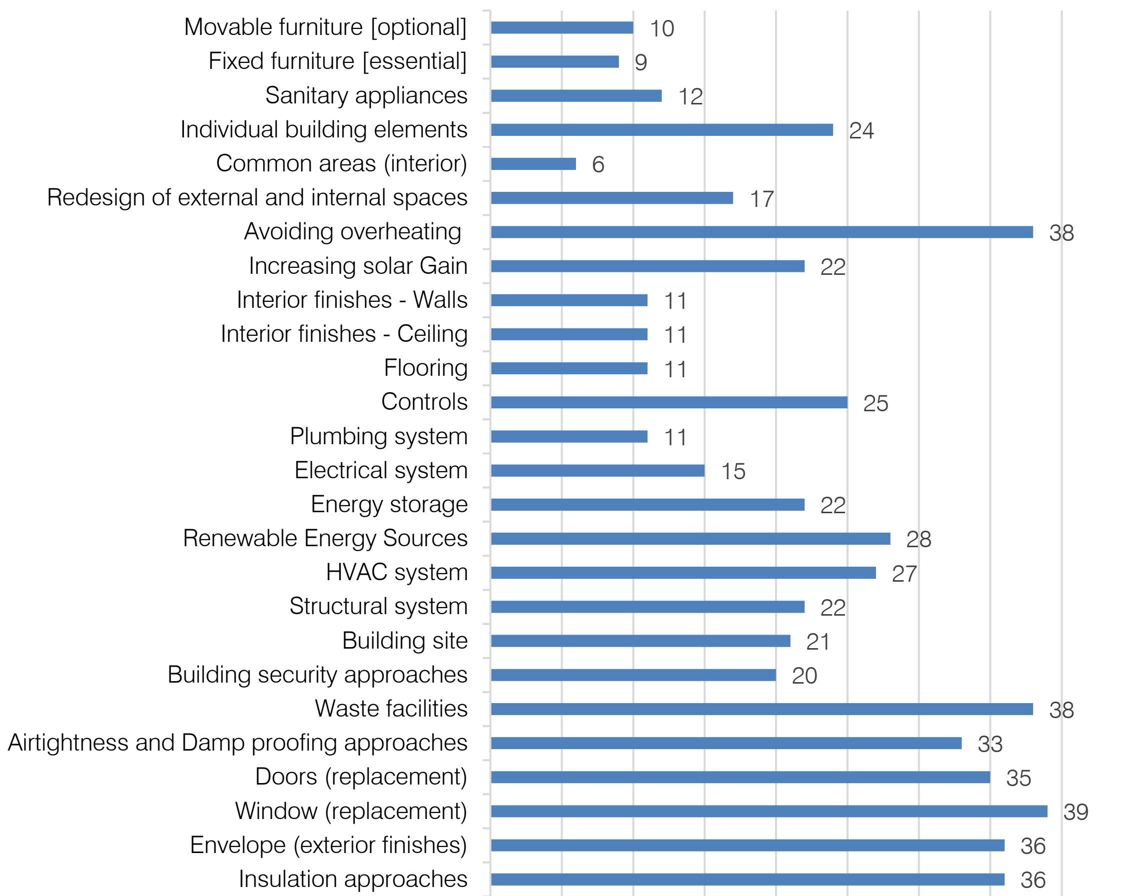


Figure 8.10. The average number of dependencies for renovation categories, from the renovation alternatives (total 139) into the sustainability sub-criteria (total 118)

8.5.2. Discussion

In previous section, the functional characteristics (renovation objectives/criteria) have been propagated to the physical components (renovation approaches) through development of a DMM to help the system architects to be aware of the effects of the decisions they make in the early design process. The DMM provides a simple, compact and visual representation of the system (here refers to renovation context) in the form of a matrix. In addition, it describes the implication of Active (Hard or technical) renovation approaches (i.e. replacement of the windows) beside Passive (Soft or architectural) renovation approaches (i.e. redesign of internal or external spaces). The evidence of a holistic renovation influence of an energy renovation (use of pure technically designed renovation scenarios) is that many of the measures taken in energy renovation, which affect architectural quality and social aspects, are not necessarily related to energy concerns (or pure technically designed renovation scenarios). In other words, implementation of energy renovation scenarios also affects ‘integrity’, ‘sociality’, ‘aesthetic’, and ‘spatial’ quality in buildings and its impacts should not be overlooked. The exploration of this concept is a way to create and to track the added values related to the other criteria in this field. For example by tracking the renovation alternative “indoor climate control”, it is realized that it influences “indoor comfort”, “energy efficiency”, “quality of services”, “investment cost” criteria, and at the same time, it adds value to all the sub-criteria under “Stakeholder engagement and education”. Surprisingly, the Active renovation approaches influence the Soft criteria and vice versa, remarkably. As well, many of the results were expected such as the cost criteria including ‘investment cost’, ‘operation and maintenance cost’, and ‘financial structures’ should be considered and prioritized as the most effective criteria, and therefore most crucial to cope with in selection of the renovation alternatives. Moreover, the renovation may bring changes in the built area, which these changes affect, most of the other Soft criteria in nature. Another expected result was the impact of ‘stakeholder engagement and education’ criteria and sub-criteria in connection to renovation approaches such as ‘energy consumption’, ‘waste facilities’, ‘controls’, ‘’increasing solar gains’, and ‘redesign of external and internal spaces’. Also the criteria ‘flexibility and management’ was expected to link to high number of dependencies.

As Danilovic et al. (2004) argued, the DMM-analysis can perform or deal with transformation of information between domains, traceability of information between domains and system elements, synchronization of information and activities between domains, verification of system models and project assumptions, integration of the individual systems into a cohesive project/program system and improved quality of decision making. Particularly, for development of a DSS that described earlier, a DMM advantages include compact format, visual nature, intuitive representation, powerful analytical capacity, and flexibility in the system. Moreover, the DMM can be applied on the one hand, as a hierarchical decomposition that includes multilevel abstraction and design parameter identification, and on the other hand, a multi-domain formulation, which includes parameter dependency identification, design cycle identification and decision structuring, and scoping. It should be noted that there exists more and more facts, which can be discussed and hence resulted from consideration of the DMM in this chapter. That means the outcomes above can certainly be expanded further.

It should be underlined that the dependencies between the components in the matrix have been addressed using the author experience; therefore the outcome could be more reliable if the co-relation between the components calibrated. This can be by addressing the correlation within i.e. '-3' to '3' or '1' to '5' or '1' to '9' intervals. This entails data collection from the experts or running simulation particularly over the quantitative criteria.

8.6. Summary

This section investigated the development of a Developing Decision Support Systems (DSS) for generation of renovation scenarios. The aim was to consider the dependency between renovation approaches while they meet different criteria or sub-criteria, and vice versa, regarding to the selection of the criteria versus application of some possible renovation approaches.

The improvement of existing buildings involves two major steps: current condition assessment and future upgrade strategies. Most of the methods focus on the first step of the improvement process, understanding or predicting energy usage but no generation of possible renovation scenarios. While the latter is about proposing of the future upgrade renovation solutions. The integrated renovation scenarios/packages that can be leveraged at an existing building – and is related to possible interactions between various renovation objectives – is not taken into consideration in most retrofitting projects. The results are, therefore, suboptimal renovation solutions, which do not reach the full scope of sustainability for refurbished building(s). The major issue here can be considered through identification of the ultimate holistic values and how the values are added by use of renovation alternatives.

Designing a large-scale complex system, such as development of holistic renovation scenarios, with a focus on sustainability requires a systematic approach toward integrated design of all subsystems (here is referred to the objectives/criteria). Domains such as sociality, identity, spatial quality, energy, and water are all coupled. Designing each one in isolation can lead to sub-optimality where sustainability is achieved in one aspect but at the expense of other aspects.

Developing DSS for generation of sustainable building renovation scenarios is ultimately an intricate, challenging task. The increasing complexity of decision problems regarding to the fulfilment of sustainability objectives/criteria, the growing number of subjects involved and keen competition between conflicting costs and interests make decisions-making difficult. Developing a Domain Mapping Matrix (DMM) enhances the required insight for the development of an operational system for architecture of decision-makings in aforementioned area.

By looking into relevant literature, evaluation of the 10 European renovation research projects, investigation of a real case, and the Danish SIGMA database, a comprehensive list of renovation approaches (i.e. insulation technologies, windows replacement etc.) was expanded and classified in 26 categories. Using empirical information, this section expanded a DMM between the recently developed criteria (18 criteria including 118 sub-criteria) and renovation approaches (26 categories including 139 alternatives).

DMM is used for modeling and analyzing system architecture of complex product development processes. Developing such a matrix specifically for renovation purpose can (1) capture the dynamics between the renovation approaches and the sustainability objectives/criteria, (2) show traceability of constraints across objectives/criteria, (3) provide transparency between the mentioned elements, (4) synchronize decisions across the domains, (5) cross-verify domain models, (6) integrate a domain with the rest of the project, and (7) improve decision making among design team, engineers, and other key stakeholders who are involved in the renovation process by providing a basis for communication and learning across domains.

A major advantage of the DMM that was developed in this section was in its compactness and ability to provide a systematic mapping among its elements (represented in rows and columns) that was clear and easy to read regardless of size. It helped to cope with the existing complexity among its elements due to the broad number of approaches and the various objectives/criteria, which need to be embarked on in a holistic renovation. Consequently, it can be used to demonstrate what the values are (sustainability objectives/criteria), how they can be created (application of renovation approaches), and where the value can be added by generation of the integrated renovation scenarios. That means the DMM can be used for understanding and tracking of the value (or added value) regarding to the other criteria (i.e. spatial quality) while the focus is on optimization of some common criteria i.e., improvement of energy efficiency or reduction of investment cost.

Using the DMM in the body of a DSS for generation of renovation scenarios can help to reduce the number of traditional design iterations as well as to find out about the holistic perspectives of the value and tracking of the added value. In another perspective, it can help to optimize the flow of "data" through the system and identify coupled elements within the system. Optimization of these two objectives can provide a great deal of insight into how a DSS should be structured.

CHAPTER VII
TECTONIC SUSTAINABLE BUILDING DESIGN

CHAPTER'S SYNOPSIS

"The reason for this chapter was discussed earlier in section 1, so as to develop a theory by looking for a pattern of meaning on the basis of the data that thesis has collected so far. Therefore, this chapter recalls the data from previous chapters besides providing further consideration and clarification of some recent renovation research projects, towards proposing a conceptual framework or theory under the topic of Tectonic Sustainable Building Design – TSBD. The TSBD is attached to Tectonics (refers to architectural articulation theory), Sustainability (refers to the holistic objectives/criteria – see chapter 5) and Holistic Multi-methodology in Sustainable Retrofitting - HMSR (refers to the integrated design methodology – see chapter 4). TSBD thinking in the field of building renovation establish a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building, emphasizing on sustainability as the ultimate goal."

9. A short introduction to Tectonic Sustainable Building Design concept for building renovation

9.1. Towards 'Sustainability', 'Tectonics', and a 'Holistic design methodology' for building renovation context

Following the overall investigation of building renovation practice in earlier chapters revealed broad types of challenges and barriers and on the top of this list there were economical issues, technical obstacles, and behavioural barriers. As discussed before, these exist due to the several reasons including variety of stakeholders involved in the process (clients, tenants, contractors, municipalities, consultancies etc. – see section 1.2), massive range of alternative renovation solutions (insulation approaches, window replacement, HVAC systems etc. - see section 8.4.3), and broad number of objectives/criteria [or sub-criteria] (i.e. energy efficiency, spatial quality, investment cost etc. – see chapter 5) that need to be embarked on. Acre et al. (2014) states that the evidence of a holistic renovation influence of an energy renovation (use of pure technically designed renovation scenarios) is that many of the measures taken in energy renovation, which affect architectural quality and social aspects, are not necessarily related to energy concerns (or pure technically designed renovation scenarios). In particular, the substantiation of the objectives/criteria itself is a highly complicated task due to the variety of expectations resulted from a holistic renovation process. Some are considered as engineering issues such as improvement of energy efficiency, and others are addressed as architectural issues such as improving of spatial quality or liveability of the building (Acre et al., 2014). To extend this discussion through broader relevant perspectives, the challenges for building renovation can be categorized through socio-technical, socio-economical and socio-environmental types. This remember us the main traditional three pillars of the 'sustainability development paradigm' including *society*, *economy*, and *ecology* (World Commission on Environment and Development, 1987) and their interfaces. That, in fact, emerges the importance of sustainability objectives and how effectively the complexity mentioned above can be reduced if the essential sustainability objectives/criteria for building renovation are identified and targeted early in the design stage ahead of further investigation and fulfilment.

The significant components to perform the design process of a holistic renovation can rationally be addressed throughout the following questions and their relevant answers:

- *Why to do a renovation?* (key: investigating sustainability objectives)
  Buildings are renovated to make changes. There are a wide array of advantages that can be obtained as an outcome of a holistic and sustainable retrofitting. The motivation for making these changes should embark on sustainability objectives/criteria in its full sense.

- *What to do for renovation*? (key: investigating renovation approaches)
  There are broad ranges of renovation approaches that together build a renovation scenario and can be applied for the renovation of existing buildings.
- *How to develop the renovation scenarios?* (key: investigating design methodologies)
  The renovation design process and selection of the renovation approaches needs to use of an equipped methodology, which is able to deal with the complexity of "soft" and "hard" criteria that are involved in the renovation projects as well as to cope with different decision makers and their different priorities in the design process. Decision making in building renovation is influenced by a number of non-technical stakeholders.

Nevertheless, by accessing to the above answers, the fundamental and in my understanding finest potential of architecture to invite us to be together or to contemplate in solitude by addressing the human scale, what we have chosen to describe as the ability of architecture to 'gesture' us, is oppressed (Hvejsel et al., 2015). In other words, to cope with the "soft" criteria (i.e. identity, spatial, sociality, aesthetic etc.) there must be extra principles to bind and interweave the renovation approaches for generating efficient scenarios. The extent of this improves the "hard" objectives/criteria (measurable criteria such as energy consumption or energy generation), while the generated scenarios affect the "soft" objectives/criteria (immeasurable criteria such as spatial quality) in parallel. It is the question of how a renovation also influence the experience of the built environment (or how to blow a soul into the buildings). Therefore, existing buildings cannot simply be renovated, but must undergo a transformation to comply with these demands holistically. In this perspective, that of conceiving a holistic renovation scenario simultaneously as a technical 'principle' and as a spatial 'gesture' revealing various architectural potential through this transformation is inevitably a *tectonics* question (Hvejsel et al., 2015).

Following the above components results in the development of holistic renovation scenarios. As response to this, this chapter develops a conceptual framework, which serves as a means to unify the platform for strategies for refining and improving the contemporary building industry seen in the light of sustainability, by supporting the decision making in order to develop the most appropriate renovation scenarios. It is entitled Tectonic Sustainable Building Design (hereafter refers as TSBD). The potential of this framework is demonstrated via analysis of a case study including evaluation of 10 European renovation research projects. According to Moseley (2016), European building sector has become decomposed and not yet able to offer efficient solutions for holistic renovation. Developing and promoting TSBD influences the current practice of building renovation significantly. To this end, the research initially provides an individual brief description about *sustainability*, *tectonics*, and an efficient *holistic multi-methodology* concepts, and later, it represents the analysis of 10 European renovation research projects and the results inform the last section where the TSBD is structured.

9.1.1. Sustainability

The term *sustainability* is an autotelic term, which means it is hailed as a priori goal in itself. It can be described as incontestable development of society and economy on a long-term basis within the framework of the carrying inclusion of the earth's ecosystems (UN, 2013). Nevertheless, sustainability development (for further information see section 1.2) refers to a dynamic process from one state towards another that means there is no exact definition about it – nor is this necessary (Butters, 2014). It meets the needs of the present without compromising the ability of future generations to meet their own needs. S*ustainability* is based on the modern information and communication systems (Afgan et al., 2002). As such, it is of special interest to verify the need for the deep understanding of sustainability as the pattern with the agglomerated set of indicators defined by the respective criteria (Afgan, 2010). Today, there is a significant range of methods accessible for appraisement of *sustainability* and its relevant criteria in the market (Haapio et al., 2008). Many of the existing assessment methods and methodologies have been developed for the design of the new buildings, but can be applied renovation projects as well, and some are particularly intended or adapted for building renovation context (Jensen et al., 2015). BREEAM (by British Research Establishment), LEED (by US Green Building Council), ATHENA (by ATHENA Sustainable Material Institute in Canada), BEAT (by Danish Building Research Institute), DGNB (by German Sustainable Building Council), DGNB-DK (by Green Building Council Denmark), BEAM Plus (by Hong Kong Green Building Council), and EcoEffect (by Royal Institute of Technology in Sweden) are some examples of these methods. As argued in section 7.2, most of the methods and tools that mentioned above have a narrow environmental or energy focus, whereas the most recent tools attempted to evaluate environment, economy and social relations in an equal circumstances i.e., DGNB-DK (for further information about the sustainability assessment methods and methodologies see chapter 5).

9.1.2. Tectonics

The term tectonic derives from the Greek word 'tekton', which signifies a carpenter or builder, and has gradually come to denote construction in general (Frampton, 1995). The poetic connotation of the term first appears in Sappho (in the seventh century BC) where the 'tekton' [the carpenter] assumes the role of the poet. This meaning undergoes further evolution as the term passes from being something specific and physical, such as carpentry, to a more generic notion of making, in the poetic sense. Sekler (1964) describes it as "the noble gesture which makes visible a play of forces, of load and support in column and entablature, calling forth our own empathetic participation in the experience" (Sekler, 1964, p. 93). In this description, the author has established a link between a 'structural concept' and how it influences the experiencing subject through spatial 'gestures' once the structural principle is manifested, or realized, through concrete 'construction'. Hvejsel et al. (2015) propose that Sekler's terms can be used as a vocabulary to articulate not 'only' the "visible play of forces", but the implications of technical interventions on the perceived spatial quality in a broader sense. In this explanation, *tectonics* can be referred as the art of construction. According to Beim (2004), Tectonic Visions in Architecture is discussed as "visionary investigations into new materials, technologies, structures, and practices of construction, as means to construct (new) meaning in architecture". In connection to this, Nilsson (2007) argues that the full *tectonics* potential in every building comes, according to Frampton (1995), from its capacity to articulate both the poetic and the cognitive aspects of its substance. Frampton (1995) makes, with reference to Semper's (2004 [1861]) distinction between symbolic and technical aspects of building, an interesting distinction between the representational and ontological aspects of *tectonics* form. Nilsson (2007) states that, this dichotomy is something in constant need of reformulation in the creation of architectural form, since every building type, technology, topography and temporal circumstances give different cultural situations and conditions. Concentrating on “poetry” characteristic of architecture, Christiansen (2015) defines *tectonics* as a fusion between the expression of form and the way it is created. The author states that when materials are processed with adequate technical awareness and insight, it is possible to create a specific form that communicates something that cannot possibly be communicated in any other way – whatsoever (Christiansen, 2015).

9.1.3. Holistic design methodology

The word ‘methodology’ was originally used to describe ‘the science of method’, which technically makes the concept of ‘a methodology’ meaningless. However, Checkland (2000) distinguishes this traditional meaning of ‘a methodology’ towards a new one including different sets of principles. He addressed ‘methodology’ as a body of methods used in a particular activity (Checkland, 2000: p 26). Following the later definition, this was discussed further in section 6.4. Building renovation can be regarded as a problem-solving activity terminated by a solution deemed satisfactory. In doing so, there are various stakeholders who are involved in the process, the sustainability objectives/criteria (including “soft” and “hard” criteria) are considered, targeted and evaluated, and ultimately an appropriate renovation scenario is developed. To succeed in this field, an efficient integrated design methodology is required that can cope with complexity of the mentioned components.

9.2. Analysis of 10 European building renovation research projects

The building renovation process usually involves multiple separated disciplines, which leads to additional costs and risk of failure. Many customers see high operating costs and poor environment as an acceptable alternative to the time-consuming, disruptive and risky renovation process. Despite remarkable number of recently finished or yet ongoing renovation research projects, Moseley (2016) argued that the European building sector has become fragmented and not yet able to offer holistic solutions for deep renovation at acceptable cost and quality. For this reason, a list of 10 recent European building renovation research projects have been analysed (see Table 9.1). The aim is to evaluate what and why the recent researches have been established and targeted. It leads to realize about possible gaps regarding their outcomes for the future of the renovation field in practice. It should be highlighted that despite the mentioned reasons of performing the analysis in this section, it has also been used for development of a comprehensive renovation approaches in chapter 6.

As also described in section 8.4.3.1, the above research projects have been selected due to their scale, history, the involved countries, and their funding that underlines their importance (for further information about the selected research projects see Table 8.3). The analysis demonstrates that the first priorities in almost all of the projects are about energy efficiency and cost, which is good but not enough. The amount of dealing with the variety of renovation approaches is promising. However, only one project is included the validation and verification of the selected scenarios after construction process. There is no “soft” criteria such as spatial quality in their agendas. None of the projects considers the design process for generating renovation scenarios and so no description to cope with the various stakeholders, which are involved into the process. As it can be resulted from the analysis, none of the projects deals with the *sustainability* in its full sense. Despite producing good results from the mentioned projects (i.e. development of digital tools by two of the projects), the issue regarding to real practice of European building renovation sector can still not be addressed comprehensively. This calls for new actions including research about converging and combining the outcomes out of the analysed projects in Table 9.1 and other projects. It should include broad perspectives, hereafter, demonstrate them under a unified and simplified platform. The platform should contain the objectives and be able to communicate them to the stakeholders. It then can help them to achieve a successful sustainable renovation, consequently. Developing a platform or conceptual frameworks such as TSBD, can ultimately influence and enhance real practice of the building renovation.

Table 9.1. Analysis of 10 European building renovation research projects

Project Name	Renovation level			Renovation project phase											Building function			Case study evaluation (renovation)	Focus on specific climate zone	Focus on building elements for renovation	Major considered criteria									Development of a digital tool
	Moderate	Deep	NZEB	Energy auditing and Renovation	Identification of the renovation actions (level of details): Low	Identification of the renovation actions (level of details): Moderat	Identification of the renovation actions (level of details): High	Identification of the renovation actions (level of details): Very high	Enhancement of renovation actions	Creation of renovation actions	Generation of renovation scenarios	Site implementation	Validation and Verification	Monitoring	Residential buildings	Public/Commercial/Office buildings	Historical buildings				Energy consumption	Renewable energy	CO2 emission	Water consumption	Indoor comfort	Payback period	Cost	Occupant behaviour	Renovation process	
iNSPiRe		+		+		+			+	+	+	+		+	+	+		+	+	+	+	+	+		+		+			
EcoShopping						+										+					+	+			+		+			
HERB		+			n/a	n/a	n/a	n/a	+	+	+	+		+	+			+		+	+	+	+			+	+			+
REFURB		+	+		n/a	n/a	n/a	n/a			+	+	+		+			+			+		+				+	+	+	
READY			+			+				+				+	+	+			+	+	+	+	+	+			+		+	
3ENCULT				+			+		+		+			+			+	+			+				+				+	
MORE-CONNECT		+	+			+				+					+	+	+			+	+				+					+
BuildHeat	+				+				+	+	+				+			+		+	+							+	+	
NeZeR	+	+	+			+			+	+					+			+	+		+	+					+		+	
RePublic_ZEB			+	+				+	+	+	+					+		+	+	+	+	+	+				+		+	

9.3. Tectonic Sustainable Building Design - TSBD for building renovation

Looking at a project holistically for potential energy savings means using an integrated design process. It is then developing a design process, which explores the interdependency between different building elements and renovation goals towards achieving a holistic sustainable renovation

(International Energy Agency-IEA task 23)[1]. Identifying and targeting the sustainability objectives/criteria and renovation approaches is therefore a key point in this process. In addition, how a renovation also influence the experience of the built environment should not be downgraded that is the question of *tectonics* theory of architecture. In this framework, for developing the TSBD:

Sustainability is considered as the most desired value for renovation of the existing building stock. For expanding of the holistic sustainability objectives/criteria in building renovation, I refer to the list of the 18 criteria (see section 7.4.2), which were developed in chapter 5 by use of Soft Systems Methodologies - SSM (Checkland, 2000) and Value Focused Thinking (Keeney, 1992).

Tectonics theory of architecture is used to articulate a linkage between technically motivated alterations and the spatial experience of a building for renovation purpose. In order to expand the *tectonics* principles for this reason, the recent studies by Jensen et al. (2017b) about development of a vocabulary between 'technical concept', 'construction', and 'spatial gestures', together with study by Hvejsel et al. (2015) about development of a tectonic approach to energy renovation in a Danish context, have been used. Both the studies have re-read the *tectonics* theory throughout the spatial and methodological conceptions of the term that is specific to, and link, the works of Semper (2004 [1861]), Sekler (1964), and Frascari (1984). They conclude that *tectonics* holds the potential to equip us with a detailed spatial view and in depth structural understanding of buildings, which can be considered significantly fitted for building renovation projects.

Holistic Multi-methodology for Sustainable Renovation - HMSR is attached to a holistic multi-design methodology for development of the renovation scenarios. For expanding its mechanism I refer to the study which was done in chapter 4. The study in chapter 4 was wrapped up by producing a multi-methodology, based on a mix of SSM and Multiple Criteria Decision Making – MCDM (Triantaphyllou et al., 1998) methods, which includes 23 steps/actions. The part of HMSR also proposes application of a Decision Support Systems – DSS (see section 8.3) for generation of the renovation scenarios concerning "hard" criteria towards addressing "soft" criteria in the next steps. As such, the HMSR (see Table 6.4) can serve as a means to structure retrofitting problems in accordance with the *sustainability* in its totality to support the decision-making and help to develop and select the most appropriate retrofitting alternatives. It was structured in three levels (see Figure 9.1) and the decision-making on third level was considered as the integrated design process implementation and evaluation for sustainable renovation and entitled *scientific decision-making*.

[1] http://task23.iea-shc.org/integrated-design-process

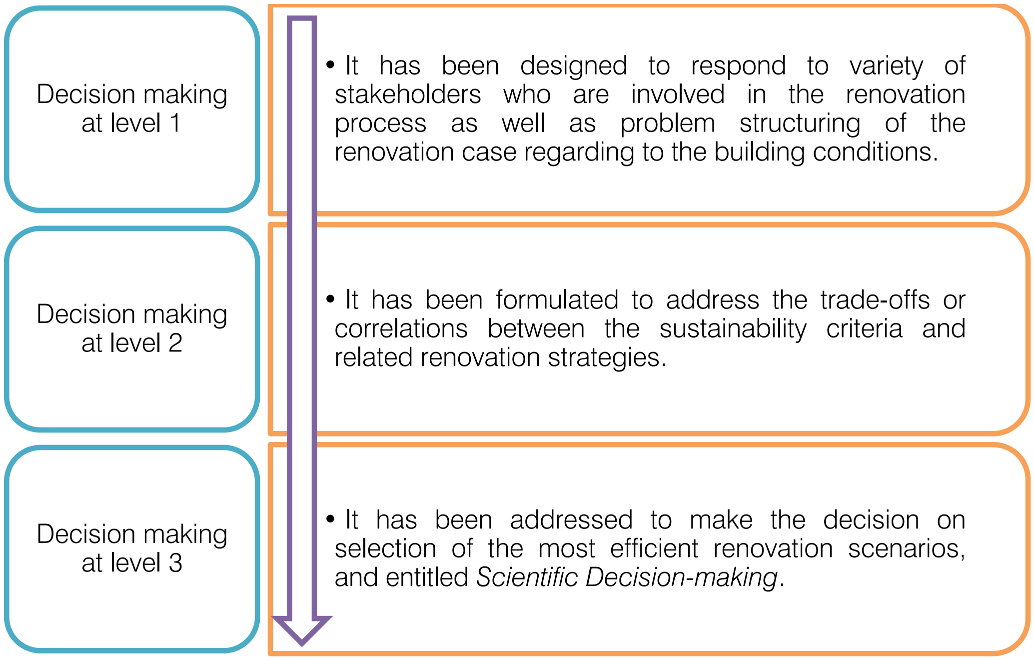


Figure 9.1. Three levels of decision-making for building renovation (for further information about the levels see chapter 4)

To some, it may be difficult to recognize the correlation between *sustainability* and *tectonics* in building renovation. For more clarification on synthesizing the concept of *sustainability* with *tectonics,* the research “Towards a Tectonic Sustainable Architecture” by Danielsen et al. (2012) which explores “Can tectonic thinking form a basis for new strategies for contemporary sustainable building practices?”, is propounded and unfolded. Danielsen et al. (2012) considered that in what manner the paradigm of *sustainability* influences the realm of the *tectonics*. They started to unpack architecture using an ancient theory by Marcus Vitruvius Pollio (in the first century AD) including firmitas (durability), utilitas (utility), and venustas (delight). In this framework, the authors defined two principles of *tectonics* with reference to Semper (1851) as 1) a result of conscious artistic work and 2) the material properties and the design of constructions, whereas the functional dimensions of architecture are paid less attention (according to Beim, 2004). However, they stated that Semper’s downsizing of functional aspects is important to be aware of when approaching the research-question stated above, which concerns how *tectonics* may affect sustainable solutions (also being functional). Consequently, *tectonics* thinking was defined as “a central attention towards the nature of the making, and the application of building materials (construction) and how this attention forms a creative force in building constructions, structural features and architectural design (construing) – can be used to identify and refine strategies for improving a contemporary sustainable building industry” (Danielsen et al., 2012, p. 12). This demonstrates the value of using *tectonics* for articulation of architectural principles to perform a building renovation alongside with sustainability objectives/criteria. In our understanding, however, the authors’ view about *sustainability* in the research by Danielsen et al. (2012) is not comprehensive enough. For TSBD framework presented in this thesis (see Figure 9.2), as stated earlier, *sustainability* is referred to the criteria developed in chapter 5, similar to Butters (2014), International Living Future Institute (2014), or SPeAR by Arup (2012) including more holistic objectives/criteria. That makes the *sustainability* in TSBD framework as the most desired and ultimate value, for issuing out the objectives/criteria in the design process towards application of certain renovation approaches to achieve them. Subsequently *tectonics* principles tailors them into each other. The result enhances both "hard" and "soft" objectives/criteria of renovation in parallel. Finally yet importantly, it is use of an efficient design methodology (here refers to use of HMSR that was developed in chapter 4 of the thesis) that eventually makes it all possible.

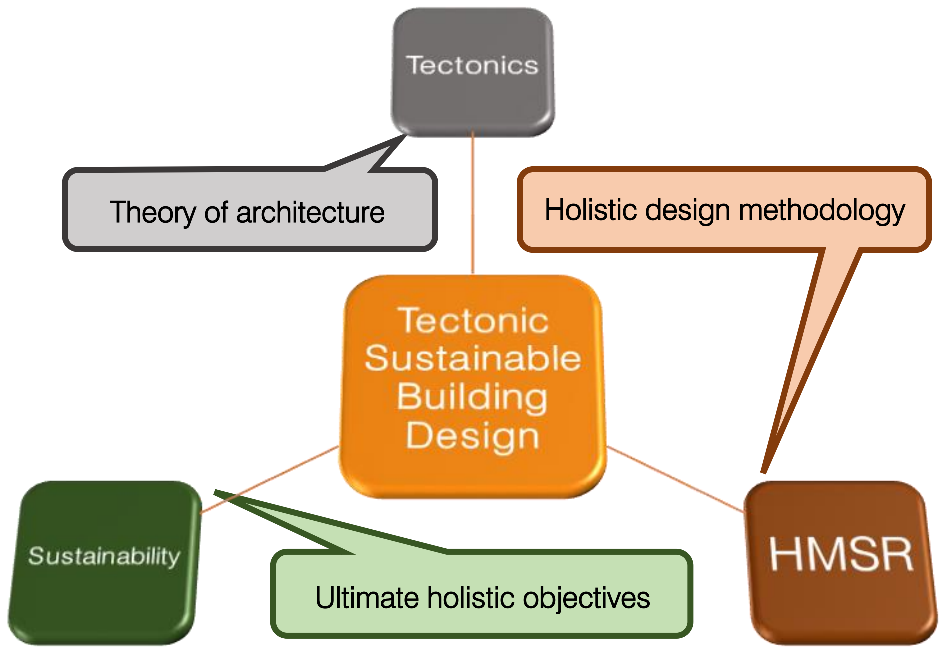


Figure 9.2. Tectonic Sustainable Building Design conceptual framework for building renovation

9.4. Summary

Investigation of the 10 European renovation research projects in this section demonstrated that the recent researches in this field are still being centralized on certain measureable objectives i.e., energy efficiency; whereas the more aesthetic or identical or social unquantifiable but essential, dimension of architectural theories as a spatial 'gesture' is hard to position within this context.

According to the result of this investigation together with the recent researches about the current practice of building renovation, it became evident that many of renovated buildings, which are claimed to be sustainable, are not alongside with sustainability objectives/criteria in its full sense.

Lastly, there was considered a lack regarding to the understanding, positioning and necessity of using an equipped design methodology to include the stakeholders (i.e. architects, engineers, clients) in order to meet all the requirements through the lens of tectonic architectural theory as well as fulfilment of various objectives which are derived into the project from sustainability perspectives.

In order to address these mentioned issues and layers detectable in the practice of building renovation today, the present section proposed a conceptual framework under the topic of Tectonic Sustainable Building Design which is attached to Tectonics (refers to architectural articulation theory), Sustainability (refers to the holistic objectives/criteria – see chapter 5) and Holistic Multi-methodology in Sustainable Retrofitting - HMSR (refers to the integrated design methodology – see chapter 4).

- *Tectonics* in TSBD holds the potential to equip us with a detailed spatial view and in depth structural understanding of buildings, which can be considered significantly fitted for building renovation projects.
- *Sustainability* in TSBD was considered as the most desired value for renovation of the existing building stock, referring to the list of the 18 criteria (see section 7.4.2), which were developed in chapter 5
- HMSR in TSBD was attached to a holistic multi- design methodology for development of the renovation scenarios linking to the study, which was done in chapter 4.

By focusing on Tectonic Sustainable Building Design thinking in the field of building renovation, one forms a strategy of establishing a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building.

It can serve as a means to unify the platform for strategies for refining and improving the contemporary building industry seen in the light of sustainability, by supporting the decision making in order to develop the most appropriate renovation scenarios.

It is worth noting that, development of the mentioned conceptual framework in this section, led to recap the outcomes of previous section as well.

CONCLUSION & FURTHER RESEARCH

CHAPTER'S SYNOPSIS

"This chapter brings together the overall findings of the thesis. It firstly covers a short summary of the previous chapters, which were provided at the end of the sections. Then, it discusses the contribution of the thesis particularly to its research questions and suggests directions for further research."

10. Conclusion & Further research

The thesis was entitled "A multi-methodology and sustainability-supporting framework for implementation and assessment of a holistic building renovation" and to finish, it has included 7 chapters consisting of 10 sections. In the present section, firstly I will provide a summary of the of the previous sections and their contributions to the thesis. In the following and as a conclusion, I quote the research questions from chapter 1 and subsequently discuss the contributions of the research work in thesis to each one, separately. The reason for designing these questions in chapter 1 was argued due to structuring and developing the research work, systematically. Addressing the conclusion by discussing the contribution for each research question, will therefore leads to form a comprehensive and at the same time systematic fashion of providing the research outcomes, which have been carried out in the thesis.

10.1. Summary of the previous sections and their contributions to the thesis

Summary of Section 1

This section provided details about the major components of the thesis including research topic, state of the art, research objectives and questions, and the research methodology that has been used for carrying it out.

The renovation problem in this regard was identified related to necessity of cultural changes, technological/physical changes. The word Holism was assigned for the combination of this spectrum of changes which needs to be performed in renovation field. To deal with Holism, the main objectives and relevant questions that the research should perform have been developed.

The main objectives were outlined as a) development of a holistic multi-methodology for development of renovation scenarios (HMSR), b) development of a sustainability framework for building renovation, c) development of a Domain Mapping Matrix (DMM) for further analysis of renovation components, and d) proposing a theory to unify the platform for strategies for refining and improving buildings seen in the light of sustainability, by supporting the decision making in renovation context (TSBD).

The research study called for an inductive approach. Moreover, the research methodology was introduced through use of qualitative research approach, and the inter- or transdisciplinary research throughout mode 2.

Summary of Section 2

This section provided a brief description about the theme of building renovation/retrofitting. The intent in this coverage was both for background and review purposes. In doing so, an appreciation was gained for building renovation context such as benefits and barriers in broader perspectives.

The intervention in renovation identified that can be divided in three levels:

a) urban fabric that deals with the effects the renovation process produces(methods) on the form of the city, the correlation between public and private regions and areas, on the quality of the built environment;
b) building blocks itself that deals with the renovation/retrofitting proceeding pursued according to very particular conditions which depend on the building's pathologies, the requirements to be faced, the level of performance to be accomplished;
c) building units that deals with the alternations entailed by the households in order to meet their preferences or their requirements.

There are also a broad range of renovation approaches that can be applied for the renovation of existing buildings including insulation approaches, replacement of existing windows, integration or replacement of existing equipment etc.

The 5 key phases in development of renovation strategies were stated as Identifying Key Stakeholders & Information Sources; Technical & Economic Appraisal; Policy Appraisal; Drafting & Consulting on the Renovation Strategy; Publication & Delivery.

The impacts of undertaking a holistic sustainable renovation were described through a) Energy System Benefits, b) Environmental Benefits, c) Societal Benefits, and d) Economic Benefits. The main barrios also were appreciated through ‘financial’, ‘institutional & administrative’, ‘awareness, advice & skills’ and ‘separation of expenditure and benefit’.

Summary of Section 3

This section provided an overview about engineering design, and systematic design approaches through identifying the principles of systems theory and thinking, which is currently employed in other domains such as ‘industrial design’ and ‘mechanical design’. The intent in this broad coverage has been both for background and review purposes. It is hoped that in doing so, an appreciation has been gained for engineering design and the approaches that have been investigated to provide more details about its methods.

A systematic design methodology should allow for a problem-directed approach and foster inventiveness and understanding. It has to compatible with the concepts, methods and findings of other disciplines. It should not rely on finding solutions by chance and it should facilitate the application of known solutions to related tasks. A design methodology should be compatible with electronic data processing, be easily taught and learned and lastly reflect the findings of cognitive psychology and modern management science; i.e. reduce workload, save time, prevent human error, and help to maintain active interest.

Contrary to ideal models of design processes, complex problems are not 'solved' in abstraction and then passed on to a more detailed level of design. In addition to evaluating feasible functional alternatives, other factors such as cost, size, availability, quality, assembly, the age of the technology, and numerous other life-cycle factors require consideration early in decision processes.

Systems theory and thinking Engineering Design realm from provides methods from, which are relevant for approaching a holistic building design. Particularly, the existing complexity in the problems of building design are similar to problems of systems theory in the following areas:

- specialization form disciplines are involved (interdisciplinarity),
- there are a number of objectives which need to be met,
- many objectives may rule out each other,
- a solution might partly define a problem.

Using systemic approaches through an adaptive procedure consisting of the iterative cycles enables us to capture and address the complexity of the concepts towards considering cause-effect relationships of decisions where the new actions and decisions needs to be taken. Hereafter, the designer will be on the way primarily to integrate various disciplines of knowledge such as social issues beside financial barriers to create seamless frame of understanding of everything.

Summary of Section 4

The discussion overviewing decision-making and Multiple Criteria Decision Making (MCDM) has covered a variety of topics. The intent in this coverage has been both for background and review purposes. It is hoped that in doing so, an appreciation has been gained for MCDM and it various methods and approaches.

Clearly, the context in which a MCDM method is used, improves the efficiency of decision-making with multiple criteria and usually conflicting criteria. Similarly, MCDM provides methods, which are relevant to cope with various criteria in building design. Particularly, the existing criteria in the problems related to sustainability for building design are similar to problems of MCDM where the criteria from different perspectives including society, economy and ecology are involved into the design process.

Almost certainly, no one can distinguish between the MCDM methods, in the way to identify the foremost method since their various capabilities are different when they face a problem. It is essential that a few different MCDM methods are applied to get the validity in MCDM methods is verified. It is believed that the results obtained by the aggregation methods are more rational and more aggregation methods will aid in the decision-making related to sustainability in the future.

It was observed that Pairwise comparison, AHP and TOPSIS are the most popular comprehensive method due to their mechanism, understandability in theory, and the simplicity in application in multi-criteria decision-making problems.

Summary of Section 5

This section provided a consideration about the essence of complexity in the building design process. The systematic approaches through an adaptive procedure consisting of the iterative cycles were identified suitable for building design process. It can be underlined that the job of building designer in new age movement has to turn more into the orchestration of ecosystems and environments in order to achieve their overall functionality by seeking an equilibrium between the different objectives comprehensively.

Summary of Section 6

This section initially explored the decision-making process in renovation context using either MADM or MODM methodologies. Thereafter, it addressed the notion of 'methodology' and 'design methodology'. In this consideration, methodology was indicated as a body of methods used in a particular activity. Methodologies and their differences between design and science contexts were also appreciated. In this consideration, "Operation Research" was found as a Scientific Design concept and "Systems theory and thinking" as a Design Science concept.

Further, following the previous chapter of the thesis (chapter 2 and 3), I briefly discussed SSM, MCDM, and usefulness of the mix of these two. Based on the characteristics of the renovation problem, consequently, this section produced a multi-methodology, using a mix of SSM and MCDM methods entitled HMSR. The HMSR was structured in three levels including 23 steps. It can serve as a means to structure retrofitting problems in accordance with the sustainable paradigm to support the decision-making and help to develop and select the most appropriate retrofitting alternative.

A case study was introduced as a means to demonstrate how the HMSR could be applied in practice. The case exemplified the complexity of renovation processes due to i.e. involvement of a large number of stakeholders, with different priorities spanning both "soft" and "hard" criteria. The case study aimed to demonstrate how the HMSR could potentially help overcome this complexity by suggesting a mix of activities and methodologies from SSM and MCDM in a unified multi-methodology.

Summary of Section 7

This section by overviewing existing sustainability evaluation methods and methodologies, included the development of a new simplified (in terms of application and representation) holistic sustainability decision-making support framework which applies to the structures of the built environment regarding to building renovation. The procedure for development of the framework has been a consensus-based process. In order to develop, the research employed a multi-dimensional research strategy that involves a variety of approaches including literature review; exploration of some well-known existing assessment methodologies; conducting individual and focus group interviews; and eventually it included the application of SSM with VFT to problem of knowledge management in building renovation, as a complex issue, challenging from case to case and difficult to act upon. The outcomes were validated using two rounds Delphi study.

The framework has been divided into the two parts. The external/outer part (the Characteristic Diagram) which can be used for the collection of the required data on pre-design or start-up phase of the retrofitting projects; and the internal/inner part (that is the main part of the developed framework) works as Value Map.

The developed sustainability Value Map for building renovation consisting of three categories – Functionality, Accountability, and Feasibility – with a total of 18 sustainable value-oriented criteria and 118 sub-criteria. The major part of the criteria in the Functionality category are quantifiable while the qualitative criteria have been listed in other category named Accountability. From other side, Feasibility category contains a mix of quantitative (i.e. cost criteria) and qualitative criteria such as advantages in using an efficient renovation process where it influence the key stakeholders.

The framework can both be utilized as a holistic sustainability framework to audit, develop and assess building renovation performance, and support decision-making during the project's lifecycle. It is a holistic sustainability decision-making framework to support the development of renovation projects and communicate the outcomes with relevant stakeholders. Early in a project, it can be used to identify key performance criteria, and later evaluate/compare the pros and cons of alternative retrofitting solutions either during the design stage or upon the project completion.

Summary of Section 8

This section investigated the development of a Developing Decision Support Systems (DSS) for generation of renovation scenarios. It is ultimately an intricate, challenging task. The increasing complexity of decision problems regarding to the fulfilment of sustainability objectives/criteria, the growing number of subjects involved and keen competition between conflicting costs and interests make decisions-making difficult. Developing a Domain Mapping Matrix (DMM) enhances the required insight for the development of an operational system for architecture of decision-makings in aforementioned area.

By looking into relevant literature, evaluation of the 10 European renovation research projects, investigation of a real case, and the Danish SIGMA database, a comprehensive list of renovation approaches (i.e. insulation technologies, windows replacement etc.) was expanded and classified in 26 categories. Using empirical information, this section expanded a DMM between the recently developed criteria (18 criteria including 118 sub-criteria) and renovation approaches (26 categories including 139 alternatives).

DMM is used for modeling and analyzing system architecture of complex product development processes. Developing such a matrix specifically for renovation purpose can (1) capture the dynamics between the renovation approaches and the sustainability objectives/criteria, (2) show traceability of constraints across objectives/criteria, (3) provide transparency between the mentioned elements, (4) synchronize decisions across the domains, (5) cross-verify domain models, (6) integrate a domain with the rest of the project, and (7) improve decision making among design team, engineers, and other key stakeholders who are involved in the renovation process by providing a basis for communication and learning across domains.

A major advantage of the DMM that was developed in this section was in its compactness and ability to provide a systematic mapping among its elements (represented in rows and columns) that was clear and easy to read regardless of size. It helped to cope with the existing complexity among its elements due to the broad number of approaches and the various objectives/criteria, which need to be embarked on in a holistic renovation. Consequently, it can be used to demonstrate what the values are (sustainability objectives/criteria), how they can be created (application of renovation approaches), and where the value can be added by generation of the integrated renovation scenarios.

Summary of Section 9

Investigation of the 10 European renovation research projects in this section demonstrated that the recent researches in this field are still being centralized on certain measureable objectives i.e., energy efficiency; whereas the more aesthetic or identical or social unquantifiable but essential, dimension of architectural theories as a spatial 'gesture' is hard to position within this context.

To deal with the issues, the present section proposed a conceptual framework under the topic of Tectonic Sustainable Building Design which is attached to Tectonics (refers to architectural articulation theory), Sustainability (refers to the holistic objectives/criteria – see chapter 5) and Holistic Multi-methodology in Sustainable Retrofitting - HMSR (refers to the integrated design methodology – see chapter 4).

- Tectonics in TSBD holds the potential to equip us with a detailed spatial view and in depth structural understanding of buildings, which can be considered significantly fitted for building renovation projects.
- Sustainability in TSBD was considered as the most desired value for renovation of the existing building stock, referring to the list of the 18 criteria (see section 7.4.2), which were developed in chapter 5
- HMSR in TSBD was attached to a holistic multi- design methodology for development of the renovation scenarios linking to the study, which was done in chapter 4.

By focusing on Tectonic Sustainable Building Design thinking in the field of building renovation, one forms a strategy of establishing a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building.

It can serve as a means to unify the platform for strategies for refining and improving the contemporary building industry seen in the light of sustainability, by supporting the decision making in order to develop the most appropriate renovation scenarios.

10.2. Conclusion

10.2.1. Thesis contribution to Research Questions 1

The RQ1 was formed as: *How can a design methodology for sustainable retrofitting be developed and equipped via mixing methods from Engineering Design and Decision-making realms?*

A review of the barriers for building renovation in chapter 1 revealed a lack of methodologies, which can promote sustainability objectives and assist various stakeholders during the design stage of building renovation/retrofitting projects. To this end, the thesis explored the notion of complexity in building renovation. It identified retrofitting as a highly complex and socio-technical system and subsequently investigated and addressed the concept of *Holism* for it. In this regard, the thesis in section 5 explored systematic approaches through an adaptive procedure consisting of iterative cycles are suitable for future of building design process. It was identified that following the mechanisms and principles of the methodologies and methods which exist in other domains, can enable us to deal with the essence of complexity in the new age movement and building design process.

Focusing on the structured problem in chapter 1 to address *holism*, the consideration in chapter 2 revealed that using Engineering Design methods through use of systems theory and thinking (particularly use of SSM) for building renovation context could be a way to develop an integrated design process, capable of dealing with the complexity, to capture and communicates it among the key players/decision makers/stakeholders, including non-expert decision makers and occupants. In general, application of SSM in a renovation context was considered appropriate to deal with the society, because, it promotes an appropriate way of problem structuring, group decision-making and group learning, and hence it encourages discovering of the knowledge and improvement of the learning about sustainability goals among the stakeholders towards supporting the design decision making in building renovation process.

Similarly, the consideration in chapter 3 represented that using Decision-making methods (particularly use of MCDM) for building renovation context can be a potential way to deal with evaluation of multiple conflicting criteria in decision-making processes when selecting the most appropriate renovation scenarios/packages. In addition, it corresponds to resolve the trade-off between criteria (typically based on the preferences of a decision maker) when a solution performs well in all criteria.

In the followings, the thesis explored decision-making processes and frameworks in building renovation context, which identified a need for introducing three different decision-making levels to help stakeholders in the renovation process to discuss their project “on the same level” and make transparent decisions in a rational order. Therefore, two decision-making framework were developed, and the decision at the third level of the second framework concentrating use of MODM (Multiple Objective Decision Making) was considered as a scientific design approach for building renovation context. Ultimately, it wrapped up by presenting a multi-methodology, based on a mix of SSM and MCDM methods, which can serve as a means to structure retrofitting problems in accordance with the sustainable paradigm to support the decision making and help to develop and select the most appropriate retrofitting alternative.

It is the main aim of the research that the proposed HMSR, through a ‘proactive’ approach, can help consultancy companies and housing associations, or even municipalities, to deal with the increased complexity and wicked nature of building renovation. Further, it is the aim that the proposed HMSR can address issues related to both *cultural* changes (subjects to essence of various stakeholders, and above all, behavioral barriers to improve the building occupants’ learning about the sustainability and the sustainable living) and *technological/physical* changes (subjects to physical and/or technological changes to the building to promote sustainability in a holistic sense) simultaneously. Application of MCDM beside SSM in the Architectural domain can be considered as the novelty in this study, and the intention is to promote such methodologies in order to deal with the interdisciplinarity and transdisciplinary characteristics of the problems in this domain.

The society in our world today, has become more responsive, more adaptive and dynamic, and in cyber-physical perspective is creating the internet of things. Therefore, further development of this world does not follow our traditional design and engineering processes but results in a more organic model. It should be underlined that the job of a building designer in new age movement has to turn more into the orchestration of ecosystems and environments in order to achieve their overall functionality by seeking an equilibrium between the different objectives comprehensively. Therefore, new approaches to building design, and the methods and tools that support them, must be preceded by new ways of imagining and thinking. The complexity of issues within the domain should be explored through broader perspectives and hence the traditional design approaches should be re-considered and equipped to become enabled to deal with its level of complexity and multifaceted nature. The buildings should be considered not as the sum of single technical interventions in a reductionist line of thinking, but as a whole, which specifically requires of adaptation into the process.

10.2.2. Thesis contribution to Research Question 2

The RQ2 was formed as: *What are the main holistic objectives/criteria and sub-criteria for a sustainable retrofitting in terms of their specific change requirements*?

Addressing this question included the development of a new simplified (in terms of application and representation) holistic sustainability decision-making support framework, which applies to the structures of the built environment regarding to building renovation. It can both be utilized as a holistic sustainability framework to audit, develop and assess building renovation performance, and support decision-making during the project's lifecycle. It is a holistic sustainability decision-making framework to support the development of renovation projects and communicate the outcomes with relevant stakeholders. In order to develop the framework, the thesis employed a multi-dimensional research strategy that involves a variety of approaches including literature review; exploration of some well-known existing assessment methodologies; conducting individual and focus group interviews; and eventually it included the application of SSM with VFT to problem of knowledge management in building renovation, as a complex issue, challenging from case to case and difficult to act upon. The outcomes were validated using two rounds Delphi study.

As the result of developing this new framework through series of interviews, workshops, meetings, conferences and reviewed literature, it might be concluded that present takes on sustainability objectives fulfilment in this area (the building renovation) is not holistic enough and not examining the greater chain of effects. Intelligibly there is a lack of systems thinking in this context, though, we need to examine new thinking approaches to illustrate it more holistic with much more integrity and awareness of different stakeholders and their priorities within a building renovation. It is the roadmap to overcome such complex problems, which can be obtained only if we succeed in amplifying trans-disciplinary or multi-disciplinary perspectives. Therefore, the focus in this context must be shifted from a technical evaluation to sustainability – from eco-technology to the whole picture. As such, if the goal is further sustainable development paradigm, it entails developing integrated design processes and assessment methodologies besides holistic decision support frameworks.

10.2.3. Thesis contribution to Research Question 3

The RQ3 was formed as: *What are the major elements for development of a Decision Support System (DSS) and generate holistic renovation scenarios*?

Designing a large-scale complex system, such as development of holistic renovation scenarios, with a focus on sustainability requires a systematic approach toward integrated design of all subsystems (here is referred to the objectives/criteria). Domains such as sociality, identity, spatial quality, energy, and water are all coupled. Designing each one in isolation can lead to sub-optimality where sustainability is achieved in one aspect but at the expense of other aspects. The studies for this research question investigated the development of a DSS for generation of renovation scenarios with the aims to represent and navigate across existing dependencies between its elements. As such, the renovation sustainability objectives/criteria and the renovation approaches were discovered, explored and structured through development of a DMM (Domain Mapping Matrix). The list of comprehensive renovation approaches was expanded by looking into relevant literature, evaluation of the 10 European renovation research projects, investigation of a real case, and the Danish SIGMA database. A major advantage of the DMM that was developed in this study was in its compactness and ability to provide a systematic mapping among its elements (represented in rows and columns) that was clear and easy to read regardless of size. It helped to cope with the existing complexity among its elements due to the broad number of approaches and the various objectives/criteria, which need to be embarked on in a holistic renovation. It hence identified the most effective renovation approaches as well as the most affected objectives/criteria. Consequently, it can be used to demonstrate for what the values are (sustainability objectives/criteria) in building renovation context, how they can be created (application of renovation approaches), and where the value can be added by generation of the integrated renovation scenarios (use of the DMM).

Using the DMM in the body of a DSS for generation of renovation scenarios can help to reduce the number of traditional design iterations as well as to find out about the holistic perspectives of the value and tracking of the added value. In another perspective, it can help to optimize the flow of "data" through the system and identify coupled elements within the system. Optimization of these two objectives can provide a great deal of insight into how a DSS should be structures.

10.2.4. Thesis contribution to Research Question 4

The RQ4 was formed as: *How can the interaction between architecture, sustainability objectives and an equipped design methodology be addressed through development of a conceptual framework?*

Addressing this question set out the findings regarding to the evaluation of 10 European renovation research projects into development of a conceptual framework under the topic of TSBD - Tectonic Sustainable Building Design. TSBD seeks for interaction between architecture, sustainability objectives and an equipped design process. It is therefore attached to the *tectonics* (refers to architectural articulation theory), the *sustainability* (refers to the holistic objectives), and a *holistic multi-methodology* - HMSR (refers to the integrated design methodology). By focusing on TSBD thinking in the field of building renovation, one forms a strategy of establishing a link between the intentions embedded in the architectural transformation and the way these are perceived by the user/owner of the building, what refers as articulation of architecture theory by using tectonics principles. It hence influences the experience of the built environment in human scale. Furthermore, it can serve as a means to unify the platform for renovation strategies for refining and improving the contemporary building industry seen in the light of sustainability, and supporting the decision-making ahead of developing renovation scenarios as holistically as possible. Above all, it provides a clear focus in the design process and a common language among the stakeholders who are involved in the process, which leads to improve the current practice of renovation.

10.3. Further research

10.3.1. Future research work about contribution to Research Question 1

The concept of HMSR needs further development, including more explicit examination upon recent developed SSM and MCDM techniques. In this thesis, I have explored that the retrofitting context may benefit from using a mix of methods, but in order to utilize the full potential of this concept, it needs to be practiced in different circumstances. The application of MCDM methods including MADM or MODM, and how they affect the developed HMSR, can be studied further as well. Moreover, future studies can concern the development of a conceptual framework of a possible Decision Support System (DSS) using MODM.

10.3.2. Future research work about contribution to Research Question 2

According to the procedure of consensus-based process for the development of an effective sustainability decision-making framework that applied for this thesis, this study also provides an outset step intended for the establishment of a sustainability decision support and assessment tool suited to building renovation context. It therefore needs further developments including the assessment items and benchmarks (Lee, 2012; Lee et al., 2008) as well as software. It is worth noting that there is a huge potential in order to consider and develop such a decision-making framework further into the areas including Generative Design Systems, Computational Design, Performative Architecture, Decision Support System (DSS), and ultimately Building Information Modelling (BIM) as cutting edge technologies today (Ahmad et al., 2017; Jalaei et al., 2014; Whalley, 2005).

10.3.3. Future research work about contribution to Research Question 3

A complete modeling system, which can detect any system in its complexity, is called multiple-domain matrix. This combines different DSMs and DMMs into one comprehensive model, which also allows analyzes across multiple domains and different types of relations. For this purpose, in the future, the aggregated DSMs can be determined and used as specific views into the DMM. Application of DSMs and DMMs to different systems allows a much more targeted handling of complex systems. The matrices therefore should be developed by interviewing system architects with fixing rules. It concerns calibration of the dependencies between the elements in the DMM in order to be used as the main body of a holistic DSS for generation of most efficient and appropriate renovation scenarios.

10.3.4. Future research work about contribution to Research Question 4

The study in future concerns expanding of the TSBD framework for Building Design in general. That means move from building renovation to design of new buildings. For this reason application of digital tools through framework of BIM (Building Information Modelling) is proposed and structured as an integrated design methodology (following the concept: BIM is a Methodology neither tool nor method). It hence is replaced with the HMSR in this thesis. In this regard, BIM's notion needs to be addressed as a methodology and then it should get processed and equipped by use of both Soft Systems Methodologies - SSM (where a design problem is able to be formulated) and Hard Systems Methodologies - HSM (use of decision support systems and simulation tools) through an effective design process (from conceptual design to detail design stages) for developing a holistic sustainable building design. Further research can also explore the notion of tectonics through sustainability and vice versa; as well as the effects of recent technologies and digital tools on tectonics expression (known as algorithmic tectonics).

10.4. Author suggestion for further improvement of the AEC industry

Rise of new paradigms such as sustainability and its development during the last two decades has led to increase the complexity level consisting of broad range of objectives/criteria and expectation in AEC industry. To cope with the increased level of complexity, new approaches to building design, and the methods and tools that support them must be preceded by new ways of imagining and thinking. The complexity of issues within the domain should be explored through broader perspectives and hence the traditional design approaches should be re-considered and equipped to become enable to deal with its level of complexity and multifaceted nature.

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APPENDIX

Appendix 1 - A list of technologies suitable for the refurbishment of existing buildings from 'RePublic_ZEB' project for context of ITALY

The RePublic_ZEB retrofitting research project (for further information about the project see Table 8.3 in chapter 6) has gathered the energy efficiency measures that are suitable for the refurbishment of public buildings towards nZEB level. In the following, the list of technologies can be seen, including information on which of the national reference public building types could be applied, the typical energy saving due to the application of the technology, as well as the typical value for the return of investment.

- *National characteristics of technologies*

Some of the technologies and its application have some national characteristic that summarized below:

- **Refurbishment of building structures:** In Italy the common opaque wall retrofit measure is the external insulation finishing system, when feasible, thanks to its easy application, since it allows the works without forcing the residents to leave. Furthermore, the application of the insulating material from the outside allows the total coverage of thermal bridges. The most common insulating materials on the market are the mineral wools and the expanded polystyrene (EPS); in the last years the use of EPS with graphite panels and of the vegetal panels (wood fibre, mineralized wood wool) is increasing. For facade-related restrictions, the wall internal thermal insulation is applied. In case of cavity wall insulation, the blown mineral fibre, the cellulose fibre, the expanded perlite, and in some cases the recycled newspaper are used. According to nZEB target, the best practice could consider the cavity (if any) together with the external wall thermal insulation. The most common insulation for roofs is the extruded polystyrene (XPS); lately, high density materials like wood wool or fibre wool are sometimes considered as to increase the opaque component thermal inertia insulation. For slabs under the attic (or false ceilings) insulation, the most used solution is the felt mineral wool, while the insulation of the first floors on unconditioned spaces usually employs the XPS or the mineral wool panels. Another new technology is the thin multifoil insulation made up of multi-layered reflective films, only a few microns thick. These layers, which are separated by wadding, foam, sheep's wool etc. are sewn together to form a thin insulating blanket. It is three to five times thinner than traditional thick insulation (including air spaces) but performs to the same standard. These products are perfectly adaptable for insulating residential, commercial and industrial buildings, in roofs, attics, walls and floors.

Concerning the transparent components, the common retrofit measure consists of the windows replacement with low-e double glazing filled with gas (North Italy) or air (Centre and South Italy), with wood (residential) or PVC (non-residential) frames. Shadings are basically still considered in new buildings, especially for residential buildings; in case of non-residential buildings major renovations the external venetian blinds or the external roller awnings are spreading.

- **Refurbishment of the building technical system:** in Italy the most common retrofit measure consists of the boiler replacement with a new condensing generator; nevertheless, the use of new technologies is spreading, especially the heat pumps.
    - *Heat pumps:* The most common heat pumps are those air-to-water or air-to-air. Lately, the groundwater heat pumps are also considered, especially in cities where rivers are available. Limit values are fixed for COP/GUE and EER (if feasible) in order to reach national tax incentives; values depend on the technology and on the system power: COP 3,8-5,1; EER 3,2-5,1; GUE 1,38-1,60. Furthermore, the national authority for the electricity has defied a new tariff for private users in case of heat pumps installation.
    - *Biomass:* the use of biomass boiler is spreading thanks to the national tax incentives and thanks to the latest technologies and the advanced engineering solutions (automatic extraction of ashes, automatic loading of pellets and chips and automatic cleaning of heat exchangers, power regulation by remote control, storage tank, integration with solar panels). By now this solution is often used combined with a traditional technical systems.
    - *District heating:* In Italy the district heating arrangement is mandatory in case of new buildings and major renovations. The Italian primary energy factor for the district heating is based on the energy production technology of the power-plant, such as on the primary energy source. Therefore the primary energy saving depends also on the district heating supplier at local level. If not available at local level, the primary energy conversion factor for district heating is considered totally non-renewable equal to 1,5.
    - *Thermal solar collector:* In Italy the typical end use for solar collectors is the DHW production. The most common technology is the flat plate solar collector; the vacuum tube collectors are less common because of the higher costs. Nevertheless, an innovative system is spreading that uses vacuum tube collectors with the water as energy carrier instead of the glycol and that admit lower maintenance costs. The thermal solar collectors for heating purposes are less common due to economic reasons and to the impossibility to use the thermal energy in summer period.
    - *Photovoltaic system:* In Italy PV panels are mandatory in case of new buildings and major renovations; the peak power to be installed is equal to half of the building footprint. The Italian average PV system size is around 35 kW. The 70% of the PV panels is polycrystalline, more than 20% monocrystalline. PV panels have to be grid connected and the self-consumption of the electricity produced by the PV system is more convenient.

Performance levels and specific investment costs of the proposed energy efficiency measures

The following tables give more information of how each technology listed in can be applied in practice, which are the materials and the solutions to be used, their main thermal characteristic parameter relevant values and the referred specific costs.

Building envelope

Vertical opaque components available retrofit measures

EEM	Number	Technology	Parameter		Cost	
			λ [W/mK]	Thickness [m]		
External wall thermal insulation	1	External insulation EPS 100 panels	0,036	0,05	6,00	[€/m²]
				0,08	9,46	
				0,10	11,80	
				0,12	14,20	
				0,16	19,00	
	2	External insulation MINERAL WOOL panels	0,036	0,05	16,24	[€/m²]
				0,08	23,44	
				0,10	29,30	
				0,12	35,10	
				0,16	46,73	
	3	Cavity wall CELLULOSE FIBRE floating	0,038	-	125	[€/m³]
	4	Cavity wall MINERAL GLASS floating	0,034	-	150	[€/m³]
	5	Cavity wall MINERAL WOOL floating	0,038	-	150	[€/m³]
Internal wall thermal insulation (unheated space)	6	External insulation EPS 100 panels	0,037	0,06	3,83	[€/m²]
				0,08	5,10	
				0,10	6,38	
				0,12	7,64	
				0,14	8,92	
				0,16	10,19	
	7	External insulation MINERAL WOOL panels	0,035	0,06	7,56	[€/m²]
				0,08	10,10	
				0,10	12,60	
				0,12	15,13	
				0,14	17,65	
				0,16	20,17	

Horizontal opaque components available retrofit measures

EEM	Number	Technology	Parameter		Cost	
			λ [W/mK]	Thickness [m]		
Roof/last floor thermal insulation	8	External insulation XPS panels	0,038	0,06	17,34	[€/m²]
				0,08	23,12	
				0,10	28,90	
				0,12	35,76	
				0,14	42,42	
				0,16	50,88	
	9	External insulation MINERAL WOOL felts	0,042	0,06	3,34	[€/m²]
				0,08	4,24	
				0,10	5,13	
				0,12	5,82	
				0,14	6,79	
				0,16	7,75	
	10	External insulation MINERAL WOOL panels	0,039	0,06	14,15	[€/m²]
				0,08	18,97	
				0,10	23,58	
				0,12	28,30	
				0,14	33,01	
				0,16	37,74	
			0,036	0,06	15,48	
			0,036	0,08	20,64	
			0,036	0,10	25,80	
			0,038	0,12	30,96	
			0,038	0,14	38,15	
	11	External insulation MINERAL WOOL panels	0,035	0,05	8,04	[€/m²]
				0,06	9,24	
				0,08	12,35	
				0,10	15,42	
				0,12	18,63	
				0,14	21,88	
				0,16	25,28	
	12	External insulation EPS panels	0,33	0,06	4,25	[€/m²]
				0,08	5,67	
				0,10	7,09	
				0,12	8,5	
				0,14	9,92	
				0,16	11,34	
	13	External insulation PUR panels	0,028	0,05	15,23	[€/m²]
			0,028	0,06	17,69	
			0,026	0,08	23,27	
			0,026	0,1	28,48	
			0,025	0,12	34,02	
			0,025	0,14	39,55	
			0,025	0,16	44,92	

EEM	Number	Technology	Parameter		Cost	
			λ [W/mK]	Thickness [m]		
Ground/first floor thermal insulation	14	External insulation XPS panels	0,034	0,05	12,90	[€/m²]
			0,036	0,06	15,48	
			0,036	0,08	20,64	
			0,036	0,10	25,80	
			0,038	0,12	30,96	
			0,038	0,14	38,15	
	15	External insulation MINERAL WOOL panels	0,035	0,05	8,04	[€/m²]
				0,06	9,24	
				0,08	12,35	
				0,10	15,42	
				0,12	18,63	
				0,14	21,88	
				0,16	25,28	
	16	External insulation EPS panels	0,33	0,06	4,25	[€/m²]
				0,08	5,67	
				0,10	7,09	
				0,12	8,5	
				0,14	9,92	
				0,16	11,34	
	17	External insulation PUR panels	0,028	0,05	15,23	[€/m²]
			0,028	0,06	17,69	
			0,026	0,08	23,27	
			0,026	0,1	28,48	
			0,025	0,12	34,02	
			0,025	0,14	39,55	
			0,025	0,16	44,92	

Windows available retrofit measures

EEM	Number	Technology	Parameter		Cost	
			Ug [W/m²K]	thickness [mm]		
Window thermal insulation	18	DOUBLE GLASS Filled with air, Low-e one side coated	1,6	4/12/4	38,77	[€/m²]
		DOUBLE GLASS Filled with argon, Low-e one side coated	1,3	4/12/4	44,67	
		DOUBLE GLASS Filled with air, Low-e one side coated	1,4	4/15/4	40,24	
		DOUBLE GLASS Filled with argon, Low-e one side coated	1,1	4/15/4	46,14	
		DOUBLE GLASS Filled with kripton, Low-e one side coated	1,0	4/15/5	53,29	
	19	TRIPLE GLASS Filled with air, Low-e one side coated	1,0	4/12/4/12/4	74,33	[€/m²]
			0,8	4/12/4/12/5	81,48	
	20	STRATIFIED DOUBLE GLASS Filled with argon, Low-e one side coated	1,9	3+3/12/4	62,76	[€/m²]
			1,3	4/12/3+3	68,65	
	21	STRATIFIED DOUBLE GLASS Filled with air, Low-e two side coated	1,4	3+3/15/3+3	94,90	[€/m²]
	22	STRATIFIED DOUBLE GLASS Filled with argon, Low-e two side coated	1,1	3+3/15/3+3	99,10	
	23	STRATIFIED DOUBLE GLASS Filled with air, Low-e two side coated	1,9	3+3/12/3+3	93,42	[€/m²]
			1,6	4+4/12/4+4	101,52	[€/m²]
	24	STRATIFIED DOUBLE GLASS Filled with argon, Low-e two side coated	1,1	4+4/12/4+4	107,42	
	25	STRATIFIED TRIPLE GLASS Filled with argon, Low-e two side coated	0,7	3+3/15/4/12/3+3	148,00	[€/m²]

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EEM	Number	Technology	Parameter Uf [W/m²K]	Cost		Notes
Window thermal insulation	26	FRAME PVC	2	90,99	[€/m²]	Price for fixed windows with area < 2 m^2
			1,6	100,09		
			1,3	109,19		
			2	209,57	[€/m²]	Price for multiple casement window with area < 3,5 m^2
			1,6	230,56		
			1,3	251,48		
	27	FRAME ALUMINIUM	2	207,28	[€/m²]	Price for fixed windows with area < 2 m^2
			2	370,23		Price for multiple casement window with area < 3,5 m^2
	28	FRAME WOOD	2	116,22	[€/m²]	Price for fixed windows with area < 2 m^2
			1,8	133,65		
			2	210,25	[€/m²]	Price for multiple casement window with area < 3,5 m^2
			1,8	241,79		

EEM	Number	Technology	Parameter ΔR [m²K/W]	Cost		Notes
Window thermal insulation	29	Rolling shutter PVC	0,08	48	[€/m²] installation included	air permeability: very high
			0,14	45		air permeability: high
			0,21	43		air permeability: medium
			0,29	38		air permeability: low
			0,35	35		air permeability: very low

Window solar control

EEM	Number	Technology	Parameter solar transmittance coefficient τ [-]	Cost		Notes
Window solar control	30	outdoor blinds ALUMINIUM 800x600	0,4	251	[€]	Venetian blinds, movable
		outdoor blinds ALUMINIUM 1000x800	0,4	306		
	31	Roman blinds TISSUE	0,4	60	[€/m²]	movable

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Technical systems available retrofit measures

EEM	Number	Technology	Parameter				Cost		Notes
			Φ_{er} heating power		Φ_{er} cooling power				
Emission retrofit	1	Fan-coil	1090	[W]	830	[W]	550	[€/unit]	2 tubes fan-coil
			2350		1769		640		
			3190		2650		730		
			4100		3340		860		
	2	Floor heating/cooling		[W]		[W]	75,70	[€/m²]	30 mm thickness solution, it can be layared directly on the existing floor
					-		65,40	[€/m²]	90 mm thickness solution, it requires to be applied after the demolition of the prexisting layers. The cost doesn't include demolitions
							76,97		
	3	Ceiling heating/cooling		[W]		[W]	136,02	[€/m²]	The cost considers 45 mm thickness precast panels
Control retrofit	4	Room thermostat					from 50 to 70	[€/unit]	
	5	Zone thermostat					200	[€/unit]	

EEM	Number	Technology	Parameter				Cost	
			Volume		k_{boll}			
Storage sub-system retrofit	6	Storage vessel thermal insulation	200	[l]	1,9	[W/K]	660	[€/unit]
			500		2,5		1350	
			552		2,4		1920	
			800		2,85		1640	
			837		2,8		2130	
			979		3,1		2250	
			1000		3,1		1740	
			1500		6,29		2410	
			2000		7,47		3090	

EEM	Number	Technology	Parameter Φ_{gn}		Parameter η_{gn}		Cost		Notes
H/C/W Generator	7	Condensing boiler	500	[kW]	109,6	[%]	27.722	[€/unit]	T_{flow}= 40°C $T_{return\ flow}$= 30°C
			575	[kW]	109,6		31.492		
			650	[kW]	109,6		33.074		
			1000	[kW]	109,6		49.817		
			1150	[kW]	109,6		63.465		
			1300	[kW]	109,6		66.975		
			1440	[kW]	109,6		72.893		
	8	Biomass boiler	700	[kW]	0,93	[-]	105.000	[€/unit]	
	9	District heating	700	[kW]	0,88	[-]	21.167	[€/unit]	
	Number	**Technology**	**Parameter** Φ_{gn}		**Parameter COP**		**Cost**		**Notes**
	10	Air to water heat pump	640	[kW]	3,11	[-]	208.907	[€/unit]	
			780		3,09		224.329		
			1050		3,17		325.084		
			426		4,63		111.952		
	11	Air to air heat pump	12	[kW]	3,5	[-]	800	[€/unit]	Costs refer to a single unit (office/class room/dwelling) and the control is included
			12		4		1.000		
			12		4,5		1.200		
	12	Groundwater heat pump (water to water)	464	[kW]	4,49	[kW]	119.203	[€/unit]	
			524		4,56		136.628		
			591		4,65		145.526		
			668		4,55		154.273		
			1004		5,32		187.028		
			1132		5,30		207.279		
			1278		5,33		218.514		

Thermal solar energy

EEM	Number	Technology	Parameter				Cost	
			Surface solar collectors		κ_1			
Thermal energy from solar	13	Vacuum solar collector	2,33	[m²]	0,613	[W/m²K]	1870	[€/unit]
	14	Flat solar collector	2		3,65	[W/m²K]	880	[€/unit]

Photovoltaic system

EEM	Number	Technology	Parameter				Cost	
			Peak power [KW_p]		Efficency module			
Electrical energy from renewables	15	Poly-crystaline	2	[kW]	15,8	%	2980	[€]
			3		15,8	%	4300	
			4		15,8	%	5140	
			5		15,8	%	5680	
	16	Mono-crystaline	2	[kW]	19,4	%	3443	
			3		19,4	%	5291	
			4		19,4	%	5379	
			5		19,4	%	6390	

Lighting system

EEM	Number	Technology	Parameter				Cost	
			Luminous flux emitted Φ [lm]		Electrical power [W]			
Luminaire installation	17	Linear fluorescent lamps	< 1000	[lm]	4-20	[W]	from 9,06 € to 42,2 €	[€/unit]
			1000-2000		13-36		from 6,75 € to 65,95 €	
			2000-3000		19-58		from 9,24 € to 58,38 €	
			3000-4000		24-58		from 6,76 € to 62,85 €	
			4000-5000		41-65		from 7,82 € to 75,82 €	
			5000-6000		24-66		from 7,82 € to 57,32 €	
			6000-7000		24-80		from 9,07 € to 51,32 €	
	18	Circular fluorescent lamps	1000-2000	[lm]	22-24	[W]	from 9,55 € to 35,19 €	
			2000-3000		32-40		from 10,02 € to 24,62 €	
			3000-4000		40-55		from 14,36 € to 36,04 €	

			4000-5000		55-60		from 36,04 € to 43,42 €	
	19	Integrated compact fluorescent lamps	< 1000	[lm]	5-18	[W]	from 9,13 € to 38,21 €	
			1000-2000		17-30		from 9,31 € to 36,89 €	
			2000-3000		30-45		from 12,88 € to 56,11 €	
			3000-4000		65		68,94 €	
			4000-5000		80		81,29 €	
	20	Non-Integrated compact fluorescent lamps	< 1000	[lm]	5-18	[W]	from 5,64 € to 26,0 €	
			1000-2000		14-26		from 11,13 € to 36,49 €	
			2000-3000		28-40		from 14,47 € to 37,0 €	
			3000-4000		40-42		from 15,19 € to 64,28 €	
			4000-5000		55-57		from 15,19 € to 64,28 €	
			5000-6000		80		28,35 €	
			6000-7000		80		from 22,51 € to 33,0 €	
	21	LED Lamps	< 1000	[lm]	2-15	[W]	from 6,0 € to 89,6 €	
			1000-2000		10,5-18		from 11,0 € to 71,5 €	
	22	LED tubular lamps	< 1000	[lm]	6-10	[W]	from 14,8 € to 64,2 €	
			1000-2000		10-22		from 20,07 € to 62,6 €	
			2000-3000		20-24		from 40,0 € to 91,6 €	
			3000-4000		25-28		from 58,0 € to 123,0 €	
EEM	**Number**	**Technology**	**Parameter**				**Cost**	
Lighting control	23	Daylight control					from 33 € to 88,6 €	
	24	Occupancy sensor					from 50 € to 100,0 €	
	25	Daylight control + Occupancy sensor					from 45 € to 330,0 €	
	26	Switch programs (time control)					from 15 € to 60 €	

Appendix 2 - Retrofit measures and the energy efficiency levels and referred cost for from 'RePublic_ZEB' project for context of ITALY

The RePublic_ZEB retrofitting research project (for further information about the project see Table 8.3 in chapter 6) has gathered the information about the retrofit measures and the energy efficiency levels and referred cost.

5.6.1 Residential building

1. Opaque components considered retrofit measures

EEM	Technology	Levels 1	Levels 2	Levels 3	Levels 4	Levels 5
External wall thermal insulation	External insulation	EPS panels 0,08 m	EPS panels 0,10 m	EPS panels 0,12 m	EPS panels 0,16 m	
	Cavity wall	CELLULOSE FIBRE 0,075 m	CELLULOSE FIBRE 0,075 m			
Internal wall thermal insulation (unheated space)	External insulation	EPS panels 0,10 m	EPS panels 0,12 m	EPS panels 0,14 m	MINERAL WOOL panels 0,14 m	MINERAL WOOL panels 0,16 m
Last floor thermal insulation	External insulation	MINERAL WOOL felts 0,12 m	MINERAL WOOL felts 0,14 m	MINERAL WOOL felts 0,16 m	XPS panels 0,18 m	
First floor thermal insulation	External insulation	MINERAL WOOL panels 0,08 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	XPS panels 0,14 m	MINERAL WOOL panels 0,16 m

Parameter		Level of EEO: Existing building	1	2	3	4	5	Level of EEO: 1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
$U_{op,e}$	[W/m^{2}K]	1,19	0,34	0,29	0,25	0,2		9,46	11,8	14,2	19	
$U_{op,e}$	[W/m^{2}K]	1,19	0,38	0,35				125 €/m^3	150 €/m^3			
$U_{op,u}$	[W/m^{2}K]	0,88	0,33	0,28	0,24	0,23	0,2	6,38	7,64	8,92	17,65	20,17
U_r	[W/m^{2}K]	1,66	0,3	0,25	0,23	0,2		5,82	6,79	7,75	57,24	
U_f	[W/m^{2}K]	1,29	0,33	0,29	0,24	0,22	0,2	12,35	15,42	18,63	38,15	25,28

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2. Windows considered retrofit measures

EEM	Technology	Technology				
	Technology	Levels				
		1	2	3	4	5
Window thermal insulation	Glass thermal insulation	DOUBLE GLASS 4/12/4 Low-e one side coated filled with air emissivity < 0,05	DOUBLE GLASS 4/12/4 Low-e one side coated filled with argon emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with air emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with argon emissivity < 0,05	
	Technology	Levels				
		1	2	3	4	5
	Frame thermal insulation	WOOD FRAME multiple casement window with area < 3,5 mq	PVC FRAME multiple casement window with area < 3,5 mq	PVC FRAME multiple casement window with area < 3,5 mq		
	Technology	Levels				
		1	2	3	4	5
	Shutter	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC

Parameter		Level of EEO						Level of EEO				
Parameter		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
U_g	[W/m²K]	5,9	1,7	1,3	1	0,8		38,77	44,67	74,33	81,48	
Parameter		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
U_f	[W/m²K]	2,4	2	1,6	1,3			210,25	230,56	251,48		
Parameter		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
ΔR	[(m²K)/W]		0,35	0,29	0,21	0,14	0,08	35	38	43	45	48

3. Solar control retrofit measures considered

Energy Efficiency Measure (EEM)	Technology					
	Technology	Levels				
		1	2	3	4	5
Window solar control	Solar shading	Roman blinds TISSUE				

Parameter		Level of EEO						Level of EEO				
Parameter		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
τ	[-]		0,4					60				
-	[-]		movable									

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4. Technical systems retrofit measures considered

EEM	EEM	Technology			
		Existing building	1	2	3
Control retrofit	Improving control system	Outside temperature compensed control	Zone thermostat	Room thermostat	

Parameter		Parameter values				Cost of EEM [€]		
		Existing building	1	2	3	1	2	3
η_c	[-]	monthly values	0,98	0,995		230 €/unit	100 €/unit	

EEM	EEM	Technology				
		Existing building	1	2	3	4
H/C/W Generator	High efficiency chiller (C)		multisplit air to air	multisplit air to air	multisplit air to air	
	High efficiency generator for space heating (H)	condensing boiler + radiators	Biomass + radiators	condensing boiler + radiators	condensing boiler + floor heating	district heating + radiators
	High efficiency generator for DHW (W)	natural gas or electrical boiler	condensing boiler	heat pump		
	High efficiency combined generator for space heating and hot water (H+W)		biomass + radiators	condensing boiler + radiators	condensing boiler + floor heating	district heating + radiators
	Heat pump for heating, cooling and hot water (H+C+W)		Heat pump + fancoils	Heat pump + fancoils		

Parameter		Parameter values					Cost of EEM [€]				Notes
		Existing building	1	2	3	4	1	2	3	4	
EER	[-]		3,5	4	4,5		800 €/unit control included	1.000 €/unit control included	1.200 €/unit control included		costs refer to Φ_{gn} 12 kW
η_{gn}	[-]	0,95	0,95	1,1	1,1	0,88	105.000	49.817 + 75,7 €/m² for floor heating	49.817	21.167	costs refer to Φ_{gn} 700 kW
$\eta_{gn,Pn,W}$	[-]	values different for single dwelling	1,0	4,2			600 €/unit	1.100 €/unit			costs refer to Φ_{gn} 24 kW
η_{gn}	[-]		0,93	1,1	1,1	0,88	105.000	49.817 + 75,7 €/m² for floor heating	49.817	21.167	costs refer to Φ_{gn} 700 kW. A storage needs to be added.
COP	[-]		3,09	5,32			134.597,4 + 640 €/element for fan-coils	112.216,8 + 640 €/element for fan-coils			costs refer to Φ_{gn} 700 kW. A storage for W needs to be added
EER	[-]		2,26	4,31							

EEM	EEM	Technology				
		Existing building	1	2	3	4
Thermal energy from solar	Solar collectors		Flat solar collector	Flat solar collector	Flat solar collector	Vacuum solar collector

Parameter		Parameter values					Cost of EEM [€]				Notes
		Existing building	1	2	3	4	1	2	3	4	
A_p	[m²]		1	2	3	1	484	880	1.188	1.029	costs refer to each dwelling. A storage needs to be added

EEM	EEM	Technology					
		Existing building	1	2	3	4	5
Electrical energy from renewables	PV system		Poly-crystaline	Poly-crystaline	Poly-crystaline	Mono-crystaline	Mono-crystaline

Parameter		Parameter values						Cost of EEM [€]				
		Existing building	1	2	3	4	5	1	2	3	4	5
W_p	[KWp]		2	5	10	2	5	2980	5680	10224	3443	6390

5.6.2 Office building

1. Opaque components considered retrofit measures

EEM	Technology				
	Technology	Levels			
		1	2	3	4
External wall thermal insulation	External insulation	EPS panels 0,05 m	EPS panels 0,08 m	EPS panels 0,10 m	MINERAL WOOL panels 0,14 m
	Cavity wall	CELLULOSE FIBRE 0,165 m	MINERAL GLASS 0,165 m		
Internal wall thermal insulation (unheated space)	External insulation	EPS panels 0,10 m	EPS panels 0,12 m	EPS panels 0,14 m	EPS panels 0,16 m
Roof thermal insulation	External insulation	MINERAL WOOL panels 0,12 m	XPS panels 0,12 m	MINERAL WOOL panels 0,16 m	MINERAL WOOL panels 0,18 m
First floor thermal insulation	External insulation	MINERAL WOOL panels 0,08 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,16 m

Parameter		Level of EEO					Level of EEO			
		Existing building	1	2	3	4	1	2	3	4
		Parameter values					Cost of EEM [€/m²]			
$U_{op,e}$	[W/m^{2}K]	0,65	0,34	0,27	0,23	0,18	6	9,46	11,8	40,2
$U_{op,e}$	[W/m^{2}K]	0,65	0,2	0,18			125 €/m^3	150 €/m^3		

$U_{op,e}$	[W/m^{2}K]	1,72	0,3	0,26	0,23	0,2	6,38	7,64	8,92	10,19
U_r	[W/m^{2}K]	0,56	0,28	0,27	0,22	0,2	28,3	35,76	37,74	42,86
U_f	[W/m^{2}K]	1,25	0,32	0,27	0,24	0,2	12,35	15,42	18,63	25,28

2. Windows considered retrofit measures

EEM	**Technology**			
	Technology	Levels		
		1	2	3
Window thermal insulation	Glass thermal insulation	DOUBLE GLASS 4/12/4 Low-e one side coated filled with air emissivity < 0,05	DOUBLE GLASS 4/12/4 Low-e one side coated filled with argon emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with air emissivity < 0,05
	Technology	Levels		
		1	2	3
	Frame thermal insulation	ALUMINIUM FRAME vasistas window with area >2 mq	WOOD FRAME vasistas window with area >2 mq	PVC FRAME tilt turn window with area >2 mq

Parameter		Level of EEO				Level of EEO		
		Existing building	1	2	3	1	2	3
		Parameter values				Cost of EEM [€/m²]		
U_g	[W/m²K]	5,92	1,7	1,3	1	38,77	44,67	74,33
Parameter		Existing building	1	2	3	1	2	3
		Parameter values				Cost of EEM [€/m²]		
U_f	[W/m²K]	7	2	1,8	1,3	340,2	230,85	175,42

3. Solar control retrofit measures considered

EEM	Technology			
	Technology	Levels		
		1	2	3
Window solar control	Solar shading	Roman blinds TISSUE	outdoor blinds ALUMINIUM 800x600	outdoor blinds ALUMINIUM 1000x800

Parameter		Level of EEO				Level of EEO		
		Existing building	1	2	3	1	2	3
		Parameter values				Cost of EEM [€/m²]		
τ	[-]		0,4	0,4	0,4	60	251	306
Mob	[-]		movable					

4. Technical systems retrofit measures considered

EEM	EEM	Technology			
		Existing building	1	2	3
Control retrofit	Improving control system	Outside temperature compensed control	Zone thermostat	Room thermostat	

Parameter		Parameter values				Cost of EEM [€]		
		Existing building	1	2	3	1	2	3
η_c	[-]	monthly values	0,98	0,995		230 €/unit	100 €/unit	

EEM	EEM	Technology			
		Existing building	1	2	3
H/C/W Generator	High efficiency chiller (C)		multisplit air to air	multisplit air to air	multisplit air to air
	High efficiency generator for space heating (H)	standard boiler + radiators	biomass + radiators	condensing boiler + radiators	district heating + radiators
	High efficiency generator for DHW (W)		condensing boiler	heat pump	
	High efficiency combined generator for space heating and hot water (H+W)		biomass + radiators	condensing boiler + radiators	district heating + radiators
	Heat pump for heating, cooling and hot water (H+C+W)		Heat pump + fancoils	Heat pump + fancoils	

Parameter		Parameter values				Cost of EEM [€]			Notes
		Existing building	1	2	3	1	2	3	
EER	[-]		3,5	4	4,5	800 €/unit control included + 4590	1.000 €/unit control included + 4590	1.200 €/unit control included + 4590	costs refer to Φ_{gn} 12 kW; considers 5 external units.
η_{gn}	[-]	0,93	0,95	1,1	0,88	97.500	33.074 €	12.383	costs refer to Φ_{gn} 650 kW
$\eta_{gn,Pn,W}$	[-]		1,0	4,2		600 €/unit	1.100 €/unit		costs refer to Φ_{gn} 24 kW
η_{gn}	[-]		0,93	1,1	0,88	97.500	33.074	12.383	costs refer to Φ_{gn} 650 kW. A storage for W needs to be added

COP	[-]		3,11	4,55		125.344,2 + 640 €/element for fan-coils	92.563,8 + 640 €/element for fan-coils		costs refer to Φ_{gn} 650 kW. A storage for W needs to be added
EER	[-]		2,22	4,3					

EEM	EEM	Technology					
		Existing building	1	2	3	4	5
Electrical energy from renewables	PV system		Poly-crystaline	Poly-crystaline	Poly-crystaline	Mono-crystaline	Mono-crystaline

Parameter		Parameter values						Cost of EEM [€]				
		Existing building	1	2	3	4	5	1	2	3	4	5
W_p	[KWp]		2	5	10	2	5	2980	5680	10224	3443	6390

EEM	EEM	Technology				
		Existing building	1	2	3	4
Luminaires installation	Lighting power density (LPD)	Linear fluorescent lamps	Linear fluorescent lamps	Linear fluorescent lamps	LED tubular lamps	LED tubular lamps
Lighting control	Lighting control systems (LCS)	Manual switch on/off	2 x Daylight control	2 x Occupancy Sensor	2 x Daylight control + Occupancy sensor	

Parameter		Parameter values					Cost of EEM [€]				Notes
		Existing building	1	2	3	4	1	2	3	4	
Pn	[W/m^2]	13,64	12	8,7	5,17	4,7	46,64	96,48	120,0	168	value refers to a standard office of 17m^2
Fo	[-]	1	1	0,9	0,9		33,00	60,00	121,00		value refers to a standard office of 17m^2
Fc	[-]	1	0,9	1	0,9						

5.6.3 School building n.1

1. Opaque components considered retrofit measures

EEM	Technology				
	Technology	Levels			
		1	2	3	4
External wall thermal insulation	External insulation	EPS panels 0,08 m	EPS panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,16 m
	Cavity wall	CELLULOSE FIBRE 0,06 m	MINERAL GLASS 0,06 m		
Internal thermal insulation (unheated space)	External insulation	MINERAL WOOL panels 0,08 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,14 m
Roof thermal insulation	External insulation	XPS panels 0,10 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,16 m
Ground thermal insulation	External insulation	EPS panels 0,08 m	EPS panels 0,10 m	EPS panels 0,12 m	EPS panels 0,14 m

Parameter		Level of EEO					Level of EEO			
		Existing building	1	2	3	4	1	2	3	4
		Parameter values					Cost of EEM [€/m²]			
$U_{op,e}$	[W/m^{2}K]	1,2	0,32	0,28	0,24	0,19	9,46	11,8	35,1	46,73
$U_{op,e}$	[W/m^{2}K]	1,2	0,46	0,42			125 €/m^3	150 €/m^3		
$U_{op,u}$	[W/m^{2}K]	1,07	0,31	0,26	0,23	0,2	10,1	12,6	15,13	17,65
U_r	[W/m^{2}K]	1,55	0,34	0,32	0,27	0,21	28,9	28,3	42,42	57,24
U_f	[W/m^{2}K]	1,51	0,32	0,27	0,23	0,2	5,67	7,09	8,5	9,92

2. Windows considered retrofit measures

EEM	Technology	Levels 1	2	3	4	5
Window thermal insulation	Glass thermal insulation	DOUBLE GLASS 4/12/4 Low-e one side coated filled with air with air emissivity < 0,05	DOUBLE GLASS 4/12/4 Low-e one side coated filled with argon with argon emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with air with air emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with argon emissivity < 0,05	
	Technology	**Levels** 1	2	3	4	5
	Frame thermal insulation	FRAME ALUMINIUM vasistas window with area >2 mq	FRAME PVC vasistas window with area >2 mq	FRAME PVC vasistas window with area >2 mq		
	Shutters	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC

Parameter		Level of EEO: Existing building	1	2	3	4	Level of EEO: 1	2	3	4	5
		Parameter values					Cost of EEM [€/m²]				
U_g	[W/m²K]	4,26	1,7	1,3	1	0,8	38,77	44,67	74,33	81,48	
Parameter		Existing building	1	2	3	4	1	2	3	4	5
		Parameter values					Cost of EEM [€/m²]				
U_f	[W/m²K]	2,55	2	1,6	1,3		340,2	150,13	163,78		
ΔR	[(m^{2}K)/W]		0,35	0,29	0,21	0,14	35	38	43	45	48

3. Solar control retrofit measures considered

EEM	Technology			
	Technology	Levels		
		1	2	3
Window solar control	Solar shading	Roman blinds TISSUE	outdoor blinds ALUMINIUM 800x600	outdoor blinds ALUMINIUM 1000x800
		Roman blinds TISSUE/outdoor blinds ALUMINIUM		

Parameter		Level of EEO					Level of EEO		
		Existing building	1	2	3	4	1	2	3
		Parameter values					Cost of EEM [€/m²]		
τ	[-]		0,4	0,4	0,4		60	251	306
Mob	[-]		movable						

4. Technical systems retrofit measures considered

EEM	EEM	Technology			
		Existing building	1	2	3
Control retrofit	Improving control system	Outside temperature compensed control	Zone thermostat	Room thermostat	

Parameter		Parameter values				Cost of EEM [€]		
		Existing building	1	2	3	1	2	3
η_c	[-]	monthly values	0,98	0,995		230 €/unit	100 €/unit	

EEM	EEM	Technology			
		Existing building	1	2	3
H/C/W Generator	High efficiency chiller (C)		multisplit air to air	multisplit air to air	multisplit air to air
	High efficiency generator for space heating (H)	standard boiler + radiators	biomass + radiators	condensing boiler + radiators	district heating + radiators
	High efficiency generator for DHW (W)		condensing boiler	heat pump	
	High efficiency combined generator for space heating and hot water (H+W)		biomass + radiators	condensing boiler + radiators	district heating + radiators
	Heat pump for heating, cooling and hot water (H+C+W)		Heat pump + fancoils	Heat pump + fancoils	

Parameter		Parameter values				Cost of EEM [€]			Notes
		Existing building	1	2	3	1	2	3	
EER	[-]		3,5	4	4,5	800 €/unit control included + 4590	1.000 €/unit control included + 4590	1.200 €/unit control included + 4590	costs refer to Φ_{gn} 12 kW; considers 5 external units.
η_{gn}	[-]	0,77	0,95	1,1	0,88	255.000	94.476 €	17.690	costs refer to Φ_{gn} 1,7 MW.
$\eta_{gn,Pn,W}$	[-]		1,0	4,2		600 €/unit	1.100 €/unit		costs refer to Φ_{gn} 24 kW
η_{gn}	[-]		0,95	1,1	0,88	255.000	94.476	17.690	costs refer to Φ_{gn} 1,7 MW. A storage for W needs to be added.

COP	[-]		3,11	4,65		376.032 + 640 €/element for fan-coils	261.946 + 640 €/element for fan-coils		costs refer to Φ_{gn} 1,7 MW. A storage for W needs to be added
EER	[-]		2,22	4,2					

EEM	EEM	Technology					
		Existing building	1	2	3	4	5
Electrical energy from renewables	PV system		Poly-crystaline	Poly-crystaline	Poly-crystaline	Mono-crystaline	Mono-crystaline

Parameter		Parameter values						Cost of EEM [€]				
		Existing building	1	2	3	4	5	1	2	3	4	5
W_p	[KWp]		2	5	10	2	5	2980	5680	10224	3443	6390

EEM	EEM	Technology				
		Existing building	1	2	3	4
Luminaires installation	Lighting power density (LPD)	Linear fluorescent lamps	Linear fluorescent lamps	Linear fluorescent lamps	LED tubular lamps	LED tubular lamps
Lighting control	Lighting control systems (LCS)	Manual switch on/off	2 x Daylight control	2 x Occupancy Sensor	2 x Daylight control + Occupancy sensor	

Parameter		Parameter values					Cost of EEM [€]				Notes
		Existing building	1	2	3	4	1	2	3	4	
Pn	[W/m^2]	15,2	13,36	9,69	5,76	5,24	139,92	289,44	360	504	value refers to a standard class room of 46m^2
Fo	[-]	1	1	0,9	0,9		66	120	242		value refers to a standard class room of 46m^2
Fc	[-]	1	0,9	1	0,9						

5.6.4 School building n.2

1. Opaque components considered retrofit measures

EEM	Technology				
	Technology	Levels			
		1	2	3	4
External wall thermal insulation	External insulation	EPS panels 0,08 m	EPS panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,16 m
	Cavity wall				
Internal thermal insulation (unheated space)	External insulation	MINERAL WOOL panels 0,08 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,14 m
Roof thermal insulation	External insulation	XPS panels 0,08 m	MINERAL WOOL panels 0,10 m	MINERAL WOOL panels 0,12 m	MINERAL WOOL panels 0,16 m
Ground thermal insulation	External insulation	EPS panels 0,08 m	EPS panels 0,10 m	EPS panels 0,12 m	EPS panels 0,14 m

Parameter		Level of EEO					Level of EEO			
		Existing building	1	2	3	4	1	2	3	4
		Parameter values					**Cost of EEM [€/m²]**			
$U_{op,e}$	[W/m^{2}K]	1,4	0,34	0,29	0,25	0,2	9,46	11,8	35,1	46,73
$U_{op,e}$	[W/m^{2}K]	1,4								
$U_{op,u}$	[W/m^{2}K]	1,07	0,31	0,26	0,23	0,2	10,1	12,6	15,13	17,65
U_r	[W/m^{2}K]	0,95	0,3	0,28	0,24	0,19	23,12	28,9	33,01	37,74
U_f	[W/m^{2}K]	0,96	0,29	0,25	0,21	0,19	5,67	7,09	8,5	9,92

2. Windows considered retrofit measures

EEM	Technology	Technology				
	Technology	Levels				
		1	2	3	4	5
Window thermal insulation	Glass thermal insulation	DOUBLE GLASS 4/12/4 Low-e one side coated filled with air with air emissivity < 0,05	DOUBLE GLASS 4/12/4 Low-e one side coated filled with argon with argon emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with air with air emissivity < 0,05	TRIPLE GLASS 4/12/4/12/4 Low-e one side coated filled with argon emissivity < 0,05	
	Technology	Levels				
		1	2	3	4	5
	Frame thermal insulation	FRAME ALUMINIUM vasistas window with area >2 mq	FRAME PVC vasistas window with area >2 mq	FRAME PVC vasistas window with area >2 mq		
	Shutters	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC	Rolling shutter PVC

Parameter		Level of EEO						Level of EEO				
		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
Ug	[W/m²K]	4,28	1,7	1,3	1	0,8		38,7	44,67	74,33	81,4	
Parameter		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
Uf	[W/m²K]	5	2	1,6	1,3			340	150,13	163,78		
ΔR	[(m²K)/W]	0,15	0,35	0,29	0,21	0,14	0,08	35	38	43	45	48

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3. Solar control retrofit measures considered

EEM	Technology	Technology				
		Levels				
		1	2	3	4	5
Window solar control	Solar shading	Roman blinds TISSUE	outdoor blinds ALUMINIUM 800x600	outdoor blinds ALUMINIUM 1000x800		
		Roman blinds TISSUE/outdoor blinds ALUMINIUM				

Parameter		Level of EEO						Level of EEO				
		Existing building	1	2	3	4	5	1	2	3	4	5
		Parameter values						Cost of EEM [€/m²]				
τ	[-]	0,8	0,4	0,4	0,4			60	251	306		
Mob	[-]		movable									

4. Technical systems retrofit measures considered

EEM	EEM	Technology			
		Existing building	1	2	3
Control retrofit	Improving control system	Outside temperature compensed control	Zone thermostat	Room thermostat	

Parameter		Parameter values				Cost of EEM [€]		
		Existing building	1	2	3	1	2	3
η_c	[-]	monthly values	0,98	0,995		230 €/unit	100 €/unit	

EEM	EEM	Technology			
		Existing building	1	2	3
H/C/W Generator	High efficiency chiller (C)		multisplit air to air	multisplit air to air	multisplit air to air

	High efficiency generator for space heating (H)	standard boiler + radiators	biomass + radiators	condensing boiler + radiators	district heating + radiators
	High efficiency generator for DHW (W)		condensing boiler	heat pump	
	High efficiency combined generator for space heating and hot water (H+W)		biomass + radiators	condensing boiler + radiators	district heating + radiators
	Heat pump for heating, cooling and hot water (H+C+W)		Heat pump + fancoils	Heat pump + fancoils	

Parameter		Parameter values				Cost of EEM [€]			Notes
		Existing building	1	2	3	1	2	3	
EER	[-]		3,5	4	4,5	800 €/unit control included + 4590	1.000 €/unit control included + 4590	1.200 €/unit control included + 4590	costs refer to Φ_{gn} 12 kW; considers 5 external units.
η_{gn}	[-]	0,77	0,95	1,1	0,88	255.000	94.476 €	17.690	costs refer to Φ_{gn} 1,7 MW.
$\eta_{gn,Pn,W}$	[-]		1,0	4,2		600 €/unit	1.100 €/unit		costs refer to Φ_{gn} 24 kW
η_{gn}	[-]		0,95	1,1	0,88	255.000	94.476	17.690	costs refer to Φ_{gn} 1,7 MW. A storage for W needs to be added.
COP	[-]		3,11	4,65		376.032 + 640 €/element for fan-coils	261.946 + 640 €/element for fan-coils		costs refer to Φ_{gn} 1,7 MW. A storage for W needs to be added
EER	[-]		2,22	4,2					

EEM	EEM	Technology					
		Existing building	1	2	3	4	5
Electrical energy from renewables	PV system		Poly-crystaline	Poly-crystaline	Poly-crystaline	Mono-crystaline	Mono-crystaline

Parameter		Parameter values						Cost of EEM [€]				
		Existing building	1	2	3	4	5	1	2	3	4	5
W_p	[KWp]		2	5	10	2	5	2980	5680	10224	3443	6390

EEM	EEM	Technology				
		Existing building	1	2	3	4
Luminaires installation	Lighting power density (LPD)	Linear fluorescent lamps	Linear fluorescent lamps	Linear fluorescent lamps	LED tubular lamps	LED tubular lamps
Lighting control	Lighting control systems (LCS)	Manual switch on/off	2 x Daylight control	2 x Occupancy Sensor	2 x Daylight control + Occupancy sensor	

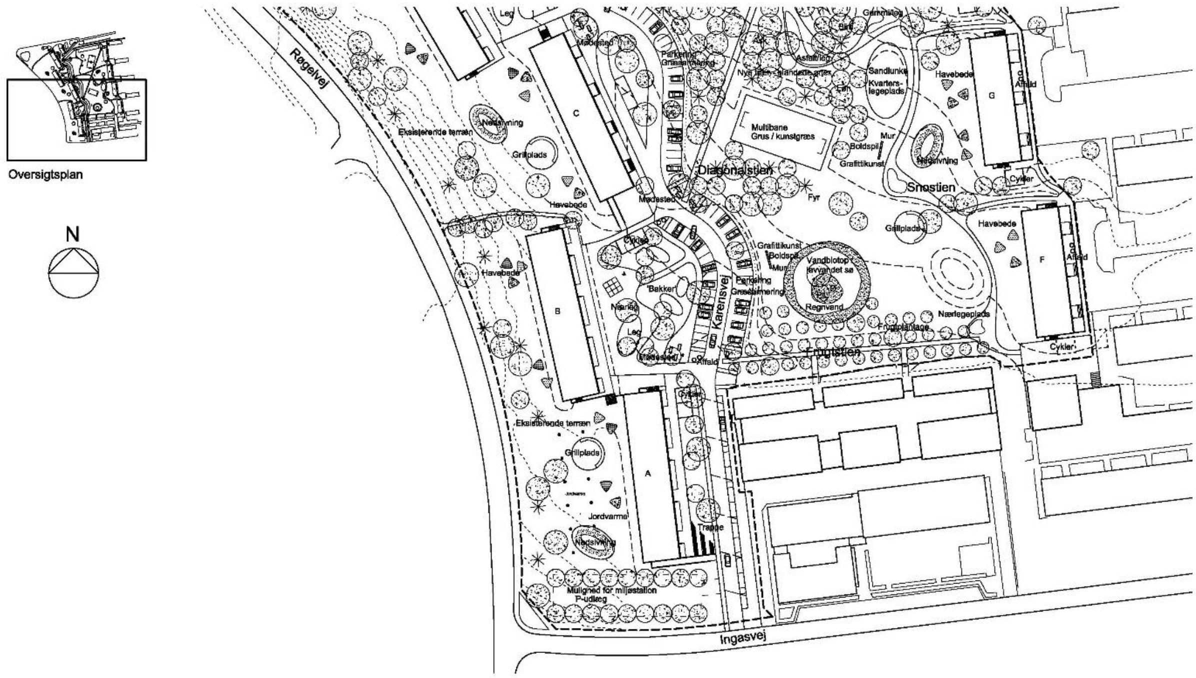
Parameter		Parameter values					Cost of EEM [€]				Notes
		Existing building	1	2	3	4	1	2	3	4	
Pn	[W/m^2]	15,2	13,36	9,69	5,76	5,24	139,92	289,44	360	504	value refers to a standard class room of 46m^2
Fo	[-]	1	1	0,9	0,9		66	120	242		value refers to a standard class room of 46m^2
Fc	[-]	1	0,9	1	0,9						

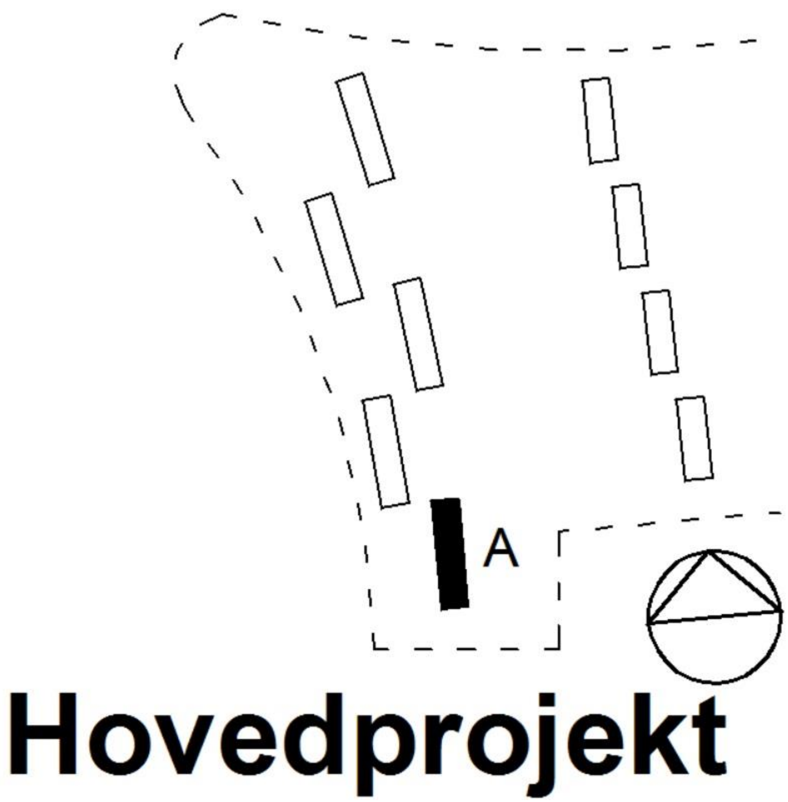
Appendix 3 – The renovation of the building block 'A' related to the Skovgårdsparken renovation project located in 8220 Brabrand, Denmark

In the following I will provide a small selection of the as-built drawings belongs to only 'building block A' (that means 1 building block out of the 9 – this is due to the similarities between the building blocks) renovation. These will be provided only for further understanding of the case, which has been analyzed in section 8.4.3.2.

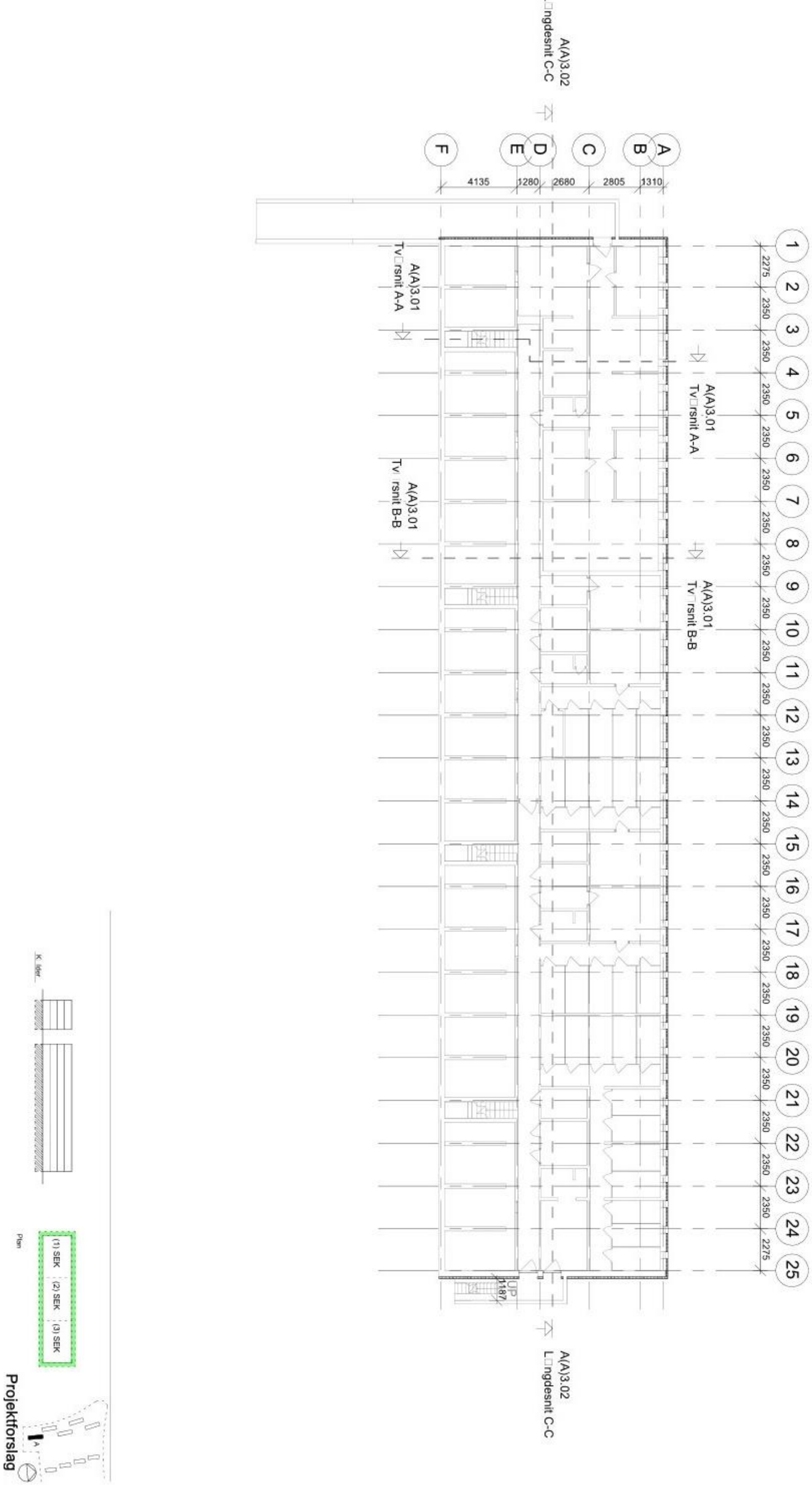
- Site plan of Section 3 of Skovgårdsparken -

- Building block ‘A’ position in Skovgårdsparken renovation project –

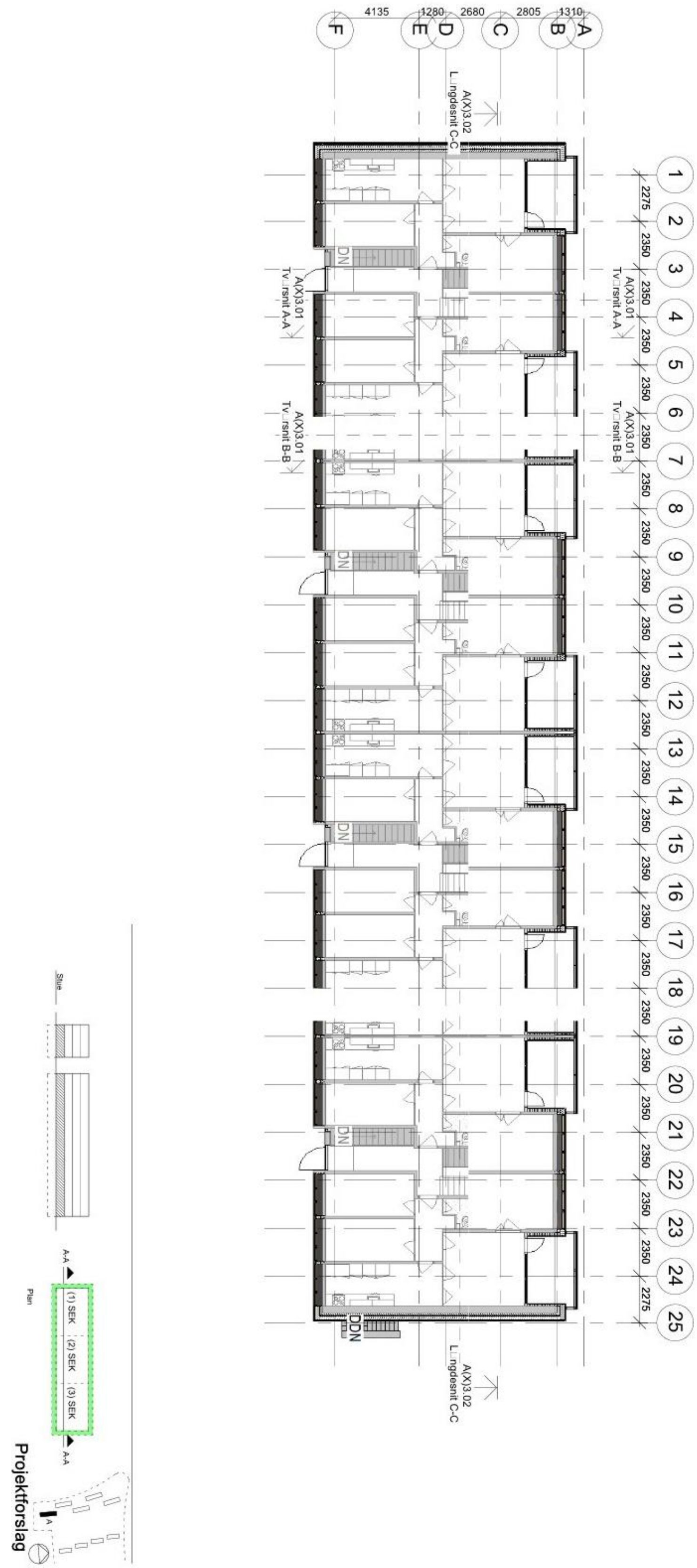




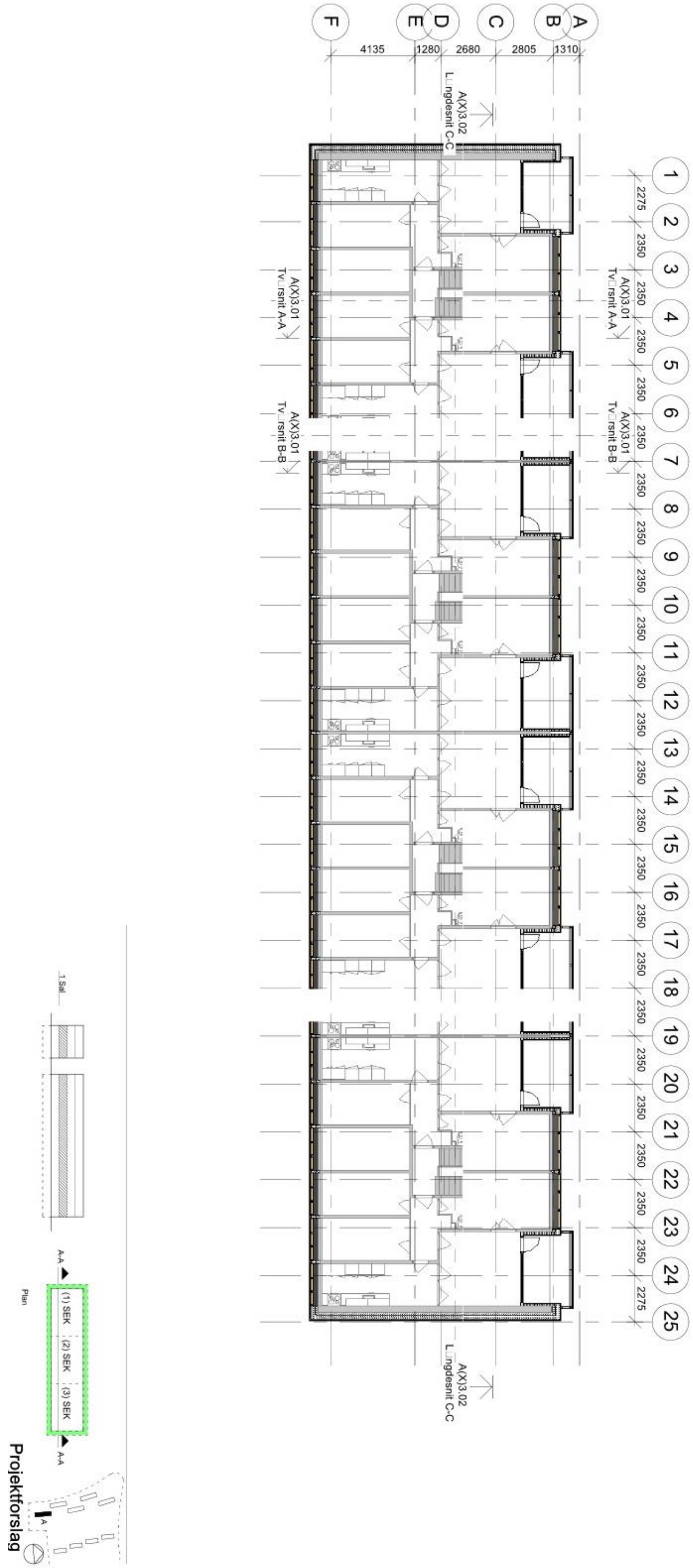
- Block ‘A’ Basement plan (as-built) -



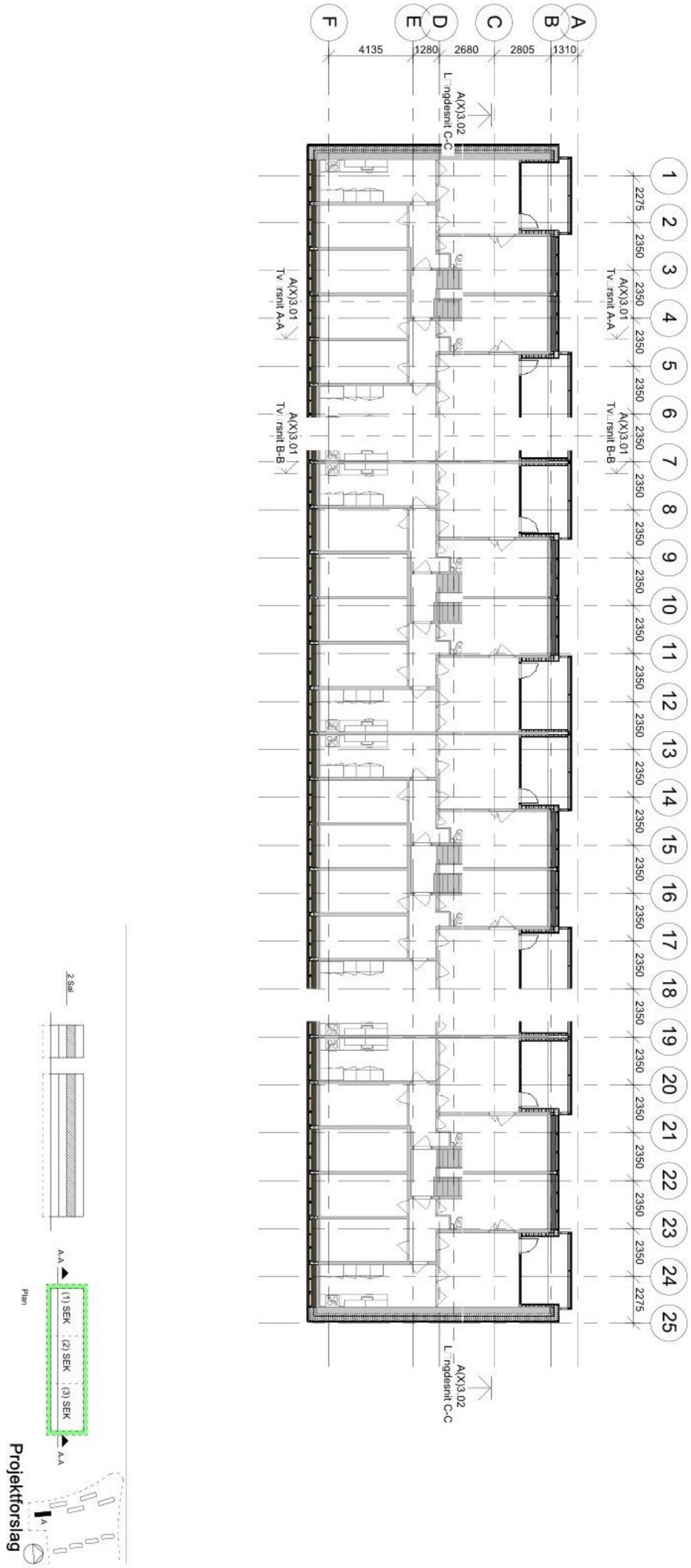
- Block ‘A’ Ground floor plan (as-built) -



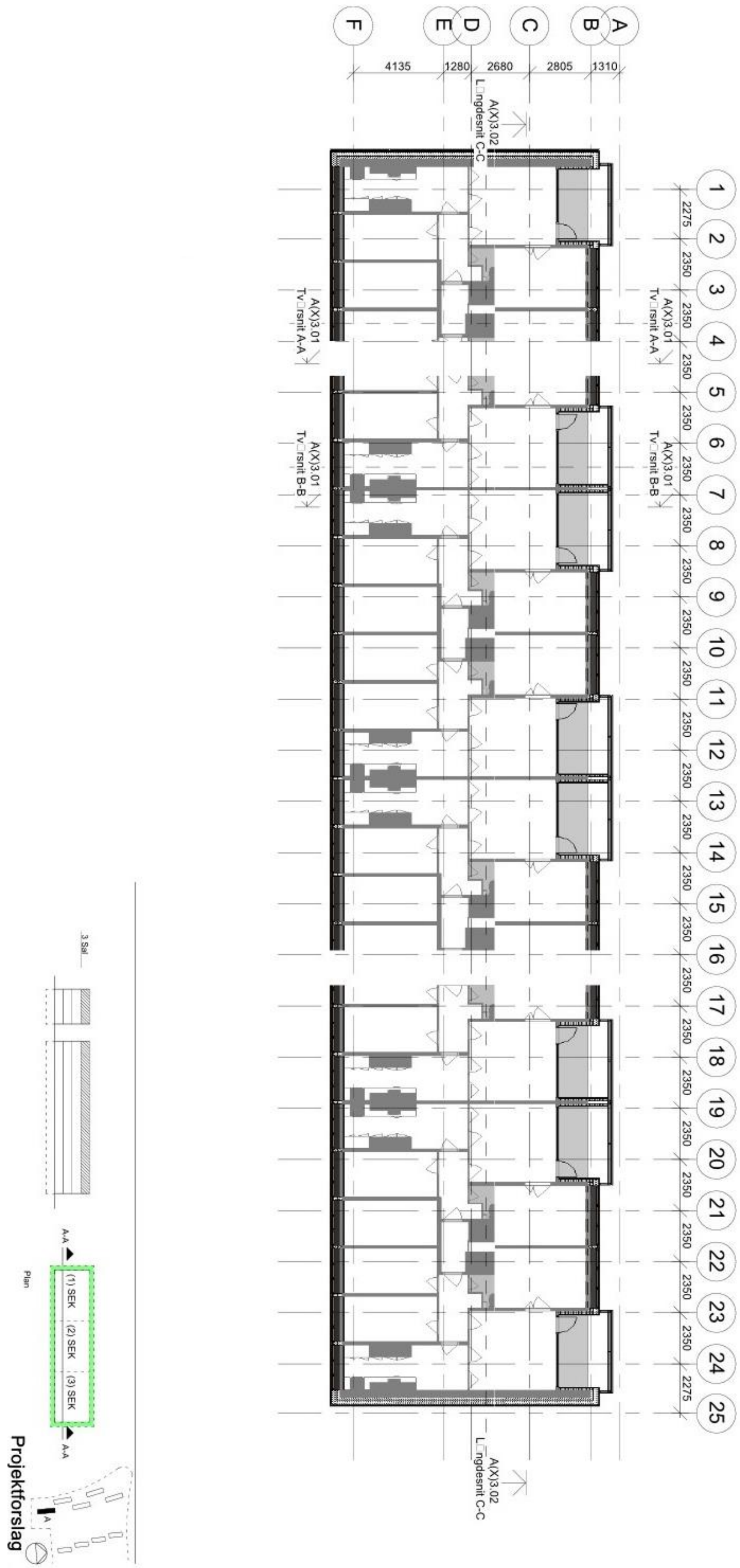
- Block ‘A’ First floor plan (as-built) -



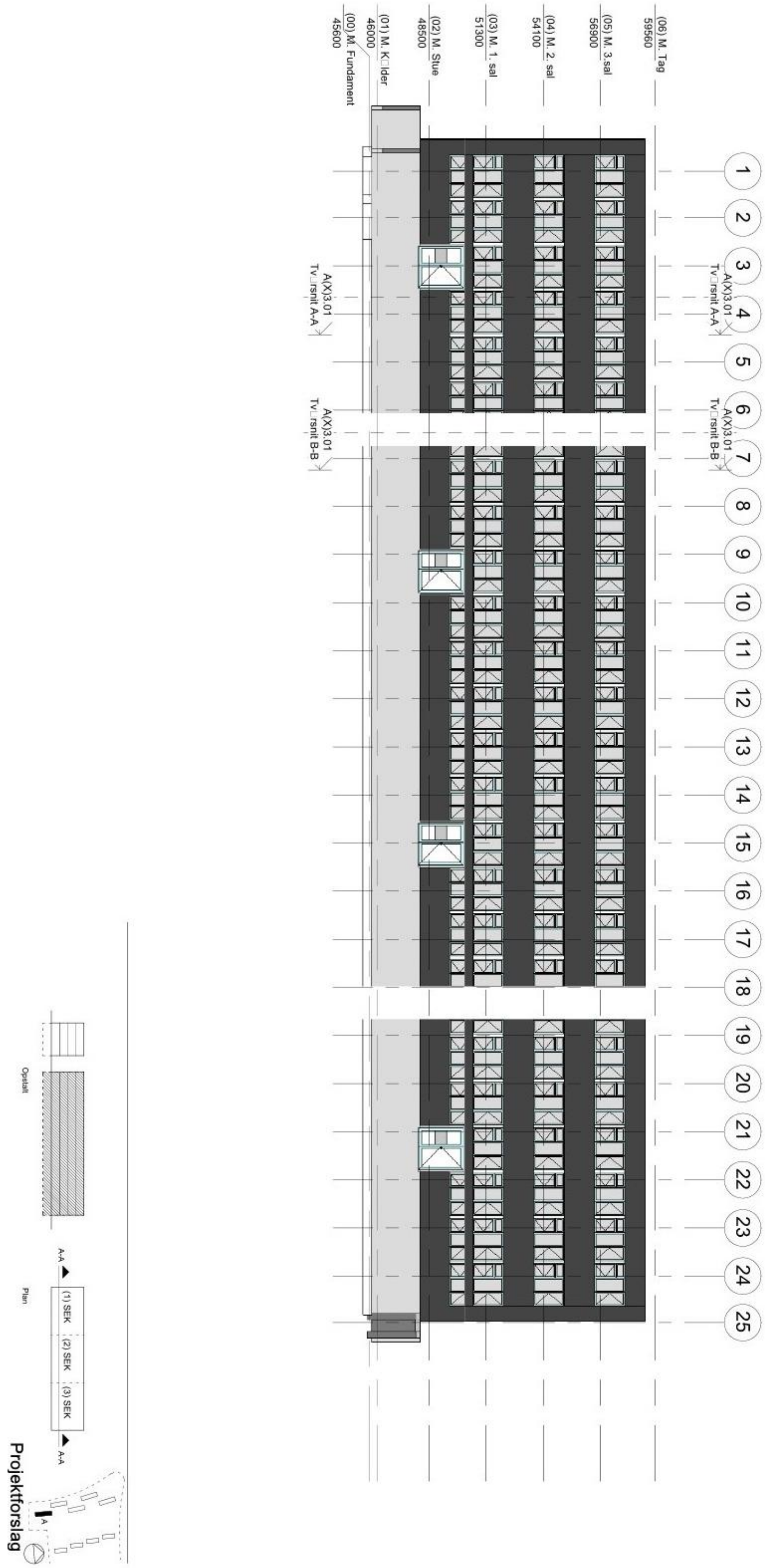
- Block ‘A’ Second floor plan (as-built) -



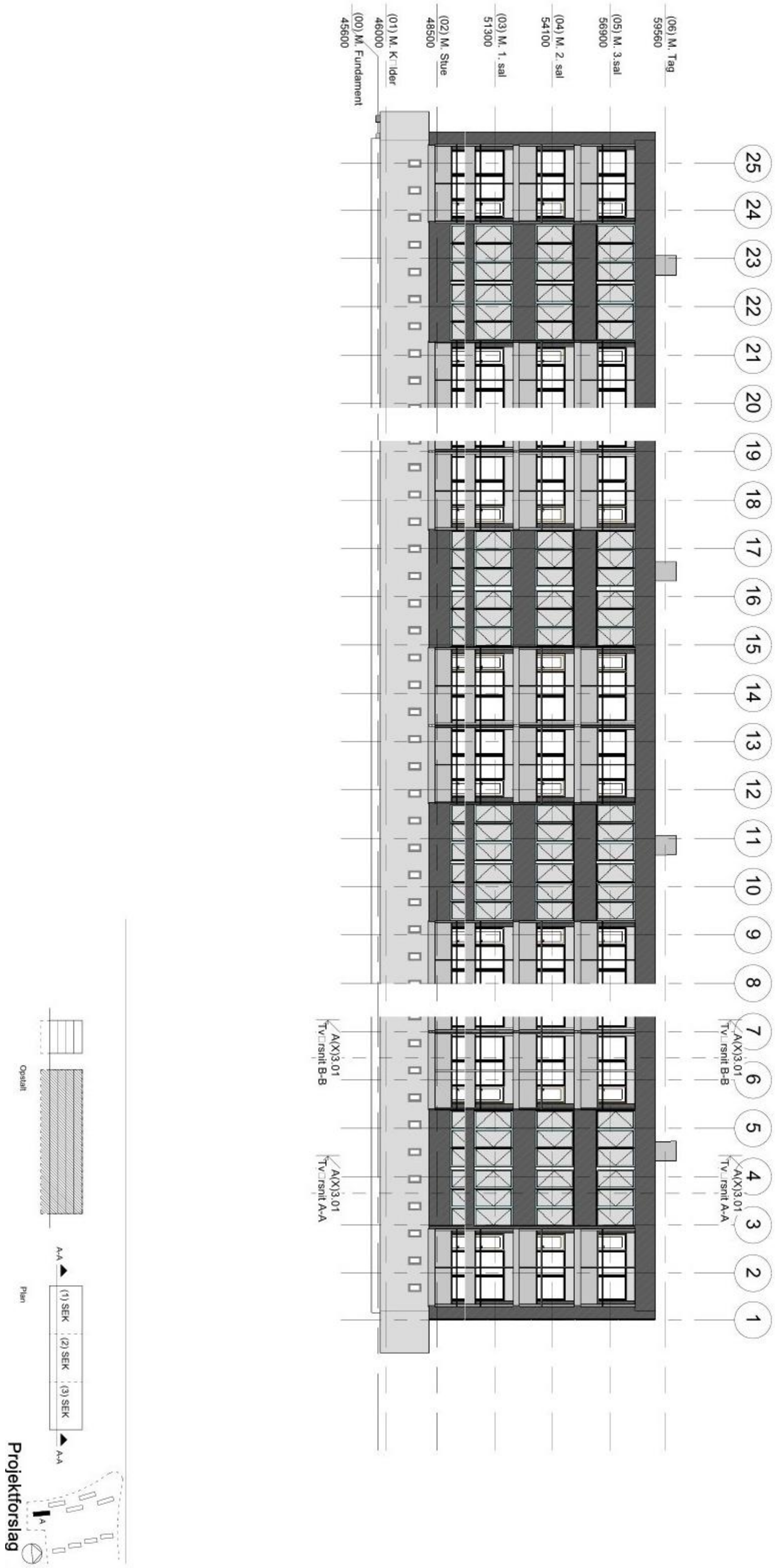
- Block 'A' Third floor plan (as-built) -



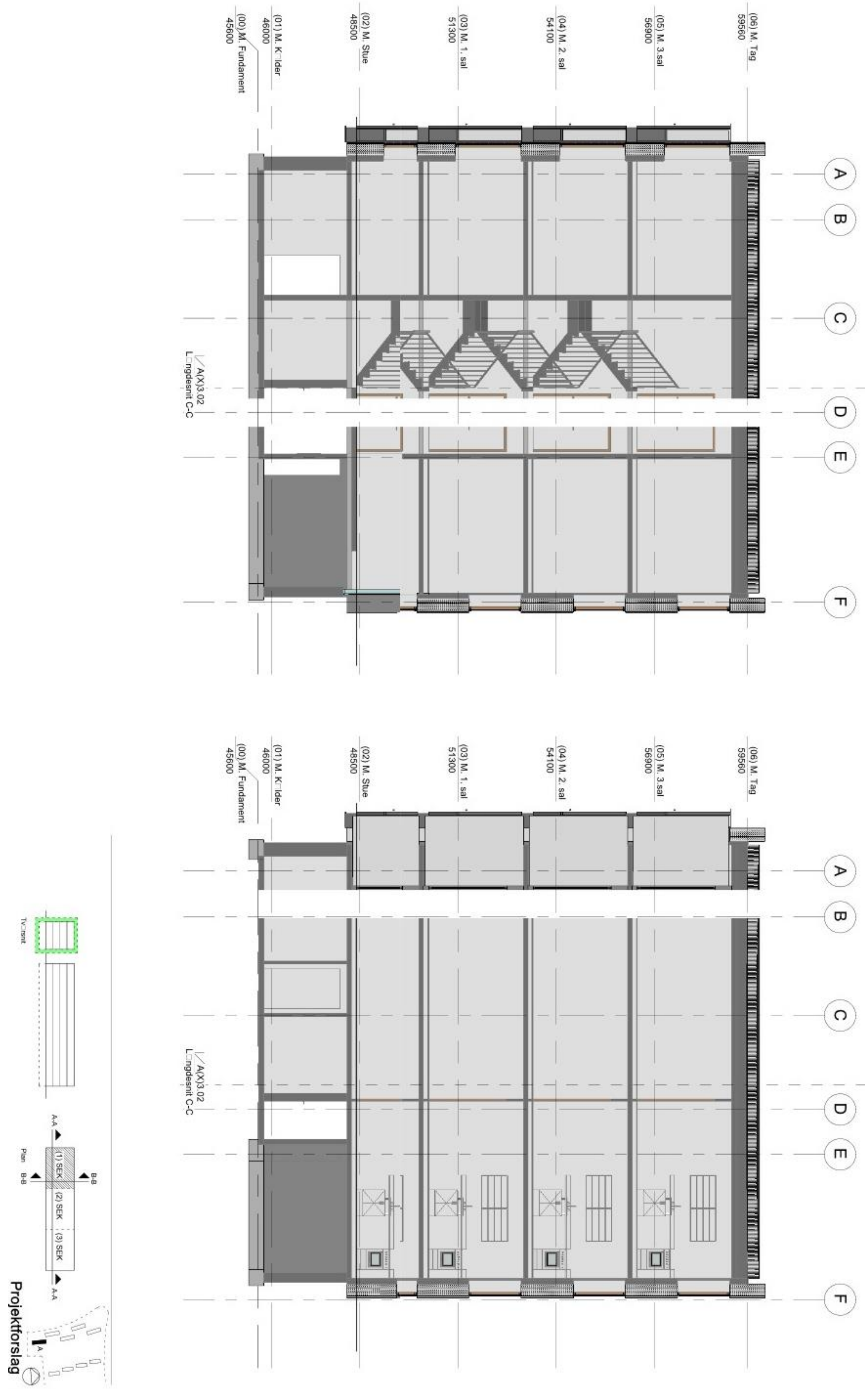
- Block ‘A’ Elevation east (as-built) -



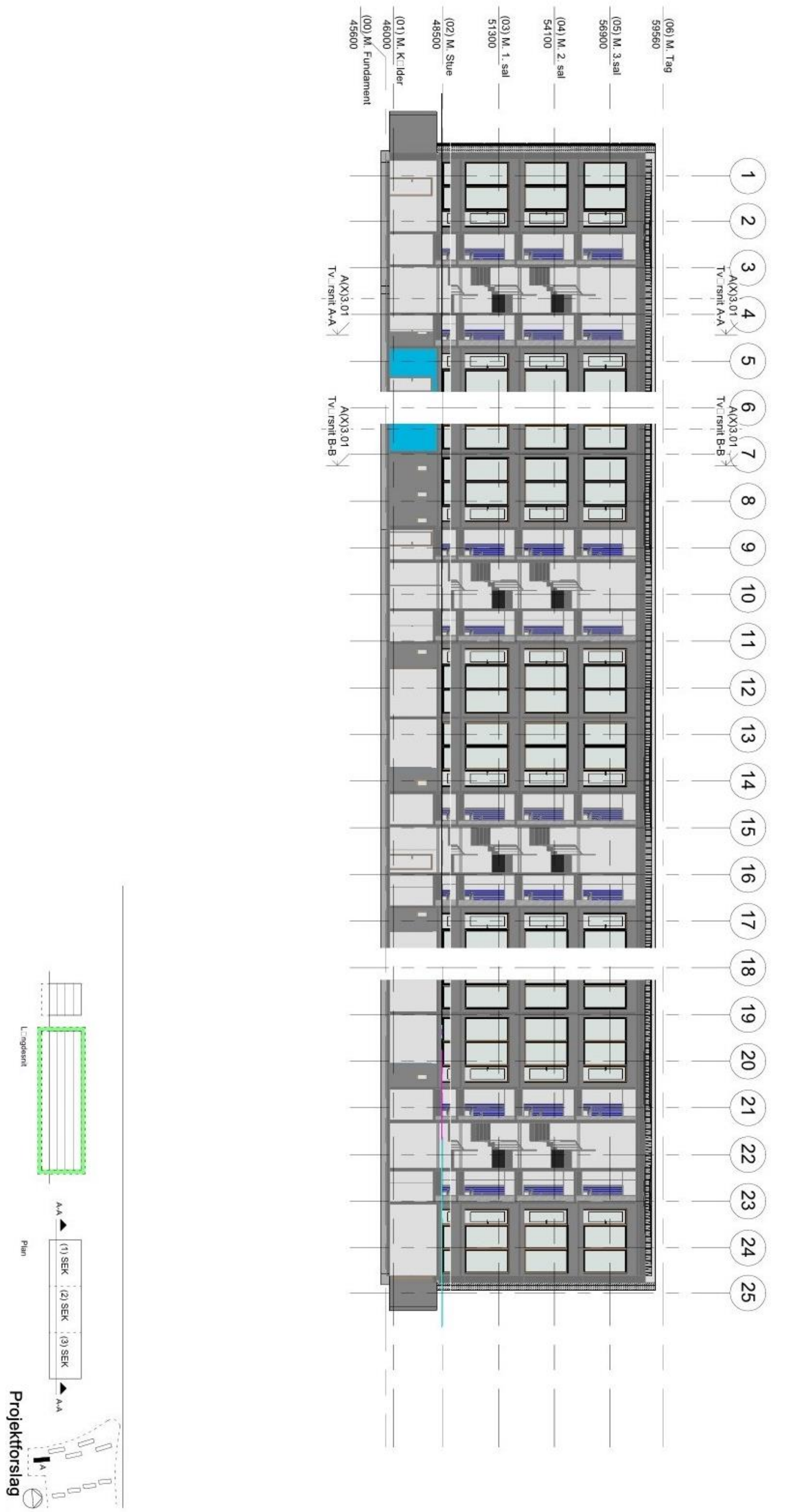
- Block ‘A’ Elevation west (as-built) -



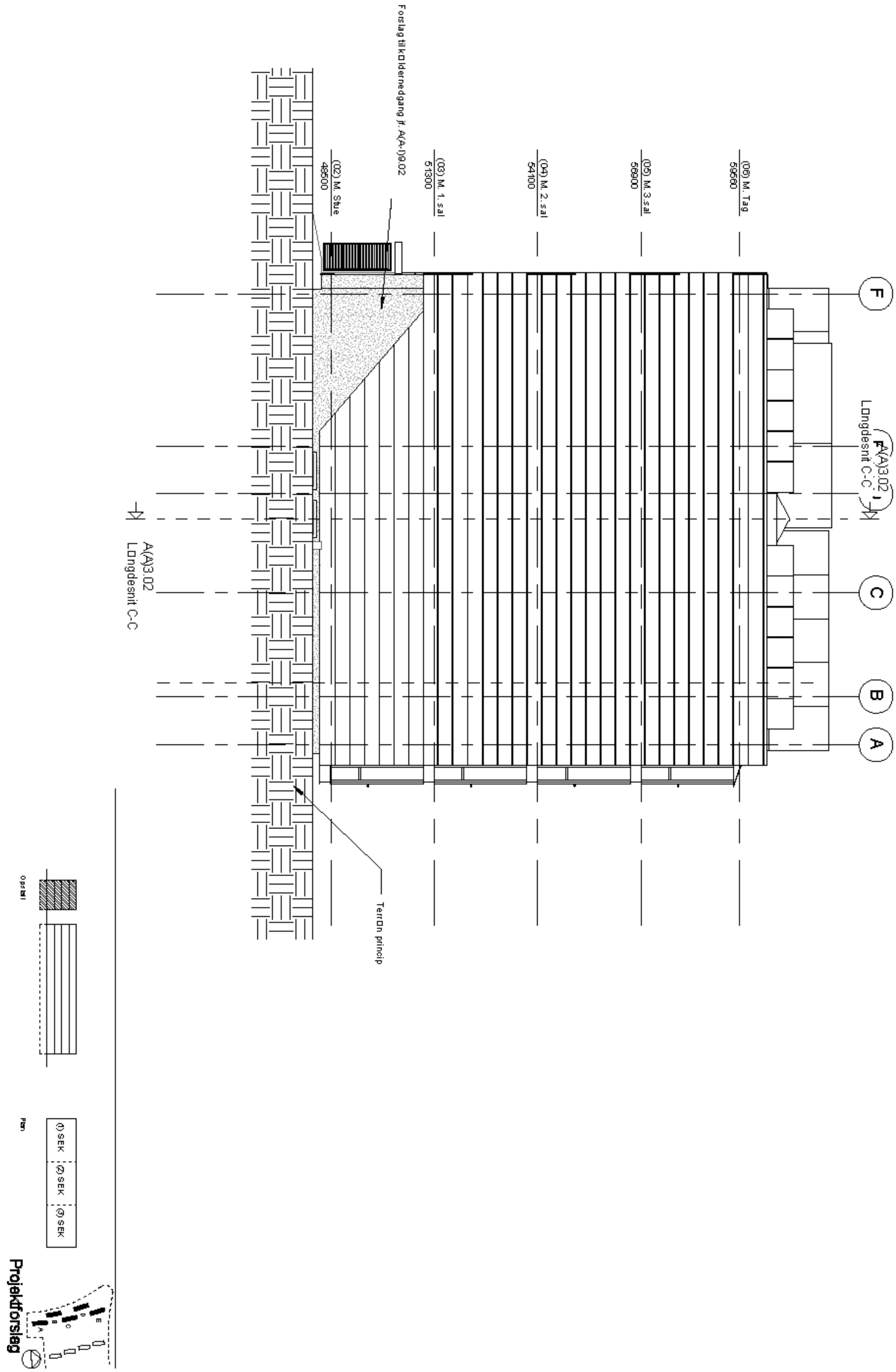
- Block ‘A’ Cross section A-A & B-B (as-built) -



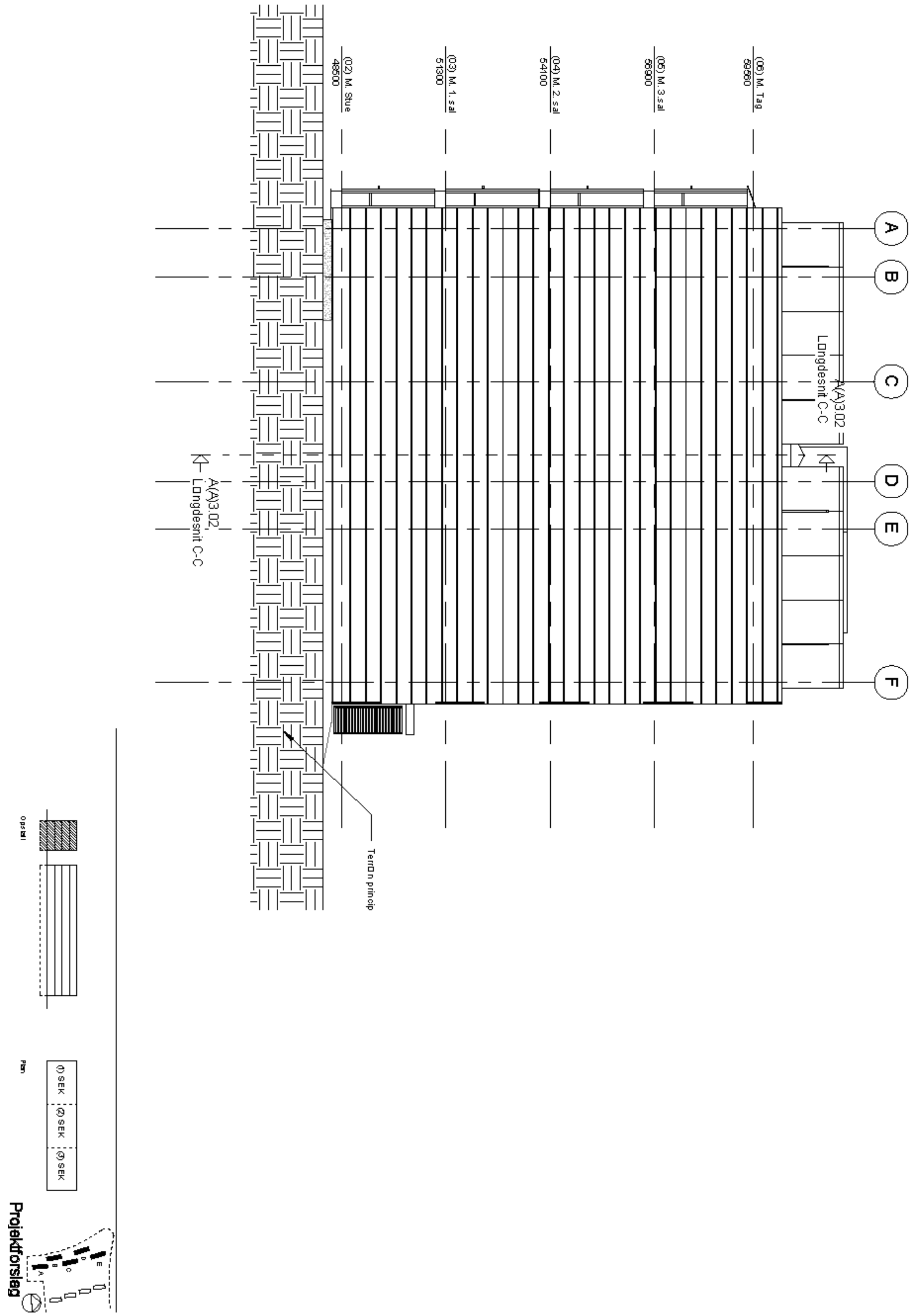
- Block 'A' Longitudinal section C-C (as-built) -



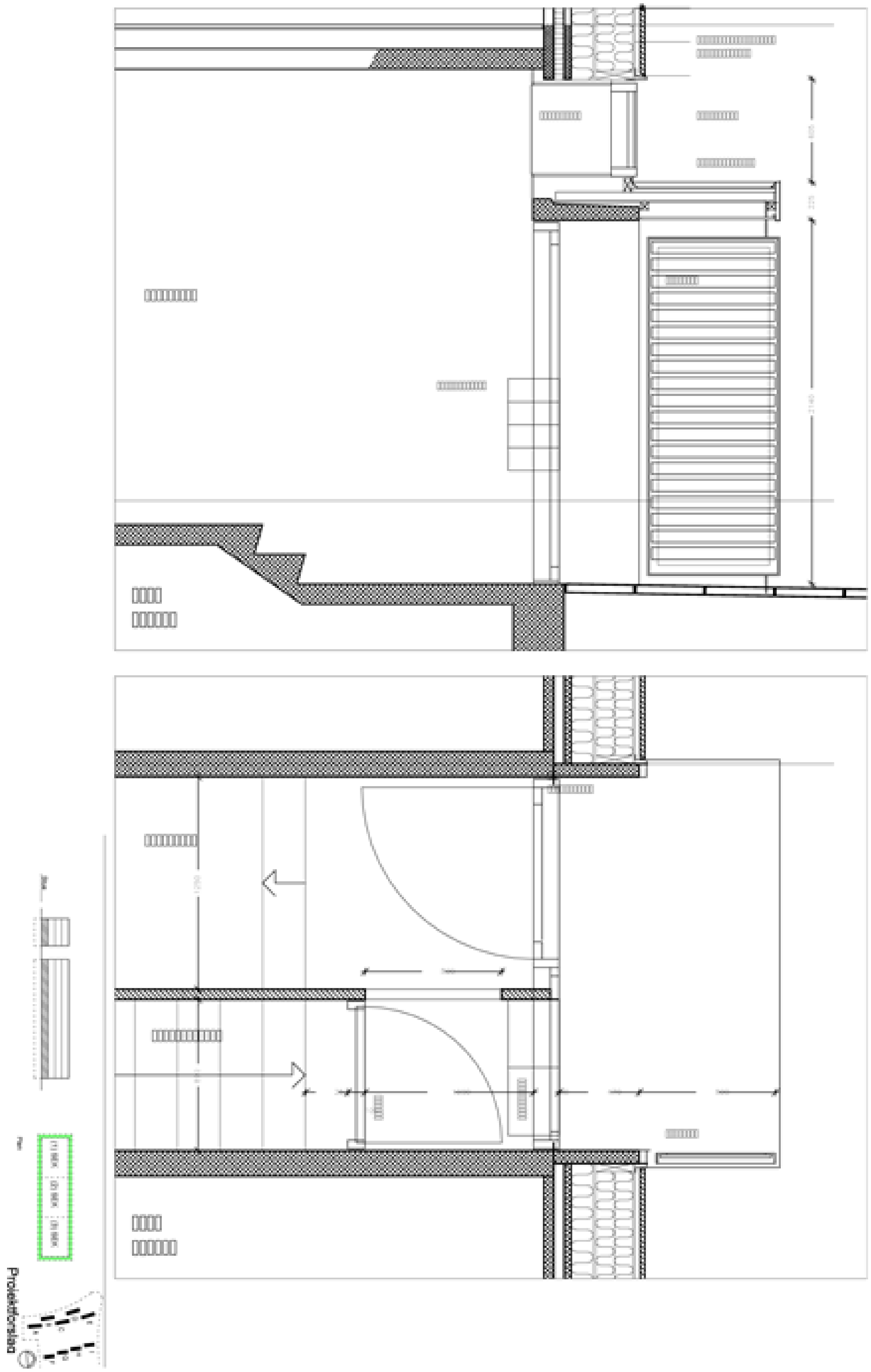
- Block 'A' Elevation north (as-built) -



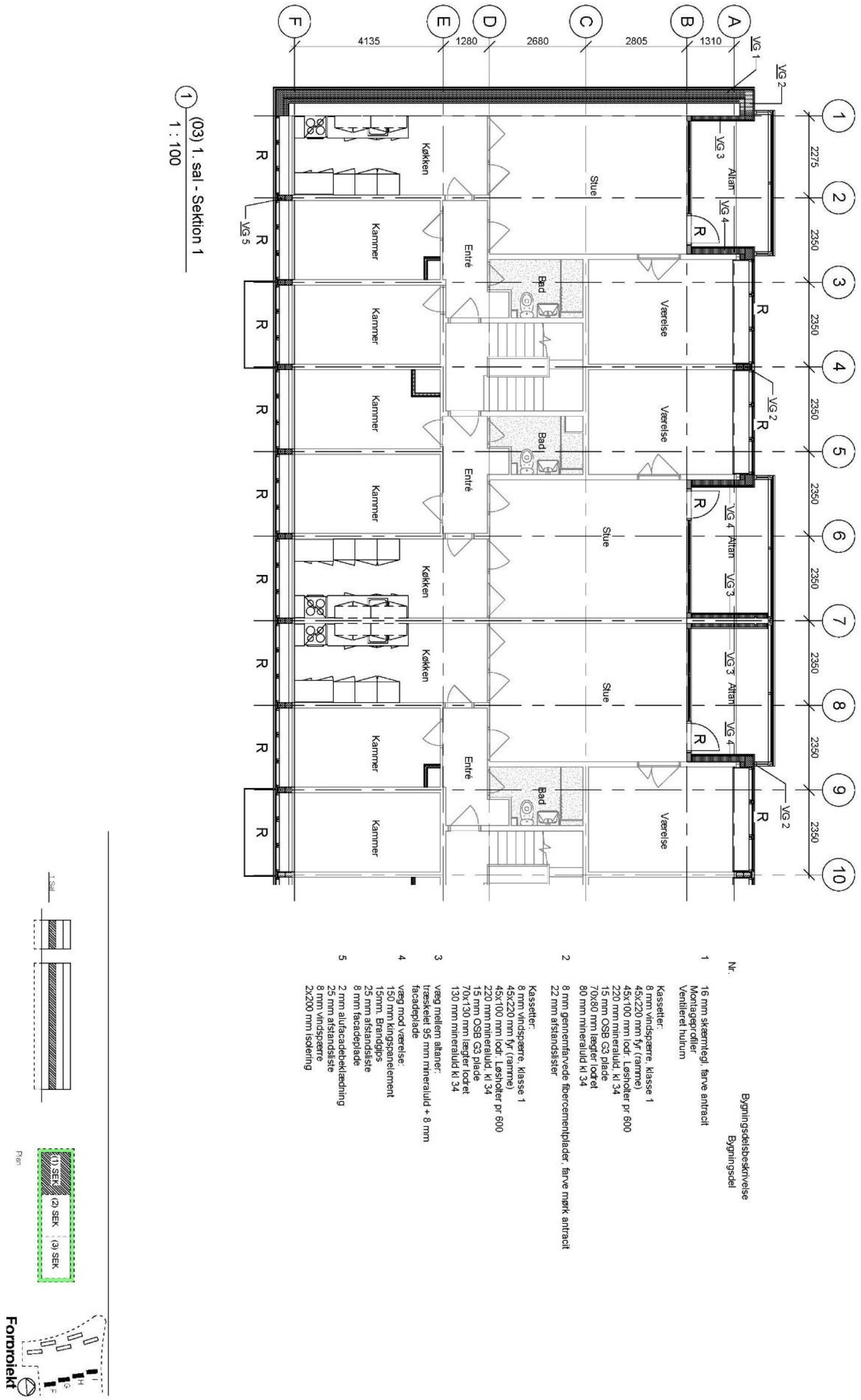
- Block ‘A’ Elevation south (as-built) -



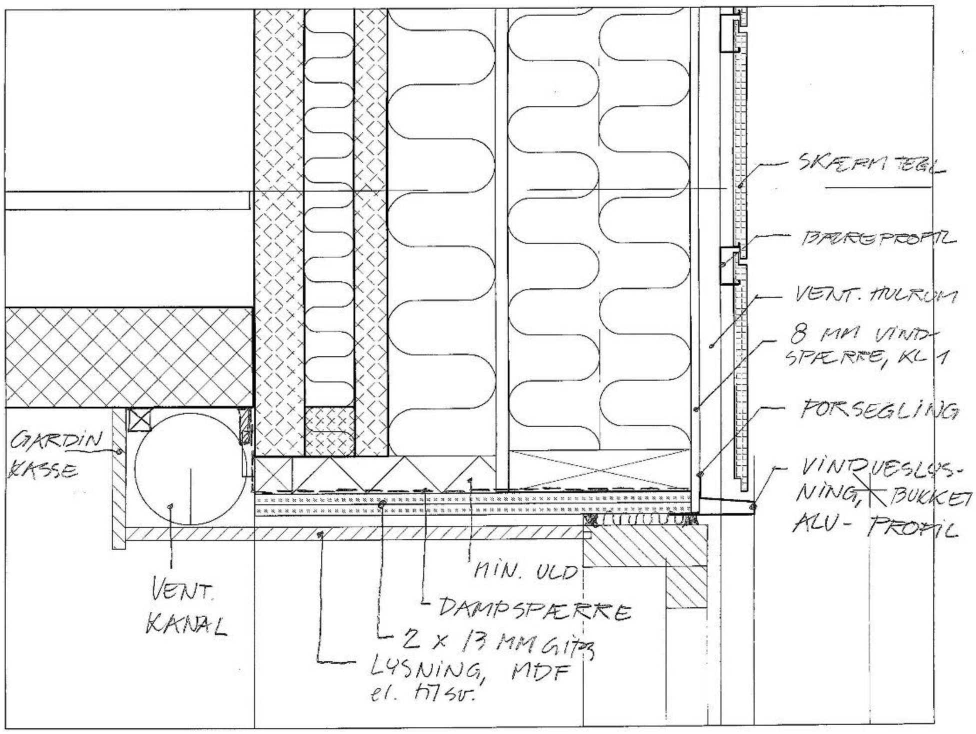
- Block ‘A’ Entrance (as-built) -



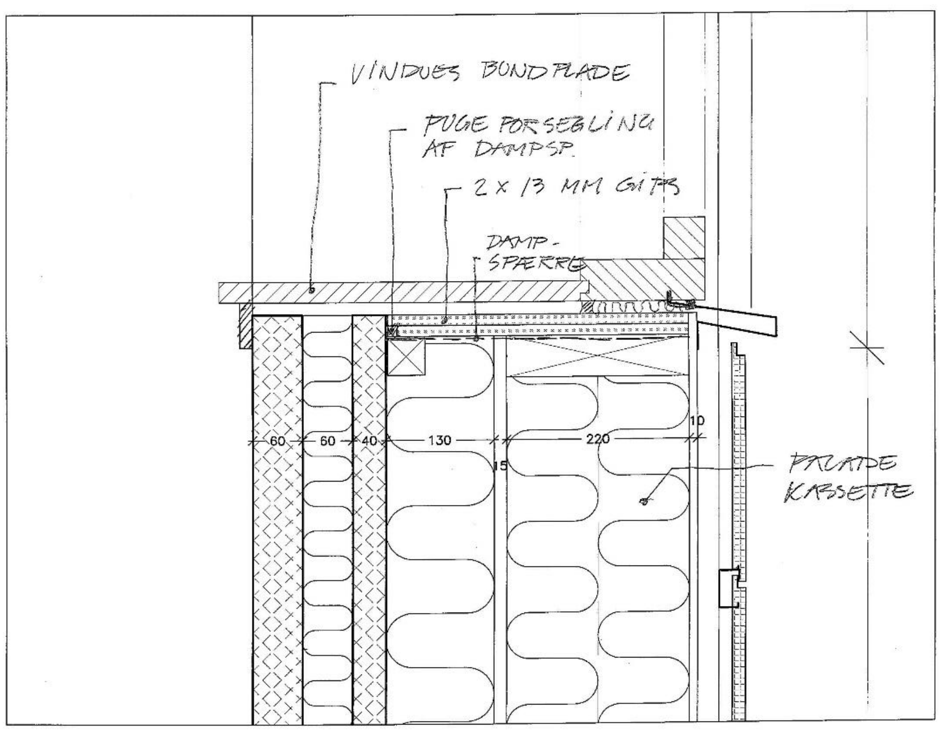
- Example given for the details about wall structure and insulations -



- Example given for the details about wall structure -

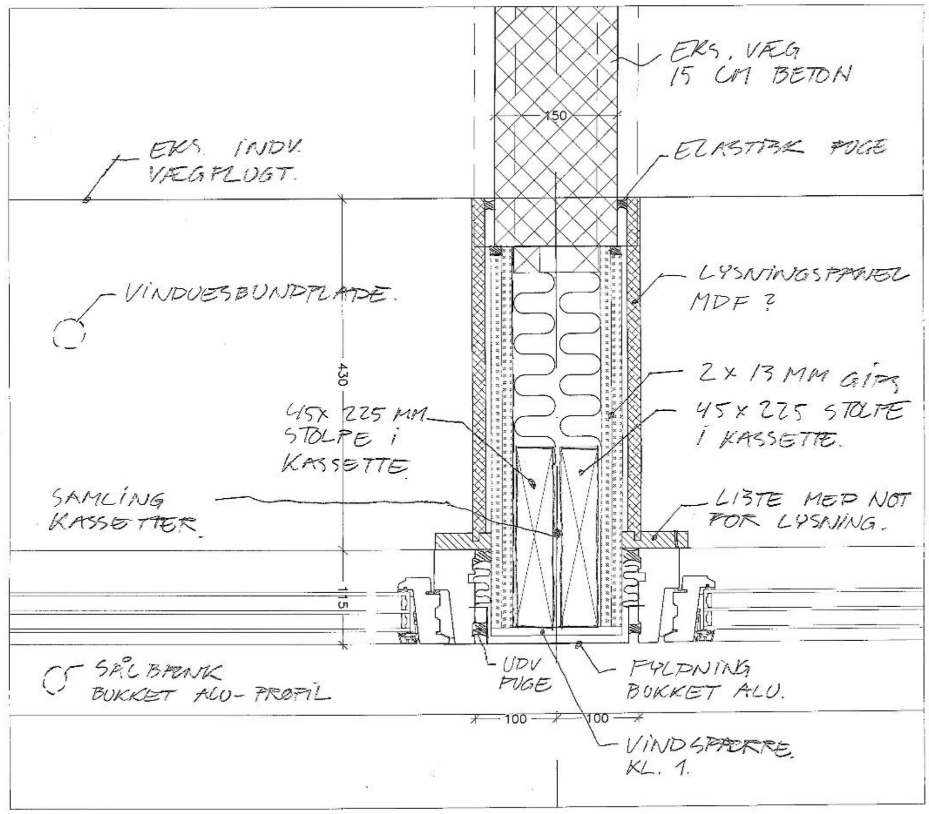


Lodret snit, vindue i indgangsfacade, overkarm
1 : 5

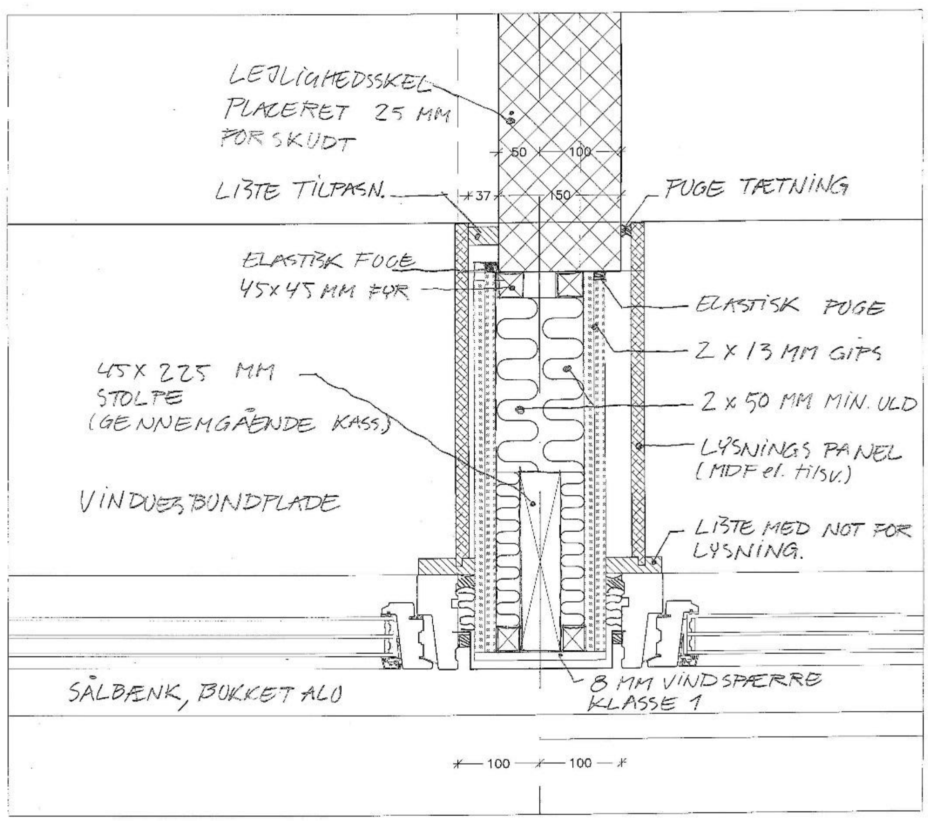


Lodret snit, vindue i indgangsfacade, bundkarm
1 : 5

- Example given for the details about wall structure -



Vandret snit, Lejlighedsskel - samling kassetter
1 : 5



Vandre snit i lejlighedsskel (25 mm forskudt),
kassett ; gennemgående

Aliakbar Kamari, b. 1987, was graduated from Department of Architectural Engineering at IAU, IRAN in 2009 and subsequently joined as an architect engineer in consultant corporations, twice, more than 4 years. Since 2010, he commenced his postgraduate degree and then graduated from Department of Civil Engineering in the field of Construction & Management at University of Pune, INDIA in 2012. Then, he worked as an instructor in "Tehran Institute of Technology" since 2013 involving in research and teaching activities over the topic "Building Information Modeling" (BIM) and its related software. He spent the triennium of his Ph.D studies for a fully funded double degree Ph.D program in Department of Architecture, University of Palermo, ITALY, and Department of Engineering, Aarhus University, DENMARK, carrying out an INTERDISCIPLINARY research study related to Renovation/Retrofitting of the Existing Buildings. In this period, he has collaborated to the Danish RE-VALUE research project as well. Some of Aliakbar's works have been published in conference proceedings and journals.

Aliakbar's research study in this thesis has explored development of a multi-methodology and sustainability-supporting framework for implementation and assessment of a holistic building renovation. The thesis adopted a multi-dimensional approach, namely the qualitative research approach, and the inter- or transdisciplinary research throughout mode 2. It includes the terms Building Renovation/Retrofitting; Sustainability; Sustainable Renovation; Methodology; Design Methodology; Multi-methodology; Problem Structuring; Soft Systems Methodology (SSM); Multi Criteria Decision Making (MCDM); Complexity; Holism; Decision Support Systems (DSS); System Architecture; Decisions Architecture; Tectonics. The outcomes propose a framework, which is intended to serve as a platform for refining and improving the contemporary building industry seen in the light of sustainability, by supporting the decision-making in the development of holistic renovation scenarios and entitled Tectonic Sustainable Building Design (TSBD). Aliakbar is vastly interested to perform further research related to concept of Methodology, Design Methodology, Problem Structuring, BIM and BIM-based Decision Support Systems in building design sector. This entails to include Systems Oriented Design (SOD) principles through use of BIM. Therefore, the concept of BIM needs to be discussed, addressed, and expanded as an equipped design methodology for the future of building design sector.