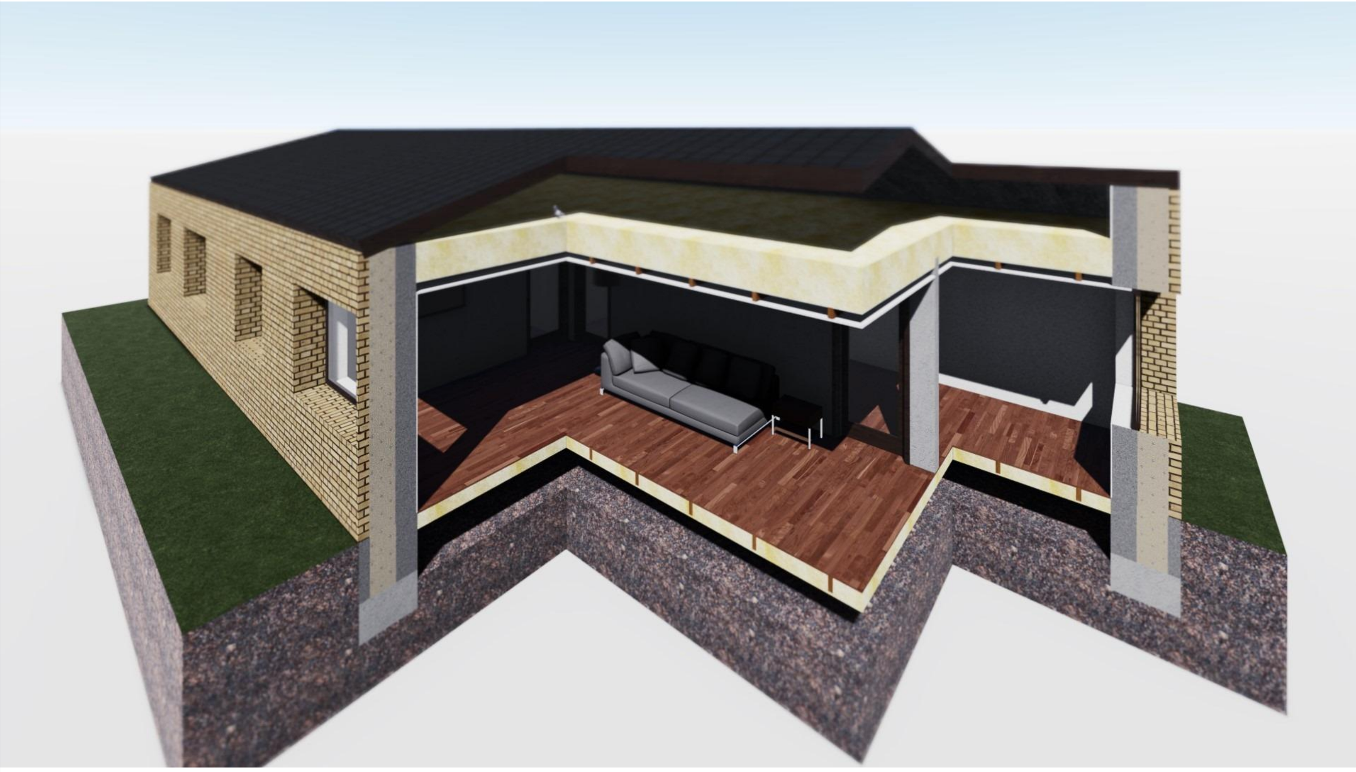
Building Energy Desing



Staged renovation methodology for single-family houses

Master Thesis

AALBORG UNIVERSITY
DENMARK

BED_1.310 Aalborg 2019 January

Building Energy Design
Master Thesis
Thomas Manns Vej 23
DK - 9220 Aalborg Øst

AALBORG UNIVERSITET
STUDENTERRAPPORT

Title: Staged renovation of single-family houses

Semester: Fourth semester

Semester theme: Master Thesis

Project period: September 2018 - January 2019

ECTS: 30

Supervisor: Michal Pomianowski, Yovko Ivanov Antonov

Projectgroup: BED4 1.310

Andras Cedl

Andras Levente Szeker

Rafael Baptista

Pages: 214
Appendix: 70 pages.

Nomenclature and Abbreviation

Nomenclature

Symbol	Unit	Description
A	m^2	Area
ach	-	Air change rate per hour
VFR	%	Volume Flow Rate
n	year	Economic lifetime
n_t	year	Technical lifetime
t_i	K	Indoor temperature
t_o	K	Outdoor temperature
η	%	Efficiency
q	m^3/h	Volume flow
r	%	Real interest rate
I	DKK	Investment Cost
$U - value$	$\frac{\mathrm{W}}{\mathrm{m}^2\mathrm{K}}$	Heat transmission coefficient
SFP	kJ/m^3	Specific fan power
P	Pa	Pressure
ppm	mg/kg	Parts per million
t	h	time

Abbreviation

Abbreviation	Full Meaning
IEQ	Indoor Environmental Quality
CCE	Cost of Conserved Energy
LCC	Life Cycle cost
$BR18$	(Dansih) Building Regulations 2018
DB	Design Builder
$PVcells$	Photo Voltaic cells
$HVAC$	Heating, Ventillation, Air-condtinioning
$EPS80$	Expanded Polystyrene
DS	Danish Standard
AHU	Air Handling Unit
CAV	Constant Air Volume
VAV	Variable Air Volume
HS	Higher Standard
MT	Maintenance
EER	Energy Efficient Renovations
EEM	Energy Efficient Measures
NPV	Net Present Value
IEQ	Indoor Environmental Quality
EU	European Union
PE	Primary energy
SE	Site energy
$NZEB$	Nearly Zero-Energy Buildings
EPC	Energy Performance Certificate
$EPBD$	Energy Performance of Buildings Directive
SBi	Statens Byggeforskningsinstitut
SFH	Single Family House

Concept definitions

To avoid ambiguity and misinterpretations, the following concepts have been defined for this thesis.

Extensive renovation
Where a majority of part of the building components and systems are renovated.

One-off renovation
Building renovation performed at once to achieve the designed goal.

Renovation Measures
Is the collective term for the followings:

- **Energy Efficiency Measure (EEM)**
  Renovation works that decrease the energy consumption of the house or provide renewable energy at the site
- non-Energy Efficiency Measure (non-EEM)
  Functional renovations that have no energy saving benefit, but otherwise improve the

usability or aesthetic of the house

- Maintenance works or Anyway maintenance Necessary replacement of building components or system required to be carried out to uphold the usability of the house.

Holistic renovation
A building renovation that includes aesthetic, functional, technical, and economic considerations.

Method
A specific course of action(s) for attaining results

Methodology
Collection of methods

Co-benefits
"Co-benefits refers to all benefits (positive or negative) resulting from renovation measures related to energy and carbon emissions optimized building renovation, besides or as a consequence of energy efficiency increment, carbon emissions reduction or costs reduction"[61].

Staged renovation
Staged renovation is a process of renovate a building that the implementation of the renovation measures applied over time in stages. The time period difference could vary from month to decades.

Preface

This project was writing in the period from 3^{rd} of September 2018 to 10^{th} of January of 2019. It is a master's thesis to obtain the master degree for the Building Energy Design program from the Aalborg Univerity. The master's thesis corresponds to 30 ECTS points, and is prepared by Andras Cedl, Andras Levente Szeker, and Rafael Baptista . The project has been guided by Associate Professor Michal Pomianowski and Ph.D. Fellow Yovko Ivanov Antonov.

The project group would like to express their gratitude to Associated Professor Michal Pomianowski and Ph.D. Fellow Yovko Ivanov Antonov for the guidance and great attention throughout the master thesis semester.

Finally, we must express our very profound gratitude to our family and friends for providing us with unfailing support and continuous encouragement throughout the years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without them. Thank you.

Abstract

To reach the 2050 goal of reduced carbon emissions in Denmark due to energy consumption, solutions for reduction and sustainable production of energy is required. Within the building sector, single family houses account for 22% of the country's total energy consumption. In the existing stock one of the largest improvements could be achieved by improving parcel houses built between 1960-1979 due to their poor energy performance and large number.

Due to various barriers the amount of energy efficiency renovations of recent years is not sufficient to reach the reduction goals of 2050. As suggested by other research, staged renovation can be a viable solution to many of the common issues with energy efficient renovations. However there is a lack of research about this, thus the goal of the thesis is to provide a better insight into the applicability of staged renovation.

The project includes the development of a staged renovation methodology, that is designed to overcome the mentioned barriers. The methodology was developed with a holistic approach, focusing not strictly on energy savings, but other aspect's that could motivate homeowners to energy renovate and reach a low energy frame for the building in the end. The development of the methodology was substantiated by a literature review, including several surveys about typical renovation practices and decision making of homeowners, their financial situation and habits, and various preferences. For testing the methodology, a parcel house was chosen, that can represent the majority of buildings constructed between 1960-79. By determining the frequency, order and size of the stages, a final implementation sequence prioritizing energy savings was concluded. To substantiate the effect of this stage renovation, the following evaluations were conducted: LCC analysis for financial application, quasi-steady state simulation for energy use and dynamic simulation for indoor environmental quality. The results show, that it is possible to implement the renovation measures into staged packages with a holistic view and in a order that takes into consideration the priority of the homeowner. Performance of the building during the stages was evaluated and improvements were concluded. The dynamic simulation are important to investigate the house condition after renovation stages. The financial evaluation of the staged renovation showed that staged renovation can be more beneficial in 30 years than maintain the house in its original conditions. The comparison of staged renovation and one-off renovation showed that staged renovation can be more beneficial when considered the house been sold.

Contents

List of Tables

List of Figures

1 | Introduction

1.1 Background

For several years, the reduction of greenhouse gas emissions has been a priority for the EU. Buildings and construction together account for 39% of energy-related carbon dioxide (CO_2) emissions in the EU (Global Status Report 2017). In Denmark, single-family houses constitute a significant part of consumed primary energy (22%), according to the Danish Energy Agency. During the period of 1960 to 1979, a large number of detached houses were built, with low requirements of thermal insulation. The amount of these houses with poor insulation poses a large potential target for energy savings. Since they will still be in use in 2050, their energy efficient renovation is much needed. Technology allows buildings to be renovated to Nearly Zero-Energy Buildings (NZEB), but to reach the 2050 goal of reducing carbon emissions, a more widespread, acceptable and cost-efficient implementation is required [39] [51] [30].

Barriers to Energy Efficiency Renovations (EER) are mostly financial-related, but there are other aspects, that have to be considered, in order to motivate homeowners. There is a need for new approaches and alternative solutions to whole-house renovations and their planning, especially for people who cannot afford the extensive investment. This is based on recent research [5] [13] and their conclusions and suggestion, what are the basis of this thesis. People are more used to maintaining their homes on a yearly basis, as they live in it. Their finances do not always allow large investments, that will also create an undesirably long disruption to their everyday life. By creating a long-term, staged renovation plan, it could be possible to remedy these issues, thus increase the number of energy-related renovations. But current literature in this field presents the idea of staged renovation only in a preliminary way. The focus is more on identifying barriers and finding motivators. There is a lack of studies, investigating its applicability. Thus there are no practical methods.

1.2 Purpose

State of the art research in the energy sector of buildings points towards over-time renovation with a holistic considerations a possible solution to overcome common barriers that slow down the number of energy renovations in single-family houses to increase all over the EU. However, these indications are rather passive, without practical methods and such renovation approaches are not well studied in Denmark. The purpose of this report is to develop and investigate the potential of a staged renovation approach that could benefit households that cannot or would not carry out an one-off extensive renovation. The underlying goal is to contribute to increasing the number of energy renovations of single-family houses in Denmark, thus reducing energy consumption, greenhouse gas emissions, along with improving human comfort. By doing this, the project adds to the existing body of knowledge, thus filling a gap within this problem area.

1.3 Research question

How does a holistic staged renovation needs to be built up so that homeowners would consider it beneficial and appealing? What are these benefits?

In order for this to be answered, there is a need to ask further sub-questions. These will, later on, guide the paper's structure.

1. What are the barriers and motivators to energy efficiency renovations?
2. How can a staged renovation pose a solution to the most relevant barriers?
3. What needs to be considered in a staged renovation for it to be more applicable in the context of common house renovation practices and current priorities of the homeowners?
4. How can an extensive renovation be divided up in order to form the basis of a staged renovation? How would the stages be ordered and according to what?
5. What are the factual benefits, such as monetary value, energy consumption and increased comfort?

1.4 Structure of the project

In order to explore recent development and shortcomings within the field of energy renovation of houses, a literature review is carried out in chapter 2. By this, barriers and motivators to energy renovation and suggestions for possible solutions are identified. Both theory and practice will be examined to obtain a representative view of the problem area. The current practices of home renovations are assessed to aid in the methodology creation.

In chapter 3, the staged renovation is developed. First, considerations for the methodology creation is presented and alter the methodology resulted from the considerations is presented.

To investigate the applicability and theoretical potential of the staged renovation methodology created, in chapter 4, the methodology is applied in a case building. First, a evaluation of renovation measures that is not part of the staged renovation methodology is made to compile the energy improvement solutions of the building components and systems. Second, the found renovation solutions are then combined as an extensive renovation. Third, the methodology is applied to the extensive renovation. The staging process is presented step by step to a scenario where the implementation order of the renovation measures prioritizes energy efficiency. However, the result of the staging process prioritizing other aspects is also presented after. Finally, the staged renovation created is by LCC analysis.

In chapter 5, the application of the methodology and the methodology itself is discussed.

Finally, in chapter 6, the conclusion of the project is presented.

1.5 Delimitation

During the literature review, several barriers and motivators of energy renovations are identified, but not all will be dealt with later on in the project. The main focus of the thesis revolves around the following aspects:

- Energy consumption for room heating
- Economy of the renovations
- Maintenance of homes
- Certain Homeowner characteristics (capital, income, wishes)
- Indoor environmental quality

The extent of the thesis is delimited by the followings, which are not part of the thesis:

- In terms of indoor environmental quality: relative humidity, acoustics, and daylight, as these are either slightly influenced by the renovations or are not considered relevant to improve given the context of single-family houses.
- Small, yearly maintenance of the house as this would not make a difference during the comparison.
- Finding the most cost optimal solution as methods for this task is well researched
- Environmental pollution, e.g. greenhouse gas emissions

2 Literature review

2.1 Background

According to the European Commission, there is a large need for renovation of the existing building stock throughout Europe : *"Currently, about 35% of the EU's buildings are over 50 years old and almost 75% of the building stock is energy inefficient, while only 0.4-1.2% (depending on the country) of the building stock is renovated each year"* stated by the Energy Performance of Buildings Directive (EPBD) [1]. At the most, construction of new buildings in Denmark accounted for only 1% of the whole building stock, and in 2014 it was 0.55%, which means the overwhelming majority of buildings are existing and will still be in use in 2050.

The share of primary energy consumption in total, for Danish single family houses is 22%, moreover, they account 51% of the primary energy consumption for heating in the existing building stock, as visible on figure 2.1.

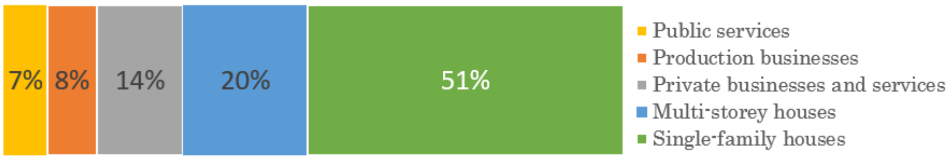


Figure 2.1: Distribution of primary energy consumption for heating in the different sectors of buildings in Denmark. Source: Strategy for energy renovation of buildings, May 2014, Danish Government

For this reason, there is a great potential in the energy retrofit of single family houses in Denmark [52] [41], moreover within detached houses built between the 1960's and 70's, for which a minimum, but rather low insulation standard was required by building regulations in 1961 (*Chapter 8, Varmeisolering*), that was only significantly tightened in 1979.

According to Stastistics Denmark data from 2018 [2], there are a total of 1,036,915 detached single-family houses occupied by homeowners, and 127,803 occupied by tenants. From this total, houses from the 1960s and the 1970s are 411,856 occupied by homeowners and 23,571 occupied by tenants. That means that a representative part, 37%, of the total of single-family housing stock are houses built in the 1960s and the 1970s.

Since these houses are approximately 50 years old, the first bigger renovation due to maintenance is expected to happen around 2020. Also they are in need of modernization and to be made functional compared to the actual life-style of its residents. For this reason, the project deals with such type of houses, due to their potential.

For the sector of single-family houses, the state aims to facilitate energy efficiency through incentives and regulatory requirements. The Building Regulations (BR) are constantly tightening their mandatory requirements in terms of energy efficiency connected to new construction and alteration, conversion or renovation of existing buildings. Also due to the EPBD, Energy Performance Certificates (EPC) are required to be issued for each building that is newly built, undergone major renovation, sold/rented out to a new tenant or for public buildings with a useful floor area larger than 250 m^2. To not only assist homeowners in energy efficient renovation, but also let them know about the benefits of comfort and energy savings, a scheme called *BedreBolig* was launched. *"BedreBolig is a nationwide scheme developed by the Danish Energy Agency, which makes it easier for homeowners to renovate their homes in an energy-efficient manner"* (SparEnergi.dk).

Despite the momentum energy renovations gained in the past decade [18], the renovation of the residential building stock is coming along rather slow [38], due to the uncertainties of economic and non-economic aspects [18]. Based on a series of yearly surveys in Denmark [7], people have been losing interest in energy renovations (net interest of 72% in 2012 fell to 55% in 2017).

2.1.1 General barriers and motivators

There are several barriers that hinder the progress of energy renovations. Galvin et al. [6] looks at policy making and groups barriers into (1) informing, (2) giving incentives and (3) demanding. Tuominen et al. [48] separate barriers based on interviews from stakeholders, into: *"(1) financial barriers (2) barriers related to information, promotion and education, (3) barriers related to organizations and decision making, and (4) regulatory barriers."*. Weiss et al. [55] exclude regulatory (direct) aspects, thus dividing barriers into (1) Financial, (2) Communicative, and (3) Procedural. A similar approach is followed by Wilson et al. [57], but (3) Decision-making is used instead of procedural. Similarities in grouping show the distinctness of some barriers, however, there is always a certain level of interrelation between them, making this a complex problem. Based on the previous considerations, to better fit for the specifics of this thesis, a grouping of barriers (and consequently motivators) was compiled, presented in figure 2.2. Group (C) Context refers to the specifics of a renovation project: the homeowner and occupants, who live in the house with certain conditions, which is located in a specific site and climate. Group (D) are other, external institutions, companies, governmental bodies that have an influence on renovation projects. The purpose of this division is to support and guide the future works and to make it easier to delimit the areas of interest. Moreover, the following literature review is addressed based on this grouping of barriers and motivators.

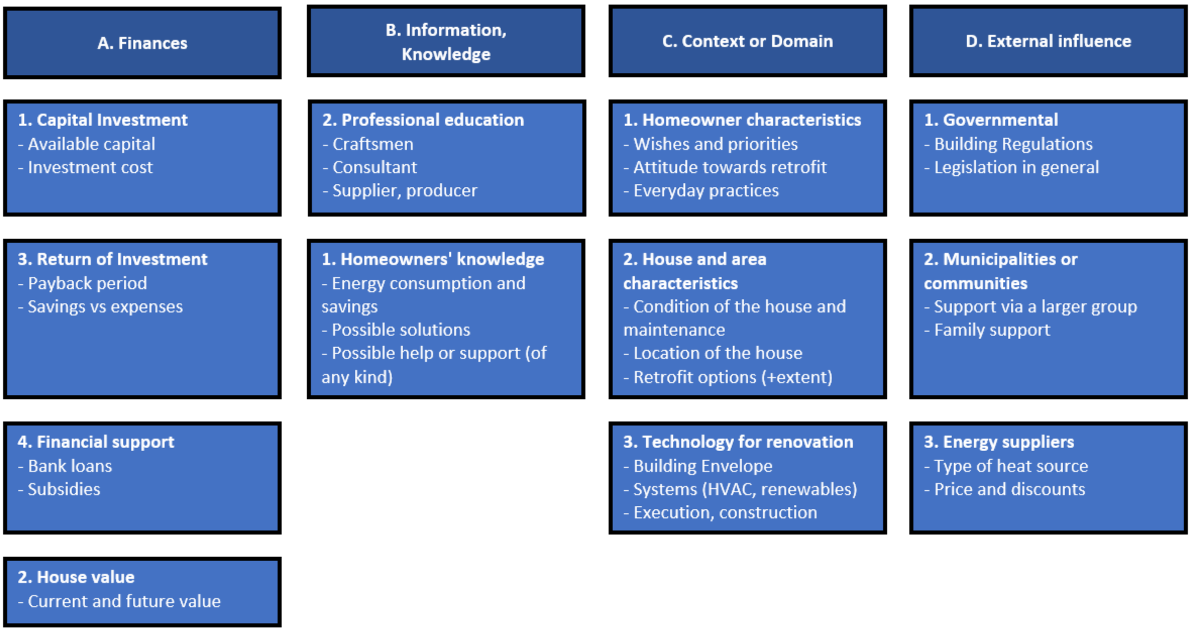


Figure 2.2: Grouping of barriers and motivators

2.1.2 Financial aspects

Due to the government's approach and current practice, the framing of energy renovations are mainly economical, which is usually the biggest barrier to energy renovations [33] [54] [25] [21] [48] [7]. Building regulations emphasize the need for payback of energy renovation (profitability) and thus treat renovation works as investments. Most homeowners, however, do not possess capital to carry out such investments. This is supported by an extensive and international review of literature that was carried out in 2014, concluding that *"people may not have the necessary financial resources and are unwilling or unable to raise a (further) loan"* [18]. Also people would rather gather savings by themselves than to ask for a bank loan [47].

This does not mean renovations are non-existent, only that larger ones are seldom carried out. In Denmark in 2016, according to a survey of owner occupied detached houses [7], 12% of the respondents spent at least 90.000 DKK on energy renovations that year, whereas 69% used only a maximum of 30.000 DKK. From this can be concluded that the extent of renovation works are rather small and only a smaller portion of homeowners invest larger sums.
As said before, homeowners might wish to upgrade their houses, but lack the finances to do so. Even those that are engaged in the decision making progress of energy renovations might still lose interest, after seeing the large sum of money that is required to be payed for extensive renovation of the house [22] [40] [5] [6]. Payback time can also act as a discouragement since energy renovations are long-term investments (more than 15 years) [22], and people in general see short-term rewards more beneficial [35]. Renovation measures should be appropriate to the characteristic of the homeowner (along with their financial capabilities) so it is possible to achieve the determined goals [22]. At the meantime, those with a larger budget should be challenged to reach higher standards of energy renovation.

Financial savings are related to the energy conservation (or production) a certain renovation can achieve. These calculated savings are based on different assumptions and variables that are difficult to predict. Suggested by [43] for the acceptance of energy efficiency renovations, reliability is a key characteristic. Unfortunately, homeowners have distrust in the expected savings as in practice these are lower then calculated [18]. One reason for this is the *"prebound"* and *"rebound"* effect. Calculations are based on comfort temperatures (usually 20°) throughout the whole building, whereas buildings with poor thermal insulation are not heated up to comfort levels, moreover not all rooms are heated. This creates a gap between calculated and actual consumption, and as a consequence in assumed and real savings. The same is true in case of buildings with high performing thermal envelopes, where occupants may create higher indoor temperatures (better comfort) compared to assumptions, thus consuming more than predicted [46]. Other factors that are crucial to the accuracy and amount of savings that can be realized are the assumptions towards future energy prices and price elasticity [18]. This unpredictability is a big issue, since reducing running costs of the home is a significant motivator [49] [60] [34] [7], but due to its previously described nature, it is not enough when it comes to decision making.

In their survey and study, C. A. Klöckner and A. Nayum [33] categorized the stages of decision-making for a house renovation. These are:

- Stage 1, Not in decision mode
- Stage 2, Deciding what to do
- Stage 3, Deciding how to do it
- Stage 4, Implementing decision

For the three transition of stages (e.g. from 1 to 2) barriers and motivators were identified and their relevance was assigned. From their work, it is understood that some barriers and motivators are predominant at specific stages. For example, homeowners' evaluate their economic capacity when they are about to enter stage 3, deciding how to renovate. Information about renovations also comes to be questioned at this stage, further discussed in the following subsection.

2.1.3 Information

Barriers and their solutions are going to be addressed in terms of the Motivation-Opportunity-Abilities (MOA) model proposed by Ölander and Tøgersen (1995).

Lack of knowledge is one of the core issues, since if people do not know there is a problem, they will not want to invest in a solution. Homeowners, in general, are not aware of their consumption, thus they do not consider savings to be substantial [6] (motivation). Framing high energy consumption as a waste or being morally wrong can instigate energy efficiency renovations [33] (motivation). By showing homeowners their consumption in relation to other buildings and current standards, they will begin to realize the possibility for savings [7] (opportunity). Also they do not know in what ways they can reduce their energy consumption [40] [7] [60] (ability). To ensure better outcomes for savings, the homeowners need information not only about renovation possibilities but also in terms of how their everyday practices could facilitate decreased consumption [53].

2.1.4 Context

In current literature there is an increasing focus on the non-financial side of energy efficiency renovations. Homeowners have a need, not only to lower operation costs, but also to cater to the "needs of comfort, convenience and belonging" [60]. These factors have been systematically understudied [33] [10] [58], but are found to be highly desirable and motivating, and can be even more so than economy [33]. This is pointed out in [36]: "Our findings indicate that people's motivation to carry out refurbishment was not so much to save energy but rather the desire to improve comfort and the need to repair." A survey of homeowners around the Northern area of Copenhagen, proves that after energy renovation, the improvement of comfort and Indoor Environmental Quality (IEQ) can be clearly experienced by the occupants [34].

Functional or comfort improvements, such as a new kitchen or terrace for the garden, do not involve economic benefit, yet are still a priority of home renovations [25]. Contrary to this, energy related renovations are still addressed in terms of feasibility (considering pay-back), instead of approaching it as comfort investment [6] [15]. Research emphasizes the importance of non-financial, co-benefits that relate to energy efficiency improvements [57] [29] [24] [43] [58] [15]. These have an impact on not just comfort, but environmental and social aspects (such as: health benefits, job creation, energy security, impact on climate change) [15]. These co-benefits create a solid ground for argumentation and motivation.

It is more likely to renovate if the building is old and IEQ is low **[M11]** Thus Bolius survey [7] was used to identify the common indoor climate issues experienced by homeowners:

- Most of the participants (55%) have not experienced indoor discomfort, but those who have, say mostly: Draft (17%), Cold walls (14%) Mould (12%)
- In general, comfort improving measures are: Increase venting (41%), Avoid smoking (34%), Increase insulation (32%), No action (22%), increase temperature (19%)
- Only 17% of people experience discomfort "always", 11% "monthly", 24% many times a year, 23% once ore even less times a year and 25% do not know.

These results are gathered from homeowners occupying different privately owned single family houses from various year of construction. Thus it is not possible to conclude directly in terms of the parcel houses the project deals with. Nonetheless it can be seen that most issues are related with thermal discomfort and air quality. Thus these will be prioritized in the later parts of the project.

Energy retrofit should be part of everyday life and not highlighted or separated from it [57] [25] [10] and solutions should be readily available to couple energy savings to minor renovations [43]. This connection of energy savings and maintenance work are emphasized by other sources [5] [6] [14], pointing towards the shift in emphasis, that are currently addressed as mainly (or even solely) energy related. As argued by Tim Ingold (2013), houses are not just buildings, but homes, that continuously evolve and change in response to its occupants and other external influences [19].

Survey results [25] showed how renovations happen throughout the years of occupation of the house. If components are changed before their lifetime expires (due to a one-off renovation), a higher environmental impact may be the consequence [14]. With extensive renovations, the disturbance of everyday life is greater, and there is also the possibility of having to move out for a longer period of time. Also, if energy improvements are addressed as one-off events, homeowners might simply procrastinate and feel the "right point in time has not come yet" as showed by Klöckner et al. 2013 [32]. Shown in this and the previous paragraph, small step taken throughout the years can be easier to adapt and less demanding to carry out.

The experience of renovation depends very much on how the homeowner(s) and occupant(s) relate to any kind of renovation in general, but also on the improvement itself. As seen on figure 2.3, Gram-Hanssen [25] puts renovation works and thus homeowners' attitude into the perspective of *Project* vs *Product*, whether it is - respectively - desirable to work on the house or is it just the outcome that is relevant. As a second axis, there is also the question of whether the work is connected with *Life Style*, being part of the identity of the people or solely *Wear and Tear* that is a must and usually a burden. Seen on the figure, the worst for energy renovations is to be at the bottom left corner. Anything, that will motivate people to change their perception and move toward the upper right area, is a solution worth exploring.

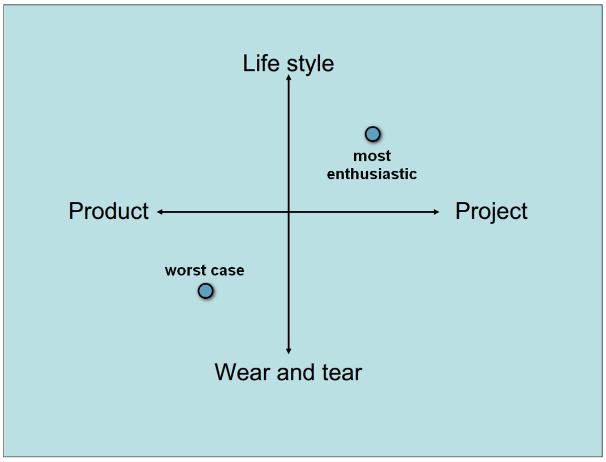


Figure 2.3: Attitude of the people towards renovation works, source **[M07]**

2.1.5 External influences

It is possible to target homeowners and educate them through communities and networks [31]. A study [27] evaluated the effect and success of municipal initiatives and argue that practical example show their success and effectiveness in terms of energy savings. These can be smaller steps and thus a gateway to larger investments and projects and therefore should not be overlooked [19].

One of the main means of the state to overcome the barriers for energy retrofit have been through the Energy Performance Certificate (EPC) for buildings, required by the EPBD. It is to calculate and evenly compare the energy consumption of buildings. Even though, within this document there are information and suggestions on how to renovate one's building, it is not enough to motivate homeowners [9] [26] [54] and can also backfire, leading to misunderstandings [6]. Moreover, it is allowed to issue it without on-site visit, based on plans, documents and historical data of the building, making renovation suggestions too general. It is suggested by Christensen et. al. [9] to broaden the purpose and applicability of EPCs as it is not sufficient in its current form.

It was seen in Germany that policy making within this field to incentivize high standard for renovations can actually be an issue [46] [22]. Small, cost efficient renovations cannot be carried out if they do not meet the minimum requirements, for which more expensive solutions will no longer be cost efficient.

In Denmark this issue is addressed in terms of *"profitability"*, which requires the energy renovation of a component to satisfy the minimum U-value and to pay itself back within 3/4 of its lifetime. Exceptions from this are:

- if there is a complete replacement of the building element (7.4.1(2))
- if damage due to condensation or health issues due to mould could occur
- if complex solutions are not profitable, smaller renovations (below minimum requirements) can be carried out if their profitability is proven.

This financial approach to energy renovations firstly makes people to observe the minimum requirements once they are deciding to carry out the renovation. However, even if a measure would be deemed profitable, it can still have an excessive cost, which the homeowner is unable to cover.

Currently in Denmark, subsidies are indirectly available, through tax reduction, in case if the renovation is done by a craftsmen (Handvaerkerfradrag); or for renewable energy provision ("Energiselskabernes Energispareindsats" (EE) [the Energy companies' Energy-saving initiative]), including heat pumps. Nonetheless, these are too low and help almost nothing in relation to the expenses extensive renovations demand [5].

In Denmark, some barriers are being addressed through a scheme, launched in 2013, called BedreBolig, that is an initiative from the Danish Energy Agency. *"The idea behind the scheme is to offer better advice to house owners when it comes to energy renovation. This is done by educating advisers, craftsmen and other relevant actors to provide more holistic counselling and to enable them to create a renovation plan for the house. The scheme is based on the One-Stop Shop concept, where the house owner can get all services from the same company, from initial advice and planning to execution and follow-up on their renovation project. Once they have the initial plan for the house, they can, for example, use it as an instrument to get a loan from their bank or collect quotations from craftsmen."* [6]

Since the initiative is very recent, there are not many reports evaluating it, but three recent reports carried out by EnergiTjenesten on behalf of three Danish municipalities showed its effects, and how it has been received by the local homeowners. The survey shows that "75% of the respondents decided to implement one or more of the improvements suggested. Out of the total number of the suggested improvements, 31% have been or are about to be implemented, 32% might be implemented, and 37% will probably not be implemented" [5]. All three municipalities offered a subsidy for having a BedreBolig-plan made, and 66% of the respondents said that they would not have requested a plan had it not been for this special subsidy provided by the municipality. These results illustrate that external advice is well received, with three quarter willing to implement the suggestions, but only a small fraction actually does so. The BedreBolig-scheme is solving issues related to information and communication barriers of energy retrofits, but there is still room for improvement. For example, their service is focused on one renovation at the time, and long-term considerations are not addressed.

2.2 Staged renovation as a solution

As previously presented, homeowners experience many obstacles that prevent them from energy efficient renovations. High costs and lack of financial capacity being the most apparent. Judging from this, in order to enable homeowners to energy renovate, a break-down of the works is required. Consumer Focus (2012) [16] analyzed a variety of British low carbon retrofit case studies; one of its conclusions suggests: *"a whole house retrofit model can work, but that a more staged approach may be more attractive for consumers as it spreads the cost and disruption over time."* Moreover, with a staged renovation plan the homeowners are able to perform renovations not only right after an expert advisement, but also later on in the future, when they are capable or willing to.

There are many benefits of a stage renovation. According to Tina Fawcett by prolonging the total time of doing retrofits, disruption and cost to householders is spread over time. It could also occur as a natural process along the years. Because of this it has the potential to be a more planned process, with work undertaken piece by piece according to the plan, as funds, willingness or opportunity allows. [13] Contrary to one-off renovations, that require larger investments and thus longer time period for savings, staged renovations over time can decrease initial investments, activating people to start renovations sooner. By this, immediate improvements are experienced by the homeowner and his/her energy bills. This motivates them to begin a constant process of improvements, allowing householders' enthusiasm to grow as they learn about energy improvements. In addition, this renovation approach can take advantage of opportunities that arise, for example maintenance or wish to extend and enhance the house.

An additional benefit of staged renovation is that it can be arranged in different ways, to better fit both the requirements of the house and need of the homeowner. This flexibility allows the combination of maintenance and energy improvements, thus reducing the partial costs of energy improvements. Also, Tina Fawcett [13] presented studies showing that homeowners are involved in a constant cycle of improvements of their homes, in average doing major improvement works each five years and even more frequently maintenance work and repairs. From the Bolius survey (2017) 74% of respondents carry out maintenance as an ongoing process, and 59% of people carry out energy renovations in connection to general maintenance. Thus, applying renovations that improve the parts of the house that need maintenance is a more natural and straightforward process.

An SBi report [44] gathers existing knowledge in practice and research within energy renovation in a local and international context, also supplementing this with further recommendations that can promote energy renovation efforts in the future for single-family houses in Denmark. The report presents Fawcett's investigation as argumentation for current renovations. The report emphasizes her finding that "for some homeowners it will often be more attractive to renovate continuously and argue that there are no energy or environmental down-sides doing this" [13].The report points out also a second article from Gram-Hanssen, based on Danish data, and it shows, among others, that the longer the time people have lived in their house the more likely it is that they have renovated:

- 0-5 years of residency: 35% have done renovations
- 5-10 years of residency: 58% have done renovations

- 20 or more years of residency: 80% have done renovations

The article also points out that it is more kitchens and bathrooms that are renovated rather than energy-efficient renovation solutions, such as after insulation [23]. These could also be arranged with energy improvements in a staged renovation plan.

2.3 Typical practices of renovation of SFH

Studies and surveys present current practices of single-family house renovations and its drivers. Studies in Denmark, UK, and other EU countries, point out that current policies are promoting energy renovation of detached houses through a technical-economic and rational approach, combined with individual behaviour of homeowners [5]. However these policies are not as effective as expected. Recent research indicates that it is because too little attention is given to social aspects which is claimed to be drivers of house renovations (Judson & Catfish, 2014). The authors concludes through their studies that refurbishment is closely interwoven with other everyday practices of the dwelling. Decision in terms of renovation works is made based on how the family occupies the home and how they will use it in the future. It is common for households to include environmental and energy related considerations, but they are not drivers for starting a renovation process. Drivers for renovations are life-style related, often involves functional improvements and making their home more comfortable by, for example, an extra bathroom, which probably leads to greater energy and resource consumption (Judson et al, 2014; Judson & Catfish, 2014).

House Renovation processes are commonly addressed in three groups: Maintenance, Functional Improvement, and Energy Improvement. Maintenance includes works done to upkeep the functional conditions of the house and it includes minor works for conservation, but also major works, such as replacement of worn out building elements or installations. These works extend the usable lifetime of the house and, per definition, does not improve the house in other ways. They are not done because of householder wish, but rather due to necessity, since the deterioration of material is inevitable.

The second group, Functional improvements, are works implemented because of households' wish and/or need. It includes adding new rooms, rearranging internal layout, new kitchen and bathroom, and aesthetic measures. These improvements are connected to occupants' life events or wishes and the requirement for the house to fit to their life style. These works do not expand the house life span, neither improve energy efficiency, but are often motivators to start a house renovation.

Energy efficiency has the greatest governmental interest. The purpose is to reduce the energy consumption of the house for both electricity and heating. When well planned energy improvements often lead to improved indoor environment. The energy efficiency of a house can be improved in two ways, reducing energy demand of the house or by improving the energy production (e.g. higher efficiency or renewable sources). While the first kind may bring improvements for the house itself, by improving indoor environment and house component quality, the second only reduces the strain on the energy grid. Measures that reduce energy demand can be coupled with maintenance works, in order to incentives homeowners to carry them out and reduce the environmental [40] [13] [5] [21] [3].

2.3.1 Common renovation measures in the last years

Several surveys have been carried out in the last years to identify common behaviours of households relating to house renovations. The surveys identify which building components and house parts have been renovated and how often this occurs. Bolius surveys performed between 2014-2018 demonstrate which parts of the house have been renovated via a large house refurbishment. This is shown in figure 2.4. Windows are what are mostly changed, which is due to their ease of installation. However, functional renovations are the most frequently done, such as kitchen, terrace/balcony. A new floor stands for the covering, which is an aesthetic improvement, same as a new roof.

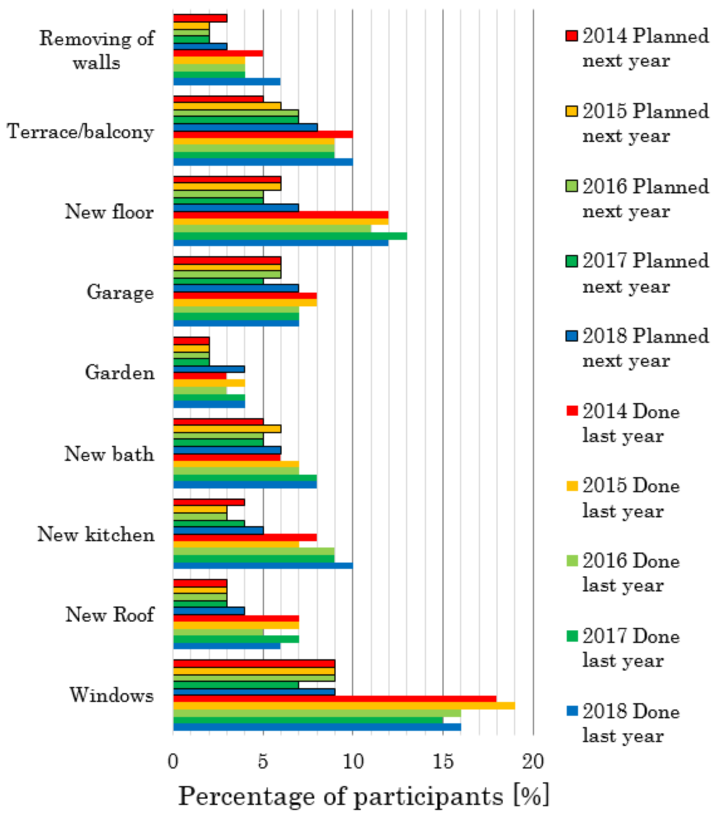


Figure 2.4: Percentage of surveyed participants who carried out larger refurbishments and planned to do so in the next year, source: Bolius Boligejeranalyse 2014-2018

A similar survey was carried out by AAU [40], but considering only maintenance and energy efficiency works. The results are presented in figure 2.5 below. The areas for improvements show the same conclusions as the previous survey results. What is different is the insulation of the attic is included which is second highest after the windows, again, most likely due to ease of installation and cheap price.

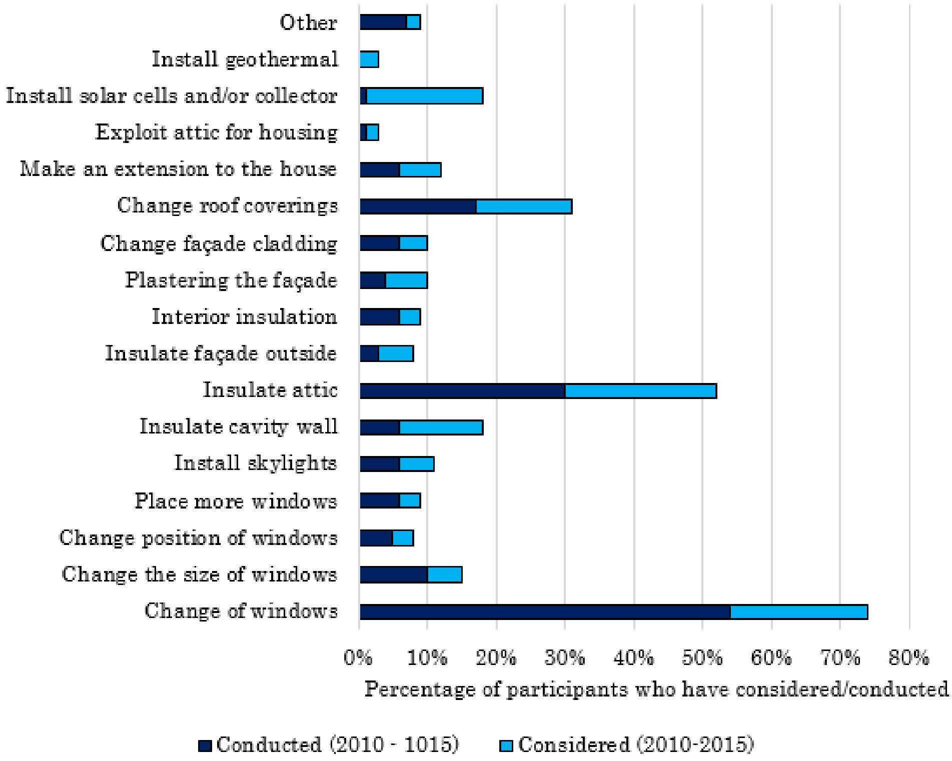


Figure 2.5: Chart showing the percentage of participants who either carried out or planned renovations in terms of maintenance and energy efficiency in the years 2010-2015

More detailed analyses are presented for each component according to the groups of maintenance, energy efficiency, and functional improvements.

Maintenance works

Roof

Seen on figure 2.5 roof coverings were changed the most in terms of maintenance. According to a survey carried out by COWI in 2012, investigating the reason of renovation deficits and lagging, roofs are in the worst conditions, as shown in figure 2.6.

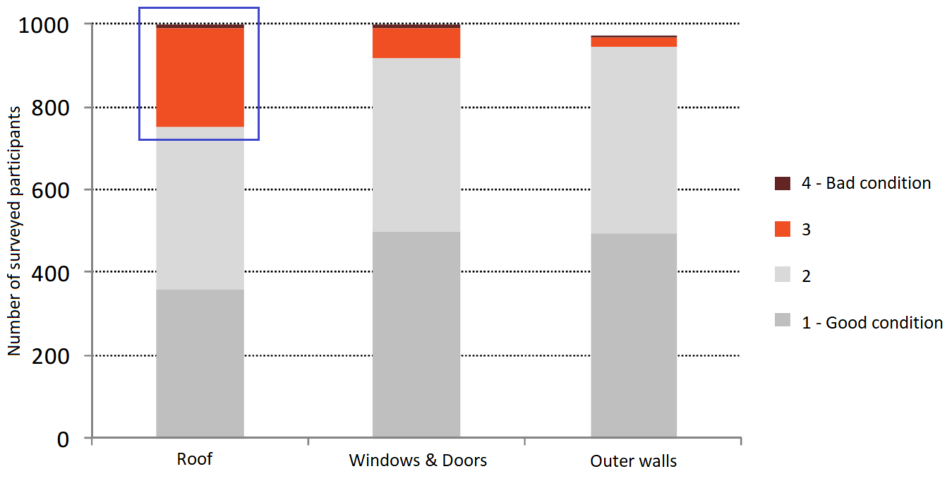


Figure 2.6: Condition of specific building components, conditions 3 and 4 require renovation. survey source: *COWI Rapport om vedligeholdelsesefterslab - Ejendomsviden August 2012.*

Outer walls
Maintenance of this component is less frequent, as seen on figure 2.5, where outer wall related maintenance are only performed by approximately 5% of the participants. This is due to the construction, as most of the single-family houses, including parcel houses, have brick facades. This is also concluded from the COWI survey, presented in figure 2.6: 1% of brick outer walls are reported to be in bad condition. In case of walls that are plastered, painted or are wooden facades 7% are reported to be in bad condition, but also 50% have been renovated (or maintained) in the past 9 years. Also people do not wish to change or have a new facade as only 6% wished to have it done [40]. This component requires and thus receives the least attention in terms of maintenance.

Windows
Reported in the COWI survey, most of the windows are 1-9 years old (25%), though there are almost as much between the ages of 30-39 years (20%) and 40-49 years (16%) There are still some windows and doors from the 1960's and 70's that have not been renovated, but the number is not as much as for roofs and walls. Windows are widely reported to be the component most renovated and changed [7] also seen from previously presented sources.

Energy Efficient Measures (EEM)

According to the Bolius surveys (2013-2018) people have been carrying out less energy related renovations and their interest towards them also decreased.

Windows
Due to the smaller service life of windows, these are the components that are more frequently changed. In the past 5 years, 54% of the surveyed participants have conducted a window replacement, which is also considered to be at the top level of their wish-list (with 35.5%) [40]. It is also not uncommon to change the window size as 10% of participants have done so in the past 5 years.

Roof
Insulation of the attic was carried out by 30% of the surveyed participants in the last 5 years [40] and the highest number of people have considered to do so in the upcoming years (22%) compared to any other measures.

Walls
It is found that walls are the least renovated building components, compared to other envelope measures. Seen on figure 2.5 only 3% of the participants have externally insulated their facade, although 6% have done so internally. This is possible due to the nature of the work, which is easier to carry out.

Renewable sources
Many have considered to install solar cells (17%), but only a very small percentage of people actually did so (1%). This shows the general popularity of them, which many would like to adapt, but only a few actually invests. Installation of geothermal heat source was not done by any of the participants and only 3% considered it in the past 5 years. Thus these are the measures least sought and implemented.

Non-energy efficient measures (non-EEM)

Kitchen and Bathroom
Seen on figure 2.4 a large percentage of people have been both planning (approx. 4-5%) and carrying out (approx. 7-8%) refurbishments of their kitchen and bathroom . These measures are also relatively more desirable according to [40] since 34% have it on their wish-list, whereas improving IEQ and comfort is only 18% and 16% respectively.

Gardens, terraces
Gardens and terraces have a relatively higher priority than energy renovations according to Bolius 2017, whereas when asked in the AAU survey (2015) people wished for reducing their energy consumption the most, 44%, and Gardens and terraces were only at 19%. To give a better account of actual conditions, according to the Bolius surveys (from 2014 to 2018) terraces and balconies are renovated by 10% of the people, but gardens are only at 4%. This shows how wishing for energy reduction can be strong, but actual EEMs performed is a lot lower, instead people work on parts of the house that give a stronger sense of improvement and have more connection to how the home is used, like terraces and gardens.

Sub-conclusion

It can be concluded that in reality, people have a strong wish for energy efficiency, but the amount of EEMs carried out does not reflect this need. According to Bolius surveys since 2014 to 2018, the top activities in terms of energy efficiency has been (in order): Change of window to more efficient one; Replacement of thermostat; Change of door; Insulation of roof; Insulation of heating pipes; Change of boiler. These are carried out by approximately 6-12% of the surveyed participants, as of 2018. Works that are easier to implement (because of installation and more knowledge available), are done by relatively more people. These measures are connected to improving the lifestyle of the occupants and how the home is used throughout the everyday life.

These renovations are carried out mostly due to necessity and are not planned out to reflect future considerations and possibilities.

2.3.2 Risk of lock-out

Carrying out either energy related or just functional renovations can be great for the present moment, but can cause issues in the future. This is defined as *"Lock-out"*, that usually happens due to incorrect or lack of planning, or due to dissatisfied customers. If the needs of the homeowner is satisfied, even though it is not to energy improve the house, it is more likely for them to later on continue in renovations, emphasizing energy efficiency this time.

A lock-out can occur due to renovating components that does not allow or limit the improvement of other components. It is also possible that due to a shallow energy efficient renovation the homeowner will be reluctant to further improve the same component. When planning a house renovation these risks must be considered.

These issues are addressed by Urge-Vorsatz, Petrichenko, & Butcher [50], who suggest when a building is renovated without considering deep renovation, it locks-out potential energy savings, since the measures applied will remain there for 20 to 40 years until another renovation takes place. This evaluation, though, is done for commercial buildings, but as Fawcett [13] argues, this 'locking-out' risk also applies to residential buildings. The analysis shows that sub-optimal measures with long lifetime, prevent other, better solutions, that save more energy to be applied. Her study gathers the measures that do not have any lock-out risk and those that are impossible or costly to upgrade once installed, shown in table 2.1. It is well presented that renovations that are extensive and costly will cause lock-out, such as renewable systems or high performing windows. If the solution is simple to carry out and market availability is high, there is no potential for lock-out.

Intervention measure		Variation in the standard of intervention	Potential for lock-out?
Wall insulation	Solid walls	Insulation varies with the depth and type of material. Unlikely to be able to increase depth without removing the original insulation	Yes
	Cavity walls	Little variation in *U*-values achieved by filled cavities	No
Loft insulation		Insulation varies with the depth and type of material. In most cases the depth of loft insulation can be increased	No
Windows		Double-glazing is now a minimum standard in nearly all situations. Can be improved by higher quality double- or triple-glazing	Yes
Draughtproofing		Can be installed more or less extensively	No
Ground floor insulation	Solid floors	Unlikely to be insulated unless the floor is being renewed. Cannot be improved once installed	Yes
	Suspended floors	Insulation varies with the depth and type of material. Unlikely to be able to increase depth without removing the original insulation	Yes
Central heating boiler	Conventional	Minimum standards are high; there is little variation in products available on the market	No
	Combi	Usually precludes use of solar water heating	Yes
Solar water heating		Effectiveness depends on design and sizing	Yes
Photovoltaics		The size of the system is important in determining the potential for electricity generation	Yes

Table 2.1: Potential of energy-efficient measures to cause lock-out

By considering a renovation in stages, and extensive renovation can be consider and planned to a building to achieve low energy consumption. Doing so, the risk of lock-out by implementing low energy saving measure is avoided. All the measures chosen to be implemented, together will make the building in the end of the process have a very low energy consumption. (this paragraph goes to sub-conclusion below)

2.4 Existing Methodologies used for renovation over-time

Some research point to renovation methodologies that can be applicable for staged renovation, and consider a holistic approach, where measures besides energy improvements - such as maintenance, functional improvements, and architectural works - are taken into consideration. These methodologies are focused on planning a holistic house renovation with cost optimum solution, or improve the communication between advisor and homeowner, rather than present a way to break down an extensive renovation in several parts to diminish overwhelming costs or disruption. However, a staged renovation must be fully planned before teared in parts that best suites the client. For that reason, this chapter will be presented methodologies that can be combined to a staged renovation planning.

Holistic methodologies were developed, to support experts and actors throughout the decision making process or to guide actors to reach higher levels of social, economic, and environmental performance. One of these are multidisciplinary decision support methods, such as EPIQR, or more simple methods, such as the ones applied in green building rating schemes. These methods have strengths and limitations. Wilson C. et. al. considers that a better integration of humanistic disciplines could be beneficial for these type of methods, as well as more openness from the engineering and economic disciplines [56]. While other methodologies that come from health and social areas lack technical practices to better integrate directly into the holistic renovation design [59].

Arabaci, U. et al. [61] present a methodology for planning house renovations that emphasizes homeowner and house needs (maintenance) in terms of functional and necessary renovations while energy improving. The methodology compere the homeowner's economy and the total renovation cost to evaluate whether is better to perform the renovation or tear down the house and build a new modern one. The results of the evaluation is presented to the owner to make it clear the gains by renovating or building a new house in terms of: financial gains by reduced cost of energy use and expected gain on property value, improved indoor climate, comfort, and life quality.

In its process, the author uses an Excel based program called "CCE-Calc2" that can quick and easily choose the most optimal solution for each house component and by consequence for the whole house. The choice of the best optimal solution is based on the lowest annual costs, based on the cost of conserved energy (CCE), the energy prices, and the expected energy use. This analysis depicts how much it costs the chosen solution compared to how much energy there is saved.

After the optimal solution for renovation has been found, it is assessed the expected property value gain when the energy-mark (EPC) of the house is improved. Finally, based on a developed excel calculation called “Nybyg vs. Renovering”, it is determined whether is most profitable to renovate or replace the old house by a new one.

Nicolas Galioto [20] has developed a method called Integrated Renovation Process for Homes (IRP4homes) that supports, informs and reassures householders to decide on sustainable renovation of their home. According to him the decision making process of energy renovation of SFH is defined as a semi-structured problem with both quantitative attributes and qualitative values based on verbal difference judgments.

Galioto assures that by using the method the homeowner gets the best of the associated benefits of the improvement works and a more adapted house to his lifestyle. That is done by the qualitative evaluation process that assess the client personal values and wishes, personalizing it, and increasing the chances of making the right decisions on selecting the best solutions. According to the author the method is constructivist because “existing knowledge is modified while new knowledge is created and exchanged between all the project stakeholders”.

His methodology’s focus is on enhance the communication between adviser and client. Though at the same time he creates a powerful methodology that evaluates the homeowner priorities of the benefits of the home improvement, helping the advisor decide which work should be done to improve his house. Nicolas minds that “can be costly and difficult to achieve renovations of buildings to very low primary energy use”. Having the owner priorities ranked, it can be used to select the implementation order of the works to best suit his aspirations, thus improving the experience on house retrofit.

Simpson, S. et al. [43] in their research paper “Energy-led domestic retrofit: impact of the intervention sequence “ investigate the implications of installing a series of retrofit measures in different sequences, over several years for a case study dwelling, representative of a English solid-wall semi-detached house. The investigation focused on the total savings on the building’s energy consumption and CO2 emissions over 25 years. The method utilized to create different retrofit sequences was by developing ‘archetype’ personas based on interviewees experience of home improvements. This personas represent actual rather than notional intervention sequences. The selection of the personas were based on identified drivers for domestic retrofit. The results of energy consumption and savings were gathered from dynamic simulations of a case study dwelling.

This article is very advantageous to demonstrate that staged renovation can be undergone in many different approaches to home renovation, and that energy efficiency is not often a main drive of renovation. The research is delimited to compare the cumulative CO2 emissions and savings between the different sequences created by the archetypes and one-off renovation (undergone at the first year) over a 25 years period. The work presented which sequence has the best potential to reduce CO2 emissions and save energy in long term.

2.5 Sub-conclusion from the literature review

From the literature review it is understood that there are many barriers to energy renovation of private houses. Many of them are being addressed to varying degree and with varying success, thus improvement existing and development of new solutions are needed. Stage renovation was suggested, but its application was not well developed.

For a stage renovation to be successful, it needs to be developed, considering many aspects of home renovations. These are:

- Being coupled with the present and future maintenance needs of the home
- Making it financially feasible to carry out over the long-term, without too high capital costs
- The homeowner being included in the process of decision making, and allowing for non-energy efficiency renovation works
- Informing the homeowner about the benefits of staged renovation and its EEMs, mostly the co-benefits, such as improved comfort and usability of the home

3 Development of staged renovation methodology

This chapter describes a methodology to stage an extensive renovation and provide a holistic assessment in order to achieve the best fit for the homeowner needs and financial capacity. The end of the renovation process aims to achieve energy frame Renovation Class 1 for Br18.

The purpose of the methodology is to build an easy-to-use tool that can be used by an energy consultant when advising a homeowner. The methodology for staged renovation is created as a complementary process to be coupled with existing methodologies of planning an extensive renovation. The methodology will help to make important decisions, to break down the extensive renovation in stages and place it on time in an economically responsible manner. It is also tailored to suit current practices of house renovations, as reported by research and surveys [13] [40], to be more appealing for homeowners and to eliminate their doubts about the benefits of energy efficient renovations.

It is not considered in this project, that a staged renovation can be better than a one-off approach. It is known that a one-off renovation, in principle, can offer a cheaper solution than a staged renovation approach. Instead, it is presented as another option for homeowners, which suits better those who prefer not to take a loan to renovate their house and that prefer to do it peace-meal, more as an integral process of living in the home.

To provide an overview of the methodology, different steps in the construction were created. They are as follows:

- Step 1: Mapping phase (Auditing)
- Step 2: Creation of holistic renovation and budget
  - Selection of renovation measures
  - Evaluation of renovation measures
  - Presentation of whole renovation and budget
- Step 3: Assigning staging data to renovation works
- Step 4: Staging the extensive renovation
- Step 5: Life Cycle Cost assessment

Comprehensive analysis of different possibilities and proposals for individual renovation measures has not been carried out. There are currently several methods that can be used to find the best renovation measures according to different requirements; the one used depends on the energy consultant's preference and/or expertise.

Step 1 of the renovation method comprises of auditing activities that complement the standard practices for planning an extensive renovation. In this step, further information about the homeowner and house is collected that are needed for the staging process. Due to the long-term nature of the staged renovation, future functional renovations desired by the homeowner are included in the renovation plan, as well as necessary future maintenance of the house.

At step 2, the renovation works are assessed. EEMs are selected and evaluated based on their related savings and cost of installation. In order to create the whole renovation package with a long-term holistic view, functional renovations (desired by the homeowner) are included. After all measures are collected, the final proposal is compiled and the final budget is calculated. The budget for Anyway Maintenance (and wished works) is also calculated to serve as a comparable baseline in contrast to energy efficiency renovations.

At Step 3, additional information required for the staging process are assigned to the individual renovation measures. This includes the energy savings of the individual EEMs and co-benefits of all renovation measures.

Step 4 is where the proper staging takes place; it is formed of many sub-steps to create renovation packages for the stages with an implementation order that reflects the homeowner's priorities. Moreover, in this step, another implementation sequence is also created with an implementation order that prioritizes energy improvement. That is also a baseline that will present to the homeowner the benefits of prioritizing energy improvement in the implementation order of the stages.

In step 5 the staged renovation is financially evaluated using the life cycle cost analysis.

Before the methodology is presented, first it's creation will be discussed.

3.1 Considerations for staged renovation

The staged renovation method is intended to be created in such a way, to overcome some barriers that prevent energy renovations in the residential sector to rise. For that reason, the methodology has a holistic approach, which means it aims to achieve high energy savings to avoid lock-outs, assess the financial capacity of the homeowner, clearly present the benefits and co-benefits, and clearly present financial evaluation of the house renovation. These will be addressed in the following subsections. Moreover, when considering a renovation to be implemented in stages, three questions suddenly appear. What are the cost constraints for each stage? How frequent should each stage occur? And how many years should the whole renovation process take? Considerations about these topics and questions are developed on the following part of this section.

3.1.1 Holistic approach of renovations

For the Swedish association of architects and engineers, a holistic view includes aesthetic, functional, technical, social, environmental and economic considerations [37]. This project will deal with aesthetic, functional, technical, and economic considerations.

As literature review showed that current renovation works are approached in a piece-meal manner, either for functional renovation, energy efficiency, or maintenance. Homeowners usually renovate, once a necessity appears (maintenance), and these procedures repeat for many times along the house ownership period. This common path, however, has many drawbacks because of the lack of planning. It can lead to lock-outs for future improvements, higher costs for the given benefits, or renovation solutions that are not the best for homeowner desires.

Moreover, the typical practices of the renovation of SFH show that the common drivers to start a renovation are often others than energy efficiency. Because of this to include renovations related to lifestyle improvements (functional and aesthetics) is a key point to make homeowners active in energy renovation.

The holistic planning has the potential to avoid or solve these problems. The final result of holistic planning often brings solutions that were not thought at the beginning of the process. Craftsmen and consultants are normally specialized in one specific area, lacking knowledge for holistic thinking or to better combine renovation solutions [17]. Combined solutions have the potential to decrease the overall cost of a renovation and also to achieve better client satisfaction.

Because of the presented reasons, the staged renovation will first be planned as a one-off renovation that includes renovation works predicted to be performed in the long-term, for only after be divided in stages. Moreover, the staged renovation methodology will be planned to achieve high energy savings to avoid lock-outs and include works not related with energy efficiency.

3.1.2 Energy efficiency aim for the end of whole renovation process

The staged renovation happens over-time, for this reason, we consider that it has the potential to achieve great energy improvement at the end of the process. That is because "small" energy improvements can be implemented in each renovation stage and the sum of the small improvements can become a great one. Therefore, to investigate the potential of the staged renovation, we fix an ambitious target. Achieve energy efficiency Renovation Class 1 in Danish BR18, at the end of the renovation process, meaning an annual primary energy consumption lower than 65.6 kWh/m^2.

3.1.3 Financial capacity of homeowners

The household financial capacity for staged renovation is assessed considering the annual income in the long term. The staged renovation method does not consider to take a bank loan to make the renovation. That is because, as presented in the literature review, homeowners have no interest in committing themselves to a debt that must be paid over a long period. Instead, the homeowner saves a specified amount annually to renovate the house. To do not compromise too much the household budget it is suggested that the annual savings should not be more than 15% of the total household income. Attention should be taken to the fact that because the staged renovation methodology already considers the large maintenance works of the house, these will not be an extra cost on the household budget. The limit of 15% of the household income will rule the total time of the staged renovation process. That is because the renovation only can be concluded after the total money saved is the same of the total cost of the renovation. For example, in a house that the total income is 400,000 DKK per year, the maximum savings for house renovation is 60,000 DKK. If the total renovation cost is 900,000 DKK, the minimal total time to conclude the renovation process is 15 years.

3.1.4 Assessment of co-benefits

The concept of co-benefits assessment to renovation measures was introduced by Ferreira M. [15] to refer to the benefits that arise from building renovation that is not energy efficiency and carbon emissions reduction. His objective was to present benefits that justify solutions beyond cost efficiency and energy reduction. He tried to include in the notion of co-benefits all the benefits that arise from a renovation project besides direct benefits identified from homeowner surveys, interviews, and expert contributions. Therefore, the co-benefits can arise from the implementation of energy improvements, directly or indirectly (e.g., less exposure to energy price variation or less outside noise), or from renovations not related to energy improvements (e.g., better house aesthetic because of new painting on the facade). His study includes benefits that impact at the private level and/or at the society level.

Because the introduction of this concept aims to aid on the staging process and demonstrate the co-benefits to the homeowner, we will focus on the private level impacts. Therefore, the categories of co-benefits for the society level from Ferreira method will be disregarded. Below is presented the categories (or typologies) of co-benefits identified by Ferreira for the private level with its definitions.

Building quality	Ease of use and control by user	Ease of use and control by the users of the renovated building is related with parameters such as the existence of automatic thermostat controls, easier filter changes, faster hot water delivery, less dusting and vacuuming or automatic fuel feeding.
	Aesthetics and architectural integration	The aesthetic improvement of the renovated building is very often mentioned as one of the main reasons for building renovation and a largely cited co-benefit of energy efficiency measures. Although, aesthetics and architectural quality of a building may also be reduced by energy related renovation measures. The impact of building renovation measures on aesthetics and architectural integration strongly depends on the building identity (related to architectural, cultural and historical values of the building and to the building context). The question of “how” measures are implemented is decisive and the quality of the design process is crucial.
	Useful building areas	The increase of useful areas of the buildings is normally related with the glazing of balconies or just the replacement of the balconies by others with bigger areas, but it also can occur with the replacement of building equipment by other with smaller dimensions. A decrease in useful area is a common negative effect from renovation measures such as interior insulation of the outer walls and the introduction of new equipment related to controlled ventilation or equipment for the building systems replacing smaller ones.
	Safety (intrusion and accidents)	The substitution of elements in the building envelope to improve its energy performance is usually done with new elements that accomplish the latest standards leading to improvements in dealing with risks such as accidents, fire or intrusion.
Economic	Reduced exposure to energy price fluctuations	The reduction of the exposure to energy price fluctuations gives the user a feeling of control over the energy bill and therefore an increased certainty on the future ability of providing the needed level of comfort to the household.

User wellbeing	Thermal comfort	Thermal comfort depends on the room temperature, but also on the radiant temperature, temperature differences, air drafts and air humidity. Measures such as envelope insulation, the introduction of glazed balconies and external shading, have an impact on these parameters and are able to change the feeling of thermal comfort (positively and negatively), even for the same levels of room temperature and humidity.
	Natural lighting and contact with the outside environment	Day lighting, particularly involving the visual contact with the outside living environment, has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. The enlargement of window areas and the introduction of roof-lights or sun pipes are renovation measures with positive effects regarding this cobenefit, while the use of glazed balconies can reduce significantly the natural lighting and views from the liveable areas and therefore produce a negative co-benefit.
	Air quality	Indoor air quality (IAQ) refers to the air quality within buildings especially as it relates to the health and comfort of building occupants. IAQ can be affected by gases, particulates and microbial contaminants that can induce adverse health conditions. Source control, filtration and the use of ventilation to dilute contaminants are the primary methods for improving indoor air quality in most buildings.
	Internal and external noise	The noise reduction benefits arising from a building renovation should be evaluated for two distinct effects, namely the reduction of the exterior noise intrusion, and the annoyance from internal noise. Renewal of building envelope presents opportunities to reduce the transmission of external noise into the interior of buildings. Although, if exterior noise is reduced, noise from within the dwelling and from adjacent dwellings becomes more noticeable (negative co-benefit). Reducing the causes of overheating in summertime by measures as shading, minimizes the use of air conditioning, providing reduced indoor noise from the operation of the equipment.
	Pride, prestige, reputation	People who have performed relevant energy related improvements in their dwellings, currently report feelings such as enhanced pride and prestige, an improved sense of environmental responsibility, or an enhanced peace of mind related with the responsibility for the family well-being.
	Ease of installation and reduced annoyance	People who have performed energy related improvements of their buildings currently justify the selection of certain renovation measure based on the ease of implementing it. When comparing different building renovation measures, the ease of installation can be used as a parameter to find the package of measures that aggregates the most benefits.

Table 3.1: Typology of co-benefits from M. Ferreira's work [15].

To evaluate the co-benefits of the specific renovation measures, Ferreira has developed a matrix of the relationship between co-benefits and renovation measures, using the matrix, the author argues that owners and promoters can be aware of the co-benefits. The evaluation of the renovation measure with the co-benefits is done by attributing signals of "+" for co-benefits that has positive impact and signals of "-" for co-benefits that has a negative impact. The number of signals that varies from 1 to 3 represents the relevance of the co-benefits as positive or negative. Below is presented a simple example of the matrix from Ferreira's work.

Table 3
Relationship between co-benefits in a private perspective and specific renovation measures.

CO-BENEFIT	Thermal comfort	Natural lighting	Air quality	Building physics	Internal noise	External noise	Ease of use	Reduced exposure to energy price fluctuations	Aesthetics/ Architectural integration	Useful living area	Safety (intrusion and accidents)	Pride/ prestige	Ease of installation
Façade insulation (external)	+++	–	+	+ +	-	+ +		+ +	– – +	+		+ +	
Façade insulation (internal)	-++	–		–	–	+ +		+ +		–		+	
Roof insulation	+++		+	+	–	+ +		+ +		+		+ +	
Ground floor insulation	+++							+ +				+	
Cellar ceiling insulation	+++							+ +				+	
Windows replacement	+++			+	–	+++		+	+		+ +	+	
Insulation of entire building envelope	+++	–		+ +	–	++		+ +	- +			+ +	
Larger window areas	–	+++											
Roof light or Sun pipes		+ +						+					
External shading	+ +					+		+					
Balconies and loggias	-++	– –		+ +		+			+ +	+ +			
Heat Pump for heating								+					++–
Biomass heating system								+					
Efficient DHW system								+ +				+	
Automatic control systems							+						
Air renewal systems	+ +		+++	+ +	–		–	+					
MVHR systems	+ +		+ –	+	– –			+				+	
Solar Thermal systems								+ +				+ +	+ +

Figure 3.1: Example of evaluation matrix for co-benefits from M. Ferreira et al work [15].

In this project the same method of evaluation will be used, with the difference of instead using signals, a number will be attributed to the relation between co-benefits and renovation measure. The number will vary from -3 to 3, to represent the relevance of the co-benefits. The negative values represent the negative impact of the co-benefits. Moreover, the typology "Ease of installation and reduced annoyance" will be excluded. That is because the staged renovation methodology has already its method to evaluate the disturbances caused by the installation of the renovation measures. Below is presented a simple example of the matrix used to evaluate the co-benefits of the renovation measures in this project.

Renovation work	Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
Façade insulation (ext)	3	-1	-1	0	1	2	3	1	0	3
Roof insulation	2	0	-1	0	1	2	0	1	0	1
Ground floor / crawl space insulation	2	-1	-1	0	-1	1	0	0	0	1
Mechanical Ventilation (with HR)	3	0	3	2	-3	-2	1	0	0	1
Windows replacement (can also be door)	2	-1	1	0	2	2	3	2	3	2
Larger window area	0	3	0	0	-1	-1	2	-1	0	2
Roof light or sun pipes	0	0	0	1	-1	-1	2	-2	0	2
External shading	3	-1	0	1	-1	0	0	0	0	1
Renewable heat source	0	0	0	-2	-2	3	0	0	0	3
Efficient DHW systems	0	0	0	3	-1	-1	0	0	0	3
Automatic control systems	3	0	2	3	-2	1	1	-1	1	2

Table 3.2: Example of auxiliary table to identify renovation measures disturbance, predecessor, and lifetime (The numbers has no relevance).

The co-benefits concept is introduced in this methodology to demonstrate improvements in the house beyond energy efficiency and reduce running cost. In this way, the methodology can have a more holistic perspective and emphasize human aspects. As presented in the Context section in the literature review, a way to motivate house renovation in the private sector is by introducing renovation measures appropriate to the characteristic of the homeowner and his needs. The co-benefits analysis of all renovation measures has the potential to demonstrate to the energy consultant and the homeowner these other improvements that comes along with the benefits of energy improvement and diminishing running cost. This assessment will also be used as a criterion to choose the implementation order of the renovation measures in the staging phase in order to reflect the homeowner priorities about the renovation.

3.1.5 Cost of a stage

The cost of a renovation stage must also reflect current practices of house renovation. That is to have average costs that reflect common expenditure for housing in the last years in Denmark. Thus, the stage cost should be in a range that homeowners feel comfortable to spend in their houses and not refrain homeowner from carrying on a house renovation. As presented in the literature review, the total cost of an extensive renovation can intimidate and discourage homeowners to start the actual renovation works. The minimum cost of a stage should also be considered. That is to the number of stages do not be so many that can become an overwhelming disturbance to the occupants.

The considerations to find the cost range for renovation stages were taken from two surveys carried out in Denmark. One carried out by AAU [40], that investigate the maximum cost that people would be willing to pay for an energy renovation and another carried out by Bolius that reflect average expenditures in large maintenance works.

The AAU questionnaire survey was carried out in 2015; the objective was to investigate the barriers and motivator factors related to project economy of energy renovations of SFH from the 60s and 70s in Denmark. The survey involved respondents from four cities, Aalborg, Aarhus, Odense, and Copenhagen. The respondents were 883 homeowners of SFH, all connected to district heating. They were chosen to represent 440,000 households of the SFH from the 60s and 70s. The confidence interval of the survey was calculated as 3.3%. That gives the survey a certainty between 91.7% and 98.3%, which points out the survey results as acceptable and trustworthy.

The survey presented to the respondents five concepts representing five different levels of energy renovation. It was presented the required investment for each concept and their given benefits. These concepts were done to define the economic limit when an energy renovation is no longer interesting for the homeowners, despite the many benefits, as well as to investigate the homeowner perspective of the prices of the five concepts compared to the obtained gains.

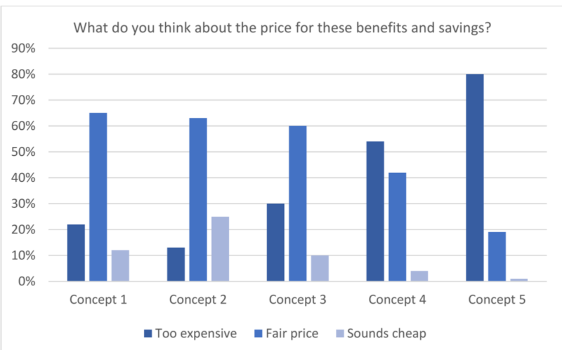
The concepts had prices that varied from 120,000 to 1,300,000 DKK; from one component retrofit to an extensive renovation. The respondents were asked to evaluate the price of each renovation, based on the given benefit, whether they consider them to be too expensive, fair price, or cheap. The five concepts with their costs and given energy savings are presented in table 3.3. The given benefits presented to the respondents are not included in the table because it was not shown in the report.

Concept	Cost	Energy consumption	Energy savings	Renovation measures
Concept 1	120,000	15,083	35%	New and larger windows; Airtightning around windows
Concept 2	160,000	16,324	30%	Attic insulation; Airtightning of ceiling
Concept 3	310,000	7,362	70%	New and larger windows; Airtightning around windows; Attic insulation; Airtightning of ceiling; Ventilation is installed
Concept 4	550,000	4,806	80%	New and larger windows; Airtightning around windows; Re-insulation of the facade; The facade is plastered; Attic insulation; Airtightning of ceiling; Ventilation is installed
Concept 5	1,300,000	6,295	70%	New and larger windows; Airtightning around windows; Re-insulation of the facade; The facade is plastered; New roof Attic insulation; Airtightning of ceiling; Ventilation is installed

Table 3.3: Renovation concepts of the survey presented in the AAU report "Energy renovation of Danish single-family houses Economy - barrier, motivation and limit" (Mortensen, A. et al)

The result of the survey showed that 60% of the respondents considered the three first concepts with a fair price in relation to the listed benefits and energy savings. Concepts 4 and 5 were too expensive to 54% and 80% of the respondents respectively, as presented by the survey graphic replicated in figure 3.2. Hence, the survey report considered that the shift of an acceptable price (where more than half of the respondents consider to be acceptable the price) to be between 310.000 DKK and 550.000 DKK (see figure 3.2).

However, when the respondents were questioned if they would be interested in a similar project at their own house the acceptable price decreased. The point that more than 50% of the homeowners are no longer interested in the investment appeared somewhere between 160,000 and 310,000 DKK, as presented by the survey graphic replicated in figure 3.2. The report concludes that besides a project being considered with a fair price regarding the given benefits, the homeowners are not interested in invest their money in similar projects. Thus the investment limit for the average homeowners was considered to be below 310,000 DKK. Probably, a little more than 160,000 DKK since only 51% of the homeowners considered Concept 1 as "Might be interested". The survey report also concluded that "the interest (in renovation projects) is affected by the price and not only the extent of the project."



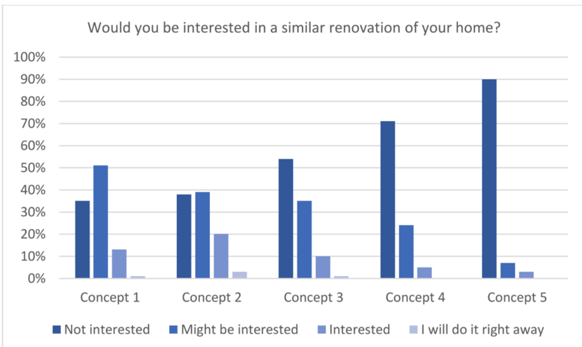


Figure 3.2: Left side - Percentage of respondents considering "too expensive", "fair price", and "sounds cheap" in relation to the question of the price of the presented concepts for the benefits and savings given [40]. Right side - Graphic with percentage of respondents interested on undergone similar projects of the concepts in their own houses [40]

When the answers of maximum investment limit were compared with respondents' annual household income a clear direct tendency appeared. The lower the income, the fewer people are interested in paying more for house renovations. Thus, the higher the household income, the larger can the investment in renovation be before it is found too expensive as presented in table 3.4.

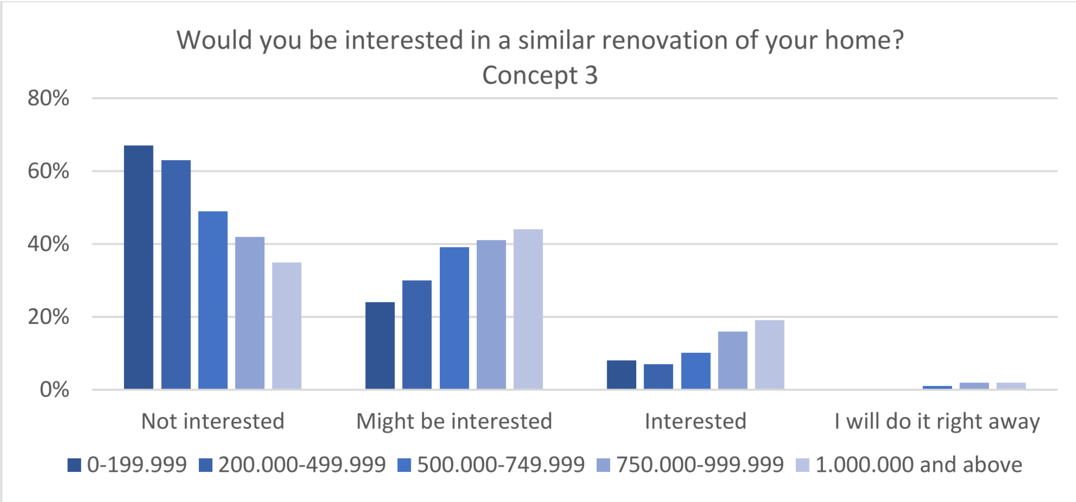


Table 3.4: Interest in performing the renovation project of concept 3 according to the different income groups

Using the data from the survey a correlation was created by the research between income and investment limited for house retrofit, as presented by the table 3.5 extracted from the survey report. The table shows by the grey cells the investment limit considered for each of the income categories.

INCOME IN DKK/YEAR ***Investment limit and price evaluation***	0-199.999	200.000-499.999	500.000-749.999	750.000-999.999	1.000.000 and above
160.000 DKK (concept 1)					
120.000 DKK (concept 2)					
310.000 DKK (concept 3) Average limit					
550.000 (concept 4) Average: Too expensive	Too expensive	Too expensive	Too expensive		
1.300.000 (concept 5) Average: Too expensive	Too expensive	Too expensive	Too expensive	Too expensive	Too expensive

Table 3.5: Investment limit (marked with grey) and the evaluation of the concepts prices influenced by income of the respondents [40]

Table 3.5 shows by the grey cells the investment limit considered for each of the income categories. renovation. Bolius is an institute that performs, analyzes and communicates quantitative and qualitative studies about homeowners and house in Denmark. The homeowners surveyed by them are evenly distributed throughout the country, they are between 25 and 79 years old, and they live in owner-occupied homes, which are either house, villa, townhouse or farm. Bolius present annually a report that presents common practices of the housing. The interview has minimum of 3000 respondents.

One of the things presented in the reports is the average expenditure in large maintenance works, which was used in this project to find values that homeowners are already used to disburse on house works. The last four reports published, from 2014-2017, had shown that people spent on average around 80,000 DKK per year on large maintenance works, where typically more than 25% of the respondents have spent more than 90,000 DKK, and around 19% had spent 150,000 DKK or more. These costs point out that homeowners would not be frightened by renovation stages costing between 80,000 and 150,000 DKK since it would not be such an unexpected amount in householders' experience.

The two surveys give different perspectives; one gives the perspective of common practices and the other wiliness to pay for house energy renovation. By the analysis of the second survey values between 80,000 and 150,000 DKK are reasonable values for the renovation stage. From the first survey, the maximum cost of a renovation stage would be some value between 310,000 and 160,000 DKK. Most likely, a value close to 160,000 DKK. Therefore a maximum value of 150,000 will be considered as most appealing for homeowners. However, as the AAU survey also demonstrated, the maximum cost one is interested in paying for a house renovation can also increase as the household income increase. That leads to another consideration. The higher the income, the higher the cost of a renovation measure can become, because of more expensive finishing or because larger house components, e.g., more area of external walls. Therefore, we consider that the maximum cost of the stages should be adjusted to the price of the most expensive renovation measure that must be executed at once, when such a measure is more expensive than 150,000DKK. Otherwise, the maximum limit remains as 150,000 DKK.

Besides the maximum limit, it is also important to consider the minimum cost. That is to avoid having too many disruptions by having too many renovation stages. Too much disturbance can decrease the homeowner's interest in continuing the renovation process. Moreover, the break-down of the renovation in small parts leads to extra costs related to initial works such as scaffolding, mobilization, initial installation services, and other services. Too many of these services will become a burden for the whole renovation cost. For these reasons, service works with considerable disturbance should not take place too often. That been said, the conclusion for a minimum limit cost of the stages will be assumed to be 80,000 DKK.

The cost limits found in this section will not be treated as a rigid restriction, but as a suggestion to help with the process of breaking-down the extensive renovation into stages with reasonable costs.

3.1.6 Frequency between stages

The previous section already gives an idea of problems that can occur on stage renovation related to the disturbances because of the number of interventions in a staged renovation. Therefore, the frequency of renovation stages is investigated in this section. There is no literature directly evaluating ideal frequency between renovations. Thus, the evidence of common practices that shows how often a house intervention happens in Danish houses was extracted from the Bolius annual report. The values found in Bolius report where then supported by evidence of renovation over-time presented by Fawcett [13].

According to surveys data from Bolius annual report, seen in figure 3.3, over the last six years less and fewer respondents have been performing large maintenance works (meaning renovations) and the percentage for "Not considered" increased. That can be because people have already performed the large maintenance in their houses, meaning they are not in need of it anymore. However, every year there is at least 20% of the participants carrying out extensive maintenance. Thus, if the results from the last six years are stretched for a longer period, e.g., 20 years, and also assumed that for every year the major number of interviewees are the same, it can be assumed that the current time interval between house works is 4 to 5 years, based on this information only.

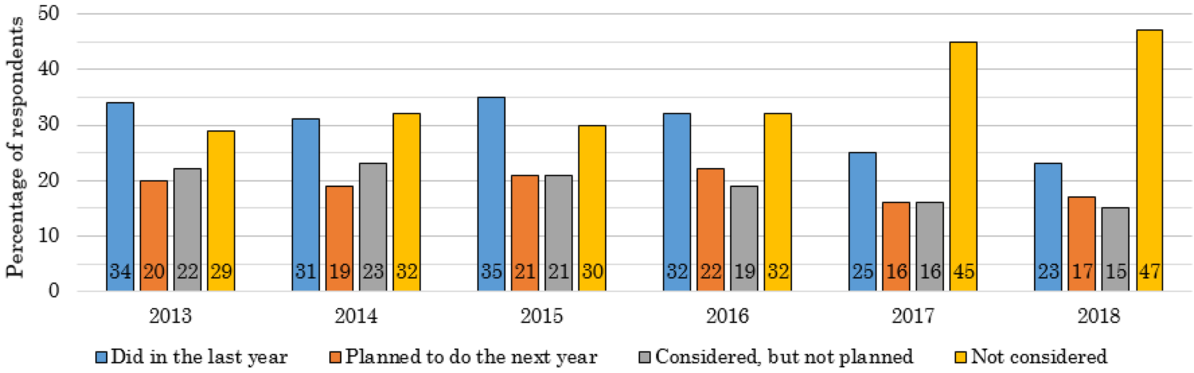


Figure 3.3: Distribution of larger maintenance works between respondents in respective years of survey

This assumed value is also confirmed by Fawcett's work, that explores the time dimension of house retrofits, in UK [40]. The article investigates the continuous cycle of house improvements that householders are involved. The study points out, on average, major improvement works are undergone on homes every five years. There is already acknowledgments of similarities between English and Danish homeowners behavior by SBi studies [45].

In the staged renovation process, other types of renovations will also take place besides major maintenance works, such as energy improvement, aesthetics, and functional works. That suggests, in the staged renovation project, interventions will happen more frequently than every four to five years. The staged renovation process will try to implement the house improvements as soon as the financial capacity of the homeowner allows. That can mean interventions happening between 2 or 3 years, for example. A so frequent intervention, if not managed well, can harm the households experience about house renovation throughout the process. For this reason, we considered that it is necessary to manage the disruption caused by the interventions. The result of the assessment should be an arrangement of the renovation works that disturbs the households as less as possible, or if the disturbance shown to be too disturbing find new solutions for the renovation itself.

We suggest estimating the disruption caused by the renovation measures in two ways. The first, by the place where the intervention occurs, if the renovation work is done inside (occupied heated rooms) or outside of the house - Unheated unoccupied areas, such as crawl space and attic, are considered outside spaces since the work done in these places will not disturb the usage of occupied rooms. The second, by the amount of disturbance, which it evaluates if the intervention caused is low, medium or high disturbing. Table 3.4 shows a definition created for the disturbance categories.

LOCATION
INTERNAL WORK - Work that at a certain point must be done with worker inside of habitable rooms
EXTERNAL WORK - The proper work can be totally done out of habitable heated spaces
DISTURBANCE
LOW - There is no necessity of store big amounts of material; it does not affect the comfort or heating consumption through the work process
MEDIUM - Necessity of store big amount of material; It has influence on comfort or heating consumption; The house can still be habitated commum used during work
HIGH - There is no possibility to leave inside the house during the work, or at least affects the common usage of the house.

Figure 3.4: Definition of disruption location and level

The usage of such evaluation happens when renovation works are being clustered together to become a staging package. To arrange them in a way that disturbs less, e.g., works done inside can be included in the same stage and work done outside in another one. Likewise, it is possible to evaluate if two stages with high disturbance are next to each other in a short time interval, causing too much disturbance to the occupants. It is suggested this evaluation to be qualitative rather than quantitative. Even though it is possible to assess quantitatively, throughout the time required for execution, the assessment of the location of the work and nature of disturbance is more comprehensive when considered by qualitative analysis. The perception of the level of disturbance in a qualitative analysis can be different from person to person. For that reason, we suggest after the energy consultant has done his evaluation of the intervention disturbances the assessment should be submitted to a second assessment by the house occupants to agree or not with the considerations of the level of disturbances.

In conclusion, the renovation stages will probably take place more often than current housing practices, which leads to the need of managing the disturbances. That is for the process do not repel the homeowners from keep performing the renovation project. The management of the disturbance is suggested to be done according to the intervention location and the potential of upsetting the occupants. The result of the evaluation should be a rearrangement of the renovation measures, or a change of the measure itself, to diminish the disruption to a level that would not harm occupants experience throughout the process. Finally, the final decision of solutions to avoid disturbance should also be discussed together with the homeowner for a final arrangement.

3.1.7 Time-frame of the whole staged renovation process

There was no available literature with a total time-frame for house renovation over-time in Denmark. The total time-frame of the whole staged renovation process in the methodology, as said before, is dependent on the total income of the households. That means that houses with low total income would need a long total period to conclude a renovation process, while a house if high total income can conclude the process in a short period.

Consider a short total period for the staged renovation process is not totally advantageous. That is because of the holistic approach, future maintenance works and wished works are included in the process, which ultimately has the potential to aid the process of housing in the long term. In this way, considering a short period, for example, 8-10 years, it will leave out of the planning maintenance works that would be necessary after 8-10 years. That would diminish the potential of a holistic consideration of the house. Moreover, the target of energy improvements, functional, aesthetic, and maintenance works make the whole renovation process a costly project - especially considering the condition of SFH from the 60s and 70s. Therefore, there we consider that would not be reasonable considering a total time-frame of a staged renovation less than 15 years.

On the other hand, renovation projects in houses with low income has the potential to elongate for many years to a horizon that is neither accessible nor appreciated. For example, in a house with a total income of 200,000 DKK, the maximum annual income for house renovation would be 30,000 DKK. For a renovation project for 900,000 DKK the minimal time-frame to conclude the project is 30 years. Present a renovation project for the next three decades for a homeowner are probably not appealing to them. In this case, the extent of the works and energy efficiency to be reached should be decreased, which is not investigated in this project. In a macro perspective, the maximum time to be considered to a staged renovation in order to contribute to the EU Energy Reduction Goal would be 30 years. However, from a micro perspective is not feasible.

That been said, we assumed that a reasonable time-frame for the staged renovation to be 20 years. That will involve probably large maintenance works of all house components. Moreover, a period larger than 15 years allows a larger proportion of SFH owners to be included as potential users of the staged renovation methodology. Otherwise, the low limit of household income would be higher. Moreover, finally, the total time will be within the time-frame to contribute the 2050 EU Energy Goal.

3.1.8 Financial assessment of the staged renovation

The staged renovation is a process that happens over-time. Therefore the financial assessment of a staged renovation must be done using a method that has a dynamic consideration in time. For this reason, there was chosen the Life Cycle Cost (LCC) analysis as a method to financial evaluate the staged renovations.

The LCC analysis has some variations, the so-called approaches. The approach select to evaluate the staged renovation is the "Full cost approach." As presented by Citherlet S. et al. [12], to evaluate the cost and economic efficiency of building renovation related to energy efficiency, it is essential to define a reference case. In this way, it is well determined the effects of a renovation with energy improvement in relation of energy use and costs. The costs included in the analysis is the full costs of renovation and costs for running the building (energy costs and maintenance costs of building components related to energy efficiency).

The reference case consists of maintenance works needed to maintain the building in its original functional conditions, without upgrading the energy performance of the building. It is a scenario, with no EEMs carried out. For this reason, the costs included in the analysis of the reference cases will be the full cost of maintenance considered for the future 20 years period and running costs (energy costs related to heating).

Because the "Full cost approach" compares costs that are different between the cases, the approach suggests that the costs that are the same in all cases can be omitted from the calculations.[12] These costs are the ones related to building systems and components that do not influence the energy efficiency or performance of the building, e.g., wall painting, internal wall, garden, etc. However, because of the holistic approach used in the staged renovation methodology, renovation measures that are not related to energy improvement, but are included because of homeowner request, will be included in the LCC analysis. The omission is optional and is done for simplification. For this study, small maintenance costs are not accounted for, even though they can differ from case to case, but these costs are not predictable, and the differences are considered irrelevant for single-family houses.

Basic concepts of the LCC analysis

The basic concept of the LCC analysis is the value of money on time, called “time value of money.” The value of money on the present day is not equal to the money spent in the future. The variation of monetary value on time is due to inflation and opportunity cost. Inflation decreases the purchasing power of money over time. For this reason, money spent in the future in various years must be brought to the same year to be comparable, which is the Present Value. Below, the formula of present value is presented:

$$PV = \frac{F_Y}{(1 + DISC)^y} \tag{3.1}$$

Where:
PV: is the present value, in year 0 [DKK]
F_Y: is the value in year Y [DKK]
DISC: is the discount rate [-]
Y: is the number of years in the future [-]

The discount rate used in this project is the average discount rate of the last 20 years in Denmark, 1.929%, informed by Danmarks Nationalbank.

The basic formula of LCC is as follows:

$$LCC = C + PV_{RECURRING} - PV_{RESIDUAL-VALUE} \tag{3.2}$$

where:
LCC: is the life cycle cost [DKK]
C: is the construction cost in year 0 [DKK]
$PV_{RECURRING}$: is the present value of all recurring costs [DKK]
$PV_{RESIDUAL-VALUE}$: is the present value of the residual value at the end of the study life [DKK]

The estimation of future costs based on today’s price must also be corrected. Some goods and services do not change their price at the same rate as inflation or the considered discount rate

— for example, the price of gas oil or district heating. In this way, the energy costs must be first corrected to its predicted future price using the escalation formula, to then bring it to present value based on the discount rate. Below is presented the formula to calculate future cost:

$$COST_{YEAR-Y} = COST_{YEAR-0} \cdot (1 + ESC)^{Y} \tag{3.3}$$

where:
$COST_{YEAR-Y}$: is the cost at year Y
$COST_{YEAR-0}$: is today's cost (at year 0)
ESC: is the escalation rate
Y: is the number of years into the future

3.2 Methodology to create a staged renovation

In this section the staged renovation methodology will be presented. The steps of the methodology will be presented and described in the same sequence presented in the beginning of this chapter. In some steps, simple examples will be presented to exemplify the outcome of the step and facilitate understanding of the explanation.

3.2.1 Mapping phase

This section explains about Step 1 of the methodology, which gathers information from the homeowner and assesses the current house conditions - information needed for the staged renovation. The following list gives an overview of these:

- Energy audit of the building
  - Building components' structure
  - Building components' condition and remaining lifetime
  - Building systems and their condition
- Future improvements wished by the homeowner
  - Aesthetic
  - Functional renovations (e.g. kitchen)
- Indoor environmental quality
  - Perception and opinion of the homeowner
  - Desired improvements
- Financial capacity of the homeowner
  - Current capital equity
  - Possible future savings

As stated before the staged renovation methodology has a holistic approach. Therefore, more information than the usual for an energy renovation is required. This section focuses on this additional information, rather than common information for energy renovation (that is dependent on the energy renovation approach chosen by the energy consultant). The additional information comprises of functional and aesthetic improvement wished or needed by the homeowner in the next 20 years; also if there is any requirement when these should be implemented. The information about the homeowner's perception and desire to improve the indoor climate should also be gathered (if the standard auditing method used does not already include it). Finally, homeowner's financial capabilities is also collected, meaning: the already available capital (or equity); household income; possible yearly savings.

The assessment of the house conditions for energy renovation inevitably includes knowing the building components and systems, knowing the house energy consumption and measure the indoor conditions. For the staged renovation, it should also include evaluating the conditions of the house components (service lifetime expectancy) with a prediction for necessary maintenance in the next 20 years.

One way to evaluate the energy consumption of the house, some energy consultants use the actual energy consumption informed in the energy bill and heating consumption. However, energy consumption is affected by household behavior. Therefore, using actual energy consumption is not appropriate to compare energy consumption before and after renovation. The assessment of current consumption should be done using Be18. The energy frame of the building should be calculated in accordance with the Danish Building Regulation and connected Danish Standards. This way, the house energy consumption found by using the program can be compared with other houses in Denmark (calculated by the same program), and the building can be energy labelled according to the EPC scheme [5].

A positive side of Be18 program is that it is a simpler and faster program to be used than Dynamic simulation programs. However, the drawback is that the program simulates using a single-zone model, losing accuracy of the energy estimation [51]. For this reason, in the Study Case chapter, the study case house will be simulated using Be18 and the dynamic simulation program Design Builder and the results of energy consumption for heating will be compared.

3.2.2 Creation of a holistic renovation and budget

This section explains about Step 2 of the method, which plans the house renovation and estimates its cost. In this step, the house renovation is planned as one-off renovation, to then, in step 4, be divide into stages.

This step is divided into two parts — the first, where the house renovation is planned as one-off renovation. Maintenance works and non-EEMs are included in the energy renovation plan, which the energy renovation into a holistic renovation. The second part, the budget of the renovation is estimated, as well as the budget of executing maintenance works needed for the house in the next 20 years. As said before, this second budget is used as a baseline that demonstrates real cost to energy improve the house when maintenance and non-EEMs are subtracted.

First part

The energy renovation is planned using the method that the energy consultant prefers. There are many methods used to select the best EEMs set. One of the most common ones is by calculating the CCE (Cost of Conservative Energy) for the solution options in order to find the most cost efficient one. Independent of the adopted method, to serve the purpose of the staged renovation, the energy improvement must be designed to achieve energy efficiency "Renovation Class 1". The energy renovation must also consider a minimum standard for the indoor environment quality (IEQ). Consequently, to be used in the staged renovation the IEQ should be designed to have comfort level Class 2 (also called "B"), according to the DS/EN 15251:2007. Dynamic simulations can be used to simulate the post renovation conditions.

Furthermore, the energy renovation must be connected as far as possible with the maintenance needs of the house and functional and aesthetic improvements. For that reason when selecting building components to be energy improved it is essential to prioritize the ones that were predicted to have their service lifetime ended in the period of 20 years. Also, when it is possible the functional and aesthetic improvements should be connected with EEMs.

The result of this part of the methodology is an extensive renovation plan, with a house that achieves energy efficiency Renovation Class 1, with minimum indoor quality Class 2. That also includes large maintenance works predicted to be implemented within the next 20 years, and functional and aesthetics improvements desired by the homeowner within the next 20 years. Thus, a holistic house renovation project planned as one-off renovation. The result of this phase will be called in this methodology "the extensive renovation".

Second part

Once that the extensive renovation is planned, as the second part of the step, the budget of the renovation is estimated. The costs are estimated for each of the renovation measures and presented individually in the budget. Professional labor is considered in the costs - even though the homeowner would prefer executed some of the renovations works himself. That is to be able to compare the renovation costs with the maintenance costs presented in the second budget estimated in this step. After that, a second budget is drawn up considering only the cost to perform the large maintenance need for the house in 20 years. This budget will present to the homeowner the cost that he will need to spend anyways even though he decides not to perform the renovation. Because the maintenance need considers 20 years, the intention is to show that the cost to maintain a house in its original condition, in the long-term, is significant. In step 5, this budget is needed to be used as a reference case to make the LCC analysis of the staged renovation, as presented in the Methodology Considerations.

3.2.3 Assigning staging data to renovation works

This section explains the step 3 of the methodology. This step is a preparation to the staging process. A series of data is attributed to the individual renovation measures that will be used on the implementation order of the measures and the creation of the stage packages.

The data that are attributed to the individual renovation measures are the remaining lifetime of the existing building component or system, the individual cost, the energy saving, and the co-benefits. The measures are also assessed according to their disturbance potential, as presented in the Methodology Considerations. Finally, an evaluation of related and predecessor measure is made. The explanation of data attribution and measure assessment is explained in the following part of this section.

After having the total energy saving of the renovation, the individual energy savings of each measure is calculated using Be18 program. The energy savings considered is primary and the actual energy (building energy demand). The remaining lifetime of the existing building component and systems, that was estimated in step 1, is attributed to the renovation measure that will replace it. Finally, the cost of the renovation measures are attributed to them.

Next, the co-benefits of each renovation measure are evaluated, using the evaluation matrix, as presented in the Methodology Considerations. They are also evaluated according to their disturbance potential, based on the presented method. Lastly, it is assessed the relationship between renovation measures, that evaluates if any measure is a predecessor of another or if measures are related. Predecessor measures are renovation works that must be executed before their successor because of technological or execution restriction. That means that predecessor measures must be implemented in a previous stage or at the same stage of the successor measure. Measures related means that there is not an order established between them, but there is a physical connection that executed together can bring benefits, e.g., lower cost or lower linear heat loss at their connections.

The result of this step is three tables. A table that has all the renovation measures with their, cost, energy savings, and co-benefits, and attributed remain lifetime, called " Measures Summary"; a second table that describes the disturbance of each measure according to its location level of disruption, called "Disruption Evaluation"; and a third table that presents related and predecessor relation between renovation measures, called "Ordering Restriction". Below, it is presented a simple example of the layout suggested to the tables:

RENOVATION MEASURES	PLACE	DISTURBANCE
Façade insulation (ext)	EXTERNAL	MEDIUM
Roof insulation	EXTERNAL	LOW
Ground floor insulation	INTERNAL	HIGH
Mechanical Ventilation (with HR)	EXTERNAL / INTERNAL	MEDIUM
Windows and door replacement	EXTERNAL / INTERNAL	MEDIUM
New window openings	EXTERNAL / INTERNAL	HIGH
Roof light or sun pipes	EXTERNAL / INTERNAL	HIGH
External shading	EXTERNAL	LOW
Renewable heat source	EXTERNAL	MEDIUM
Efficient DHW systems	EXTERNAL	LOW
Automatic control systems	EXTERNAL / INTERNAL	MEDIUM

Table 3.6: Example of table presenting disturbance consideration of renovation measures

RENOVATION MEASURES	PREDECESSOR	RELATED WORK
Façade insulation (ext)		
Roof insulation	Roof light or sun pipes	
Ground floor insulation		
Mechanical Ventilation (with HR)	Envelope insulation	Ceiling and attic works
Windows and door replacement		Façade insulation (ext)
New window openings		Façade insulation (ext)
Roof light or sun pipes		Roof insulation
External shading	Windows replacement	
Renewable heat source	Envelope insulation	DHW system
Efficient DHW systems		
Automatic control systems		Renewable het source / Mechanical Ventilation

Table 3.7: Example of table presenting predecessor and relation between renovation measures

MEASURES SUMMARY					CO-BENEFITS								
Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy									
Façade insulation (ext)	xx	xx,xxx.xx	x.xx	x.xx	0	0	0	2	1	3	0	0	3
Roof insulation	xx	xx,xxx.xx	x.xx	x.xx	2	0	-1	0	0	1	0	0	1
Ground floor insulation	xx	xx,xxx.xx	x.xx	x.xx	2	-1	-1	0	-1	1	0	0	1
Mechanical Ventilation (with HR)	xx	xx,xxx.xx	x.xx	x.xx	3	0	0	0	0	1	0	0	1
Windows and door replacement	xx	xx,xxx.xx	x.xx	x.xx	0	0	0	0	0	3	0	0	2
New window openings	xx	xx,xxx.xx	x.xx	x.xx	1	0	0	0	0	0	0	0	0
Roof light or sun pipes	xx	xx,xxx.xx	x.xx	x.xx	0	0	0	1	1	0	1	3	0
External shading	xx	xx,xxx.xx	x.xx	x.xx	1	0	0	1	2	0	0	0	1
Renewable heat source	xx	xx,xxx.xx	x.xx	x.xx	0	0	0	0	0	1	0	0	1
Efficient DHW systems	xx	xx,xxx.xx	x.xx	x.xx	0	0	0	0	-2	0	0	0	3
Automatic control systems	xx	xx,xxx.xx	x.xx	x.xx	0	0	2	1	-1	0	-1	1	1

Table 3.8: Example of table data attributed to the renovation measures (Measures Summary). The co-benefits values should not be considered as proper evaluation

3.2.4 Staging the extensive renovation

This section explains the step 4 of the methodology. In this step, the extensive renovation is divided into renovation stages, and it is ordered in a sequence that tries to reflect the homeowner preferences about the renovation.

This step is divided into two parts. In the first part, a series of values are calculated that will serve as a reference for the staging process. This part is called "Mean Values" of the staged renovation. In the second part is where the staging process takes place. The process has many sub-steps that will be presented one by one. The staging process is an iterative process where the sub-steps take place as many times as needed until the best implementation order and stage packages are found.

Mean values of the staged renovation

This section is about calculated values for the staged renovation that will guide the energy expert to plan the staged renovation.

The values help the building expert with reference values to find the number of stages, the time interval between stages, the earliest year of implementation of the stages, and the average cost for the stages. Moreover, the minimum number of years to complete the whole staged renovation project is also presented here.

Having reference numbers already in this phase is essential to guide the energy consultant on the staging phase. The values calculated in this section will be called the "Mean Values". Without these numbers, the energy consultant has no references to divide the extensive renovation into stages, or even reference of time for implementation of the stages. The Mean Values are not a restriction or an obligation that rules the staging process but guiding values that facilitate the process given the complexity of considerations due to the holistic approach.

The total period of the renovation is dependent on the total renovation cost and the household financial capacity or amount of yearly savings for the house renovation, as presented before. The average cost for the stages, or Mean Stage Cost, is the average between the minimal and maximal limits for the stage costs, as presented in the section 3.1.5. The number of stages, or Mean number of stages, derives from the division of the total renovation cost and the Mean Stage Cost. The time interval between stages, or Mean time interval between stages, is the result from the division of the minimum number of years to complete the whole project and the Mean number of stages. The earliest year of implementation of the stages is the next year after the total amount of a stage cost have been saved by the yearly savings. This calculation is made for all stages.

Below is presented a simple example of the tables that present the mentioned calculated values. The tables give an overview of the calculated numbers for an example where the annual saving is 50,000 DKK, and total renovation cost is 900,000 DKK.

DESCRIPTION	VALUE	UNIT
Renovation total cost:	900,000.00	DKK
Value available per year:	50,000.00	DKK/year
Minimum no. of years:	18.0	year
Most expensive work:	200,000.00	DKK
Minimum stage cost:	80,000.00	DKK
Mean stage cost:	140,000.00	DKK
Mean number of stages:	6	stage
Mean time interval between stages:	3.0	year

Stage no.	Earlest year
1	3
2	6
3	9
4	12
5	15
6	18
-	

Table 3.9: Tables that present example of calculated "Mean Values" (left) and earliest implementation year of the stages (right)

Ordering implementation measures

The method presented here to order the renovation measures attempts to implement the renovation measures in a sequence that best reflect the homeowner priorities to the renovation project. However, the holistic and long-term consideration (20 years) of the stage renovation method imposes some restrictions over the implementation order. Therefore, the final implementation order will hardly be the one, where the first measure to be implemented is the most desired one and the last ones to be implemented the least desired ones. There are some aspects of renovation projects that cannot be scheduled or avoided. An example of these aspects is maintenance needs that cannot be postponed to beyond the end of the lifetime of the existing components or because of the restriction on the implementation order due to precedence restriction.

For this reason, the implementation order is first arranged to consider the homeowner priority for the renovation project. After that, the order is modified considering the precedence restrictions and maintenance need. When the best order is found the measures are divided into stage packages. The process of ordering and creating stage package is explained below.

Household wishes and needs

The homeowner priority is reflected in the renovation measures by the benefits and co-benefits expressed by the "Measures Summary". For this reason, the arrangement of the implementation order is made using the Measures Summary table. Measures that have more of the benefit or co-benefits considered as priority by the homeowner is placed in the uppermost part of the list (the measures placed at the top of the list are implemented first). An example of this arrangement is if the homeowner priority is improving the Thermal comfort - using the Measures Summary table - renovation measures that have 3 points for Thermal comfort (in the co-benefits table) are placed at the top of the list. Followed by renovation measures that have 2 points and so on.

Precedent and related works

The analysis of predecessor works and related works is done using the table created in step 3. Measures that are the predecessor of another measure are placed just above its successor, and related works are placed next to each other to be executed in the same renovation stage. Programs, such as MS Project, have embedded tools to arrange these connections and precedence between works automatically, that can be used to facilitate this work step.

Need of maintenance

The next revaluation of the implementation order considers the lifetime of the current building components. The renovation measures are rearranged a second time. Renovation measures with restriction in the latest year of implementation because of the remain lifetime of the existing component are brought to a higher position to be implemented before the remain lifetime year. This arrangement is made with the assistance of the "Mean Values" tables that presented the earliest implementation year of the stages and mean cost of the stages. Using these values a first prediction formation of stage package and the year of implementation of the stages can be done. This step of the ordering must be reevaluated after the stage packages are made as part of the iterative process.

Presenting stage packages

The arrangement of stage package is made with the help of the “Mean values” too. The formation of renovation packages also affects the implementation because of cost and disturbance. Consequently, after having the stage renovation package created a reevaluation of the previous steps of implementation order is done to ensure that restrictions are not broken. The creation of the stage packages is not a straightforward task but an iterative as mentioned before. The stage renovation packages should preferably have costs within the suggested limits mentioned in the 3.1.5 section. It is desired to have internal or external renovation works grouped in a same stage as much as possible. Also, if it there is renovation measures with high disturbance, which means that the occupants need to leave the house to the renovation take place, it is the best to place these measures in the same package. In this way, it decreases the number of times that the occupants need to leave the house.

The result of the implementation order and stage packages is a suggestion of implementation order and stage packages and there is not only one solution that represents the homeowner priority. Therefore, more than one suggestion of staged renovation can be created to be presented to the homeowner.

After the staged renovation considering the homeowner priority is created a another staged renovation package and order is created, as mentioned before. This staged renovation scenario prioritize primary energy and it will be used as reference case in the financial assessment, in the next step. Therefore, this staged renovation scenario has the best arrangement of implementation order and stage packages in relation to primary energy savings. This scenario must also respect the restriction of precedent works and maintenance need.

Earliest Implementation Year of the stages

With the stage packages created the energy consultant can have the cost of each stage. By that, he can calculate the earliest year of implementation of the stages based on the annual household savings. The earliest implementation year of a stage is the next year where enough money is available to pay for the stage. After this step, the staged renovation scenarios are planned and can be implemented in the Life Cycle Cost of the staged renovation.

3.2.5 Life cycle cost assessment

This section explains the step 5 of the methodology. In this step, the staged renovation is financially evaluated considering the Life Cycle Cost of the project. The staged renovation is also compared with the two reference cases.

The financial evaluation of the staged renovation has the purpose of presenting to the homeowner the economic aspects of his house renovation, in a life cycle perspective. The life cycle cost analysis is presented for 30 years. Moreover, to be simple to understand by the homeowner, the results of the financial analysis of the staged renovation will be presented with the two reference cases. One reference case is the one suggested by the "full cost approach" (presented in Methodology Considerations) that represents the cost that needs to be spent anyway by the homeowner even if the renovation is not performed. This reference case is called in this methodology "Anyways". The other reference case is the hypothetical staged renovation scenario created in step 4, where primary energy savings is prioritized. This reference case is called "Energy Priority".

The idea of the reference "Energy Priority" is to demonstrate to the homeowner that prioritizing energy efficiency in the renovation process brings financial advantages. That is because by prioritizing energy efficiency the house energy consumption decrease earlier in the renovation process, which means lower energy bills.

The life cycle cost analysis considers the costs spent for the renovation and the cost for running the building. The running costs are the cost of energy for the space heating and electricity used by the building systems. The same ones considered by Be18. In the running costs, it is consider the reduction of energy consumption after implemented each stage. Therefore, the energy consumption of the building after each stage is taken using Be18 program. The costs of renovation are collected by the annual savings, which means that it is collected every year until sum the total cost of the renovation.

The annual energy cost of the building is calculated for each year. The annual energy consumption is the actual annual energy consumption of the building multiplied by the energy price of its energy source. The energy price of each energy source varies differently in time, thus the annual running cost for each year must be corrected to its predicted future price using the "future cost" formula presented in the Methodology considerations.

The "future" annual energy cost is summed with the annual savings to become the annual recurring cost. To the recurring costs is applied the NPV formula. Finally, the Life Cycle Cost of the staged renovation project is found by summing all recurring costs corrected to the present value.

In order to present better the life cycle cost of the project in time, the annual recurring costs corrected to the present value are plotted in a accumulative chart with the two reference cases.

The same procedure is done for the two reference cases. For reference case "Anyways" the cost for renovation is the costs for performing only maintenance works, calculated by the second budget in step 2 of the methodology. The cost of each maintenance work is accounted in the year that it takes place, not by regular savings. That is because generally homeowner do not keep programmed saving for long period to perform house maintenance. The energy consumption used to calculate the running costs is calculated by the Be18 program, calculated in the first step of the methodology for the existing condition of the house. Some maintenance works can bring some energy reductions because of the Building Regulations restrictions; these reductions in the house energy consumption must be accounted when calculating the running costs.

The costs for the other reference case, Energy Priority, is accounted exactly in the same way accounted to the staged renovation made for the homeowner - the costs for the renovation are accounted by the annual savings. The total renovation cost should be the same as the staged renovation made for the homeowner since only the implementation order of the renovation measures is changed. However, the energy consumption of the building after each stage will be different from the staged renovation made for the homeowner. Probably, there will be more energy savings after the implementation in the first stages but the final energy consumption should be the same.

The result of this step is the graphic that presents the Life Cycle Cost of the staged renovation made for the homeowner. The graphic is presented along with the two reference cases — the first that demonstrates the Life Cycle Cost of the building if the building is maintained in its original conditions and the other that demonstrates the Life Cycle Cost of a hypothetical case where primary energy savings are prioritized.

4 Application of methodology on the case study

4.1 Introduction of the case building

Figure 4.1: Langøvænget 1, house as seen from the street in existing conditions

The majority of parcel houses built between 1960-79 are very similar to each other in terms of form, size, layout and structure. 67% of them have a floor area between 100-199 m^2 (Danmarks Statistik). There is usually only one storey, with either a ground supported floor or crawl space. The walls are constructed as a load-bearing inner gas concrete and outer brick facade with a cavity in-between that is either insulated or empty. The case building, built in 1973, shares most of these characteristics and thus is considered to represent the majority of typical parcel houses built around this time.

The case building is located near Aarhus, in Tilst, at the address Langøvænget 1. The building was part of a renovation project along with 3 other parcel houses. The goal of that project was to evaluate the influence of energy efficient renovations. The compiled report and certain measurements were available from before and after the renovations. For this thesis, it was only relevant to see conditions prior to renovation (later on referred to as "Existing conditions"), which is described in more detail in the following paragraphs. Due to incomplete information, assumptions were made based on the typical solutions and characteristics of houses built at the time. The remaining lifetime of the building components and furnishing were evaluated based on photos taken before the renovation.

4.1.1 Method summary

In this chapter of the thesis, the Steps described in section *Methodology* will be applied to this case building. The following structure reflects the application of the methodology:

Step 1. Mapping phase

- Characteristics of the homeowner are defined
- The existing condition of the building and its components are described.
- The indoor climate of the building is described

Step 2. Creation of holistic renovation and budget

- Selection of EEMs
- Evaluation of EEMs
- Presentation of whole renovation

Step 3. Assigning data to renovation works for the staging process:

- Remaining lifetime of the existing building components and systems
- Individual cost of the renovation measures
- Energy savings given by each EEM
- The co-benefits given by each EEM

Step 4. Staging the extensive renovation

- Mean values of the case study are defined
- The iterative process of staging the renovation works according to Energy savings as a priority
- Additional stage scenario presented according to prioritizing Aesthetics and Prestige

Step 5: Life cycle cost assessment

- LCC analysis of the staged renovation
- Financial comparison between staged renovation and one-off renovation

Simulation results of the staged renovation

- Tools used are described
- Validation of the model
- Results of thermal comfort, indoor air quality and energy consumption

4.2 Step 1: Mapping phase

4.2.1 Characteristics of the homeowner

The occupants are a married couple with a small child. During the original AAU project a second child was born, but the newborn is disregarded in the simulations and a fix number of 3 occupants is considered.

The total household income is not known. Therefore, the household income should be assumed. The AAU survey [40] is used to define this amount. In the survey, respondents were divided into groups based on their income before taxes, ranging between the numbers of 0 - 200,000 - 500,000 - 750,000 - 1,000,000 - or above. In order to test the extent of the methodology, it would be relevant to assume the lowest income possible. Since the methodology has an ambitious energy efficiency target and a restriction on maximum time, assuming an income from the lowest category would not be realistic. A mean value from the second category presented, from 200,000 until 499,000 DKK is more suitable. Therefore, an income of 300,000 DKK will be assumed for the case study.

Since interview with the homeowner was not carried out, a functional renovation measure desired by the homeowner will be assumed. A kitchen renovation is then included in the house renovation.

4.2.2 Description of the building and its components

The building is a single story parcel house with 3 bedrooms, a full bathroom and a toilet, a kitchen and a living room. The corridor serves as a utility room, where the boiler is located and from here both the attic and the crawl space is accessible. The floor plan is seen on figure 4.2. The building's thermal envelope is summarized in figure 4.3 and is described in the followings.

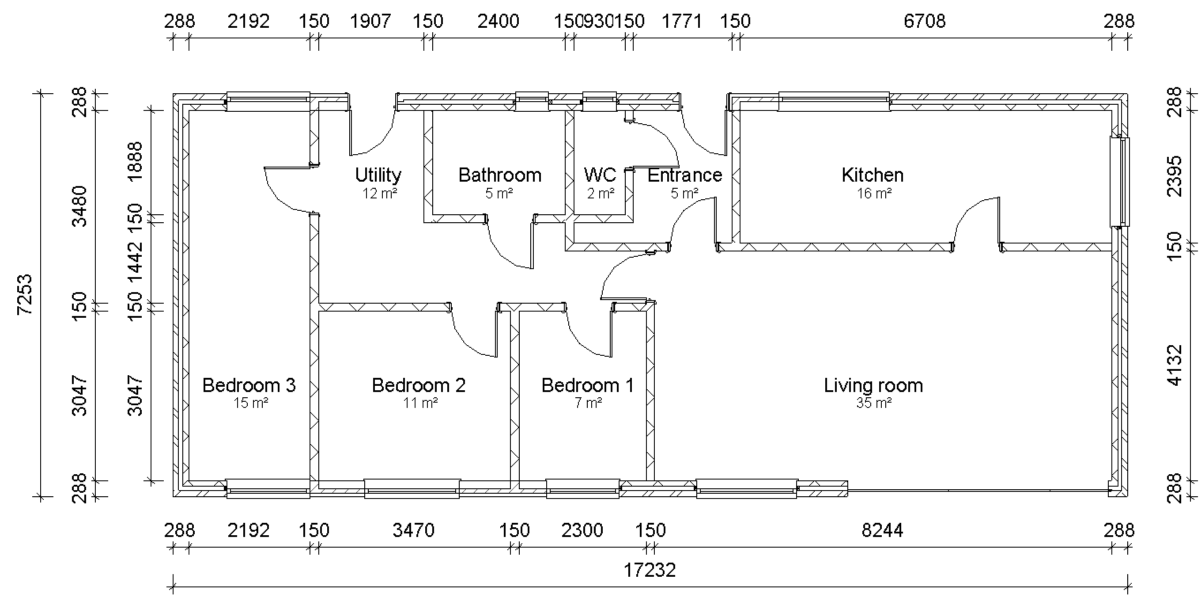
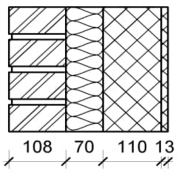


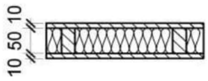
Figure 4.2: Langøvænget 1, Floor plan of the house

External wall (load-bearing)



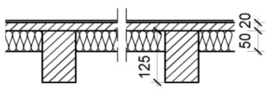
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	0.491
0.013	Plaster finish	Transfer area [m^2]	100.96
0.110	Gas concrete blocks		
0.070	Insulation (old)		
0.108	Brick façade		

Extenral lightweight wall



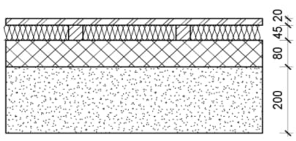
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	0.493
0.010	Wooden cladding	Transfer area [m^2]	7.63
0.050	Insulation		
0.010	Wooden cladding		

Floor above crawl space



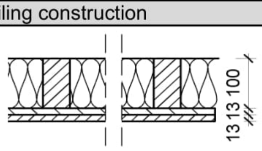
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	0.679
	Floor covering	Transfer area [m^2]	117.83
0.020	Wooden boards		
0.125	Floor joists		
0.050	Insulation between joists		

Ground supported floor



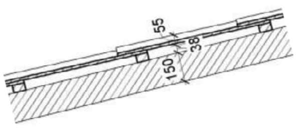
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	0.310
0.020	Floor board	Transfer area [m^2]	8.46
0.045	Floor battens		
0.045	Insulation between battens		
0.080	Concrete screed		
0.200	Leca capillary breaking layer		

Ceiling construction



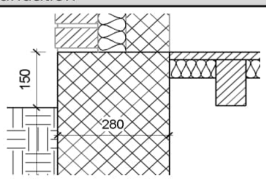
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	0.441
0.013	Ceiling boards	Transfer area [m^2]	126.3
0.013	Wooden boards		
0.100	Ceiling joists		
0.100	Insulation between joists		

Roof construction



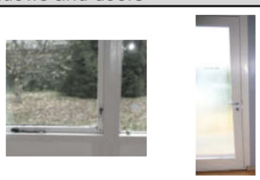
Construction (from inside to outside)		Specification	
[m]	Layer	U-value [W/m^{2}K]	n/a
0.150	Structural rafters	Transfer area [m^2]	149.5
0.038	Battens		
0.055	Fiber-cement sheets		

Foundation



Construction (from inside to outside)		Specification	
[m]	Layer	ψ-value [W/mK]	0.7
0.280	Concrete foundation	Transfer length [m]	50.8

Windows and doors



Construction (from inside to outside)	Specification	
2 layer glazing	U-value [W/m^{2}K]	2.8
	Transfer area [m^2]	28.34
	SHGC [-]	0.63
	Light transmittance [-]	0.72
	ψ-value [W/mK]	0.11
	Transfer length [m]	65.2

Figure 4.3: Summary of building components

The heated floor area is 126.3 m^2. Most of the floor is above a ventilated crawl space, with a height assumed to be 600 mm. The floor structure is a 120 mm by 50mm wooden batons with 50 mm rock wool insulation in between and wooden planks of 2mm as finishing. Part of the floor area has a ground supported floor with 45 mm insulation. The ground supported floor was assumed to be in the wet-rooms (bathroom and toilet) considering waterproofing and tile finishing requires a solid base.

The external wall is built of gas concrete blocks in its load-bearing internal part, usual to the era of construction, used due to their cheaper overall price. The exterior layer built of bricks, which it keeps the traditional look of Danish homes. The cavity is an insulation layer of 70 mm. The facade bricks have an exceptionally long lifetime (100 years or more) and requires minor maintenance, such as repairing the mortar between the bricks. The interior finishing is painted plaster.

The foundation is the external walls of the crawl space and is made of 28 centimeters of solid concrete, which means a significant cold-bridge.

The ceiling or attic partition has an structure of wooden joists of 100 mm by 50mm with 100mm insulation in-between. The ceiling is wooden board and the covering is assumed to be in good condition. There is a hatch leading up to the unheated attic, which is used for storage. The roof is made of 150 mm wooden rafters that are in good condition judging from available photos. The roof is pitched with only 16° angle and covered with fiber-cement sheets, with a short remaining lifespan, judging from photos. Also there are no waterproofing membrane under the roofing sheets.

An oil burner supplies heating and domestic hot water to the house. This has been changed already to a newer model of 20 kW with a 94% efficiency. The pipes for the heat distribution system are running in the crawl space and are insulated. The panel radiators are assumed to have a long remaining lifetime. The DHW system is one string with only a supply to the draw off points and no circulation. There is a 100l hot water tank located in the heated zone.

The infiltration is 0.304 $l/s/m^2$ heated floor area under normal conditions (during occupant hours), measured by a blower door test according to EN 13829 to be 4.4 $l/s/m^2$ heated floor area at 50 Pa. Thermographic images showed several cold bridges, such as ceiling hatch, wall and roof connections, wall and window connections, boiler and ceiling connection.

4.2.3 Measurements taken in the building

The indoor environmental quality was measured by Aalborg University from January 2009 till the end of June 2009. The measurements included indoor temperature, relative humidity and CO_2 concentration, taken in the bathroom, bedroom2, the kitchen and the living room. The last two rooms showed similarities in their indoor climate, probably because the door is left open between them. The bathroom is only occupied for short periods of time and the bedroom3 was an unheated, unoccupied room. For comparison with simulated models, the living room will be used as this is considered to be of primary importance due to its usage and location.

The hot water consumption of the family was measured as 966 $l/m^2/year$, which is almost 4 times of the standard (250 $l/m^2/year$) for single family houses in Be18. Due to its unusual value the standard consumption was taken.

Energy consumption for room heating and hot water production was measured through hot water consumption on the distribution pipes. Judging from the measurements, heating is turned off after the first of April in the living room and also reduced in the other rooms. Electricity consumption was logged, but is not compared with simulated consumption. Only the electricity need for operation of the heating system is extracted from simulation results and an average heat gain from appliances of 3.5 W/m^2 heated floor area (based on standard value in BE18) is used.

4.2.4 Evaluation of indoor environmental quality

The indoor environmental quality was defined according to DS/EN 15251 standard. To evaluate the existing conditions, the hours and thus percentage of time within certain comfort categories were investigated. The comfort ranges for thermal comfort are defined according to table 4.1. Conditions are deemed within category if deviation from it is no more than 5% for the time period. Overheating is defined as maximum 100 hours above 26°C and maximum 25 hours above 27°C. Heating season is defined from 1. October until 30. April, and thus cooling season is from 1. March until 31. September.

Category			I	II	III
Activity level	[met]	All year	1,2	1,2	1,2
Operative temperature	[°C]	Summer	23.5 - 25.5	23 - 26	22 - 27
		Winter	21 - 23	20 - 24	19 - 25
		Spring	21 - 25.5	20 - 26	19 - 27
		Autumn	21 - 25.5	20 - 26	19 - 27
Clothing level	[clo]	Summer	0.5	0.5	0.5
		Winter	1.0	1.0	1.0
		Spring	0.5 - 1.0	0.5 - 1.0	0.5 - 1.0
		Autumn	0.5 - 1.0	0.5 - 1.0	0.5 - 1.0

Table 4.1: Definition of Thermal comfort categories according to DS/EN 15251

Figure 4.4 shows the hours above and below certain temperatures, which shows that bedroom2 was unheated. Overheating is already an issue in the building since the specified hours above 26 and 27°C are exceeded.

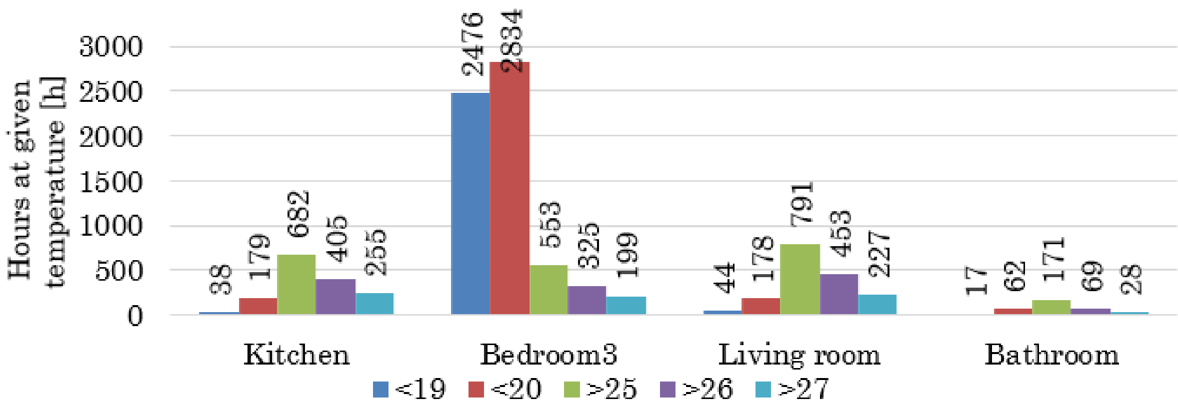


Figure 4.4: Overheating and under-heating hours shown for the four measured rooms

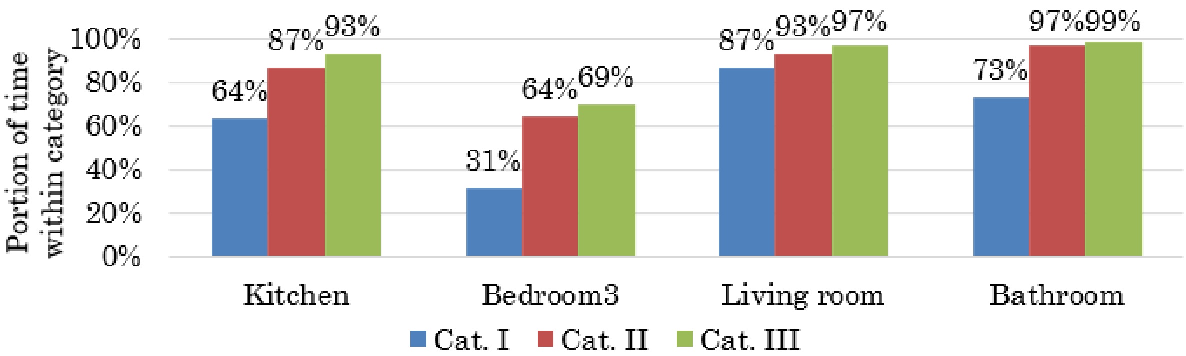


Figure 4.5: Thermal comfort categories for the four measured rooms

DS/EN 15251 defines comfort categories as CO_2 concentration above outdoor levels. Category A <350 ppm, category II <500 ppm, category III <800 and category IV >800 ppm. This standard is used throughout the rest of the report to define indoor air quality. Table 4.2 shows the existing conditions based on the measurements taken in 3 rooms. As bedroom2 was unoccupied, it is not relevant. Air quality is not up to standard requirements of any category.

	Cat I		Cat II		Cat III	
	[h]	[%]	[h]	[%]	[h]	[%]
Kitchen	1052	24%	1727	40%	3074	71%
Bedroom2	3334	77%	3678	85%	4047	93%
Living room	1377	32%	2272	52%	3665	85%

Table 4.2: Thermal comfort categories for the four measured rooms

4.3 Step 2: Creation of holistic renovation and budget

4.3.1 Selection of Energy Efficiency Measures

In case of a stage renovation, it will be required by BR18 for each individual component to fulfill the minimal requirements for thermal transmittance, since for the whole building, the target renovation class will be achieved only towards the end of the process. Thus, for this case building, two approaches were investigated.

The first is to improve the building components to fulfill the minimum requirements by BR18, along with the addition of PV cells, aiming to reach Renovation Class I in the most cost efficient way. The second is to renovate building components to a "Higher standard", reaching lower thermal transmittance than required by BR18, achieving Renovation Class I without the need for renewable sources. The reason to explore the higher standard solutions is to see if it is worth in terms of financial investment and other co-benefits.

A technical report from AAU [42] was the basis of several solutions for the BR18 standard. The paper investigated the renovation potential and cost efficiency of packaged solutions for parcel houses. The standard according to which the renovation packages were considered was BR15 minimum requirements. The most cost efficient solutions were taken as possible options for this project. Finishings were not considered relevant, thus the cheapest option was chosen for all components.

External walls

For the renovation of the external wall, 3 solutions were considered to satisfy BR18 minimum requirements. The cheapest solution is to leave the existing construction and add additional insulation after the brick facade. By doing this the daylight conditions inside the house will reduce, and construction issues with the roof overhang occur, thus such a solution was not considered. Demolishing the brick wall is relatively cheap (compared to other items in the budget), thus the existing insulation can be exchanged with new, thicker one, enough to reach the desired final U-value. The external finish is assumed to be kept the same, but is cheapest if a 20 mm thick brick tile finish is applied, whereas reconstructing the 108 mm brick wall would require a foundation which increases costs significantly.

With these considerations, to reach BR18 minimum requirements the solution presented in Appendix .2, figure .8 is chosen. To reach higher standards, with the same approach, the maximum thickness of the insulation is 400 mm, presented in figure .9. What needs to be kept in mind is the reduced daylight levels inside the building, due to the increased wall thickness. The cost of the higher standard renovation is 10.7% higher compared to the BR18.

Besides the obvious heat loss reduction due to insulation, the surface temperature of the walls will be increased, which will improve thermal comfort. Wall turn-ins at windows are ought to be constructed with 50 mm insulation, as given in DS418, page 40 Table:6.12.1a to give a value of 0.03 W/mK. Also, infiltration is reduced, but due to uncertainties the amount is only assumed. From the original 0.30, down to 0.13 l/s/m^2, the saved energy due to reduced heat loss is divided equally between the four building components responsible for this: ceiling, external wall, windows and doors, and floor.

Roof and attic partition

It is considered to renovate the attic partition in two ways, either laying down insulation mats or use granulate insulation. The price does not vary significantly between the two solutions. For financial reasons, the cheaper solution is chosen, which is the mineral wool batts. With their 0.037 W/mK lambda value, 300 mm is required to reach a U-value 0.105 W/m^{2}K. It is needed to overestimate the overall thickness to compensate for the reduced height of the insulation at the eaves of the roof. It is also important to include a vapour barrier before insulating the partition, to prevent moisture rising from the internal space and to improve the airtightness of the building. This solution is presented in appendix .2 figure .10, after which, the height in the attic is much less, thus its storage function is lost.

Another solution is to increase the thickness of the rafters and by that adding more insulation to the roof. To reach 0.12 W/m^{2}K, 150 mm insulation between the existing rafters and an additional 200 mm is required. For the proposed solution, an additional 360 mm of insulation was considered to reach a lower U-value. This is much more costly as presented in appendix .2 figure .11. The connection to the wall creates a more continuous thermal envelope (seen on figure 4.7) than it would be in case of the attic partition (seen on figure 4.6). With this solution the attic retains its storage function and it is possible to facilitate HVAC equipment and ducting later on. There is also the possibility (if the homeowner wishes) to open up the attic space in certain areas of the house, increasing interior height and also to place skylights. This is a prime example of increased costs that are not worth in terms of economic payback due to energy savings. It is needed to evaluate the pros and cons of such a choice and to understand the need of the homeowner to make the best decision, considering future plans.

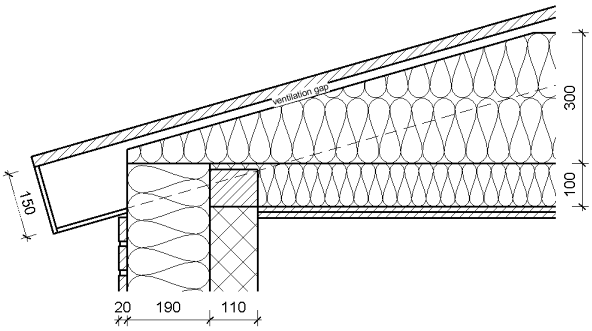


Figure 4.6: Detail of attic partition and wall connection

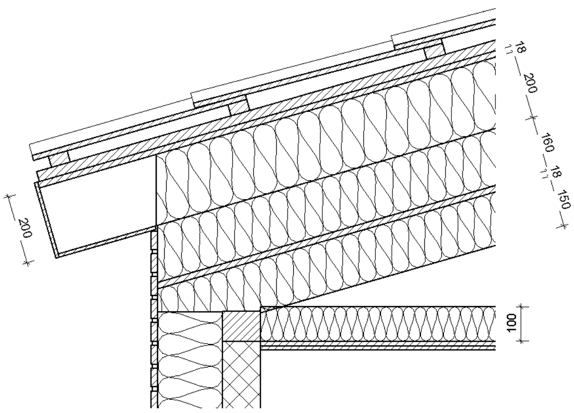


Figure 4.7: Detail of roof and wall connection

Ground floor

In building regulations it is stated that energy retrofit of components must be carried out without causing risk of moisture and mold. The renovation of the floor above the crawl space is possible only to a certain extent. More than 145 mm of insulation will cause risk of condensation [8]. Due to this, the lowest possible U-value by this solution is 0.272 W/m^{2}K, which will require a dispensation from the municipality. There is also a need for a moisture barrier, which is to be fixed to the underside of floor. This will improve the airtightness of the construction as well. This overall solution is relatively cheap, and disturbs everyday life the least, presented in appendix .2 figure .12. In terms of floor surface temperature, table 4.3 shows the conditions calculated via steady state conditions. Even though the floor does not directly face outside, the crawlspace is ventilated and conditions are not far from outdoor temperatures. Existing conditions with only 50 mm insulation were not satisfactory, and even with 150 mm it is still likely that local discomfort of cold feet is experienced.

Outdoor temp.	-12	-12	4	-1.5
Indoor temp.	20	22	21	20
Wood surf. temp. - 50 mm Ins	16.21	17.97	18.99	17.45
Wood surf. temp. - 145 mm Ins	18.52	20.43	20.22	19.01

Table 4.3: Surface temperature of the wooden floor covering, during different temperatures, for existing and renovated conditions

In the bathroom the floor is needed to be demolished to reach better thermal performance as it is minimally insulated. With 250 mm EPS80 a U-value of 0.107 W/m^2K is possible. The solution is presented in appendix .2 figure .13

If a better thermal performance is desired, the floor is to be demolished and a new ground supported floor may be constructed. The crawlspace reduces the amount of excavation required, and for this case building, it is assumed that there is no need for that due to the height of the crawl space. The amount of insulation gives a low U-value for the construction, 0.052 W/m^2K, shown in appendix .2 figure .14. With this solution it is also possible to establish floor heating in the concrete slab, that is a significant comfort improvement.

Insulation of the floor joists will reduce local thermal discomfort of cold feet, but to ensure Percentage Dissatisfied (PD) of <10% (acc. to DS/EN ISO 7730) during low outdoor temperatures, the floor needs to be reconstructed for a ground supported floor. There is also the issue of significant disturbance, as moving out temporarily is necessary.

Windows and Doors

To reach the required E_{ref} for the windows, a low enough U-value of the component is needed along with a high enough g-value. The windows presented in appendix .2 figure .15 are taken from Velfac as reliable specification and to get a price estimate of the renovated windows and doors, Velfac was contacted for a bid through their website. A different final price is possible due to the specific supplier, thus the price is considered only as an estimate. Even though the light transmittance (LT) of the existing windows are unknown, daylight conditions can be assumed to be unchanged due to the new windows having a 0.82 LT.

A higher standard for the windows and doors are presented in appendix .2 figure .16. Consideration in higher standard will have to be made in terms of other benefits than just economic payback.

In terms of airtightness it can be assumed that the change of windows will contribute to the reduction of infiltration. It is of high importance to include a vent grill in the frame in order to compensate for this and avoid issues of condensation. With the later introduction of mechanical ventilation these can remain closed, reducing heat loss from the building.

Foundation

As the existing foundation is made of concrete without any cold-bridge break, improving it is difficult and the extent is limited. Only one solution was examined, presented in appendix .2 figure .17. Excavation is needed to place 150 mm XPS insulation boards to the outer side of the foundation. Along with this, a perimeter drain can be established to help protect the foundation from moisture/water from the soil. The reduced linear loss for the construction is based on DS418, table 6.13.3 and figure 6.13.2. Performing this improvement will allow a yearly 15.2 kWh/m^2 savings, which is important to reach a low overall consumption in the end result.

Heating system

When changing the existing heat source of the house, by Building Regulations one is required to change to a highly efficient condensing boiler, to connect to the local district heating system, or change to renewable source. For the case building there is possibility for District Heating (DH) connection. To set up a ground source heat exchanger would be much more costly [42], thus only DH connection is examined.

The proposal is presented in appendix .2 figure .18, which would be used for both BR18 minimum and the higher standard. Connection is made via a heat exchanger. This way the house will not be influenced by the pressure conditions from the supply side of the system and a separate, closed circuit is established within the house. There are compact units with DHW tanks of 100l, circulation pumps for heating, expansion tanks and regulation valves, that is cheaper to buy and easier to install. The change to district heating results in a primary energy consumption, but not in the site energy reduction.

As previously mentioned in terms of the floor construction, for the higher standard, it is possible to place floor heating into the concrete screed, which is presented in appendix .2 figure .19. By doing this, the old radiators and distribution pipes would have to be removed. The saved energy is 11 kWh/m^2.year, because the losses from distribution pipes would significantly reduce. Despite this, floor heating should be considered only in terms of comfort improvements.

Domestic hot water

The existing hot water tank could be replaced with a heat exchanger to avoid having heat loss from a storage unit. This solution is not considered, since the home is used during the morning and late afternoon, so there is time for the hot water tank to recharge during midday and in the evening. Also the packaged unit solution for the district heating connection includes a tank, which reduces the price. It is considered to leave the same supply only pipe system, as circulation would result in unnecessary heat loss and there are no great distances within the house that could cause long waiting times.

Ventilation system

Installing de-centralized, facade integrated ventilation units is becoming more popular for renovation projects, since there is no need to establish a duct air distribution system. In case of this building, there is sufficient space in the attic for the duct-work, thus a centralized ventilation solution is considered. By BR18 there is a minimum air change per hour for the whole house of 0.5, which translates to 147 m^3/h. Also there must be a minimum extraction from kitchen, bathroom, toilet and utility room, which adds up to be 50 l/s or 180 m^3/h. The chosen AHU, presented in appendix .2 figure .20, is capable of providing this amount.

There will not be a reduction in energy consumption due to mechanical ventilation. The heat loss due to this air change is reduced by the heat exchanger, but there is still 4.19 $kWh/m^2/year$ that needs to be covered by the heating system. Also electricity is needed for the operation of the AHU's components, which is 7.43 $kWh/m^2/year$. All together there is an increase in Primary Energy consumption of 11.59 $kWh/m^2/year$. Ventilation needs to be considered as an improvement of the indoor air quality, which is most important during winter, when occupants tend not to ventilate sufficiently.

For a higher standard, a different AHU is presented, that provides 200 m^3/h as minimum and can go up to 30 $0m^3/h$. This is a VAV unit and there should be CO_2 sensors installed in the occupied zone. The airflow can vary depending on the need, providing higher comfort, in case there are more people present. Also, during the day, when there is nobody at home, it can shut off to conserve energy, if conditions allow it. There is also a heat pump for active heat recovery from the air condensate. The solution is presented in appendix .2 figure .21. Even though it consumes more electricity, the regulation allows to save energy, while providing the best comfort.

It can be argued that ventilation with heat recovery should be considered as saving energy, since if the same air flow would have to be provided by natural means, it would significantly increase heat losses. However occupants ventilate during cold periods less frequently, thus real occupant usage does not allow for this consideration to be valid. It is considered as a comfort improvement, above all else. For this reason, how the proposal is presented to the homeowner and understood by them is crucial to the willingness to invest.

Photovoltaic solar system

In order to satisfy requirements of renewable energy inclusion in the site energy and to achieve greater reduction of primary energy consumption for the building, solar PV is to be used. The solution is presented in appendix .2 figure .22. The array should ideally be placed on the ground, facing South, but the roof is oriented towards East and West. It is designed to be placed on the roof towards the West, where it can provide more electricity during peak afternoon loads.

All components

Table 4.4 summarizes the solutions that were presented for both approaches.

	U-value [W/m^{2}K]		
	BR18 min. requirement	BR18 standard	Higher standard
External wall	0.180	0.175	0.084
Ceiling partition	0.120	0.105	n/a
Roof	0.120	n/a	0.083
Floor - Living space	0.100	0.270	0.052
Floor - Wetrooms	0.100	0.107	0.052
Windows and doors	1.400	1.210	1.210
	Linear loss [W/mK]		
Foundation	0.12	0.31	0.31
Around windows and doors	0.03	0.03	0.03

Table 4.4: Thermal transmittance of the chosen component solutions for the two approaches

4.3.2 Component evaluation according to Building Regulations

For each of the components an evaluation for pay-back time will be carried out. This is generally carried out to help choose the most economical solution. In this case, it will be used to evaluate the components, and thus show the difference between the minimum requirements and the higher standards. Also how maintenance costs are considered is also a large influence on the prediction of the payback time. First compliance with BR18 requirements will be checked after which a more accurate calculation method will be carried out.

In case of a house renovation, there is a need to fulfill the minimum requirements by Building Regulations 18 of thermal transmittance for each component that is renovated (seen in table 4.5). However, when renovating, if the renovation is to achieve specific energy frame (Renovation Class 1 or 2), the minimal requirement for some component can be disregarded and the total primary energy requirement of the building becomes the precondition to fulfill. This needs to be lower than 87,4 kWh/m^2 and 65,6 kWh/m^2 for Renovation Class 2 and Renovation Class 1 respectively for this case building specifically. Also, in case there is no connection to district heating, part of the building's energy supply has to be covered by renewable energy.

Building component	**U-value [W/m²K]**
Outer wall and basement wall against soil	0.18
Storey partition or wall partition against room where temperature difference the rooms are 5°C or more	0.40
Terraindeck, basement floor against soil or storey partition towards the outside or ventilation ventilated crawlspace	0.10
Attic and roof construction, flat roof	0.12
Garage doors	1.80
hatches, removable windows and skylights	1.40
Renovated removable windows	1.65
Lighttunnel or similar	2.00
Building component	**ψ-value [W/mK]**
Foundation	0.12
Joint between outer wall, window or outer door, garage door or hatch	0.03
Joint between roof construction and skylight or skylight dome	0.10

Table 4.5: Minimum requirement for building components in case of renovation

The Regulations also state that renovation or change of building components must be implemented to the extent that they are profitable without causing moisture damage. The Profitability is defined as 1.33 [kWh/DKK], that is calculated according to equation 4.1. The investment cost should only include the costs related to the energy improvement of the component, meaning, disregarding the costs of maintenance and soft costs. More specifically Guidelines 4.0 states: *"In the calculation of profitability, only materials and labor are included in the energy-saving work and the strict follow-up work of the energy-saving work, and not for example: cost of roofing, scaffolding or other expenses."* In case there is a lack of profitability, it must be proven, and the profitability of a smaller conversion should be evaluated.

$$\frac{Savings[DKK/year] \cdot Component - lifetime[years]}{Investment - cost[DKK]} \tag{4.1}$$

Profitability of 1.33 refers to the fact that a component's renovation should pay itself back within 75% of its lifetime. This calculation does not consider any change in price in the future, thus is a simple and quick way of evaluation. The investment cost for each measure comprises of only the works that are connected to the energy upgrade and excludes the finishing, as previously indicated by the definition.

	Share of energy consumption	Energy consumption Initial [kWh/m².y]	Energy consumption Savings [kWh/m².y]	Gross Cost of EEM [DKK]	Cost of energy [DKK/kWh]	Life-time [years]	Profit-ability [-]	Year of payback [years]
Wall - BR18 - 190 Ins, 20 Brick tiles	18%	46.35	32.3	33,147	0.90	40	4.43	9
Wall - High sta. - 400 Ins, 20 Brick tiles	18%	46.35	39.6	48,883	0.90	40	3.68	11
Ceiling - BR18 - 300 Ins	18%	46.95	37.2	55,087	0.90	40	3.07	13
Roof - High sta. - 360 Ins	18%	46.95	40.2	235,094	0.90	40	0.78	51
Floor - BR18 - 145 Ins	18%	46.55	30.0	76,902	0.90	40	1.77	23
Floor, Bath - BR18 - 250 Ins	2%	5.3	4.8	6,244	0.90	40	3.50	11
Floor - High sta. - 600 Ins	20%	51.85	47.0	168,181	0.90	40	1.27	31
Win/Door - BR18 - Velfac 2 layer	17%	43.35	32.3	88,456	0.90	30	1.24	24
Win/Door - High sta. - Velfac 3 layer	17%	43.35	38.9	104,606	0.90	30	1.27	24
Foundation - BR18 - 150 Ins	10%	26.5	15.2	24,384	0.90	40	2.84	14
M.vent - BR18 - Nilan comfort CT200		0	-8.9	71,130	0.90	20	-0.28	-
Polar		0	-8.1	90,127	0.90	20	-0.20	-
PV - BR18 - Monocrystalline 13.28 m²		0	13.0	52,738	2.36	20	1.47	14
					E price difference			
DH, Heat ex. DHW tank	100%	243.8	-	56,451	0.44	20	4.76	4

Table 4.6: Summary of the renovation proposals and their economic viability, "profitability" according to BR18 definitions.

The two possibilities are examined. One, having the price of maintenance only and the specific energy costs associated with each component. The other is the total investment cost of the EEM (including finishings) and the price of reduced energy consumption due to this. For all cases, 30 years of consumption was considered. These are compared in figure 4.8 with the exact values showed in table 4.7 The price of oil was taken as 0.9 DKK/kWh and the price for district heating (in Aarhus region) was taken as 0.43 DKK/kWh plus an additional yearly connection and property fee of 1060 DKK.

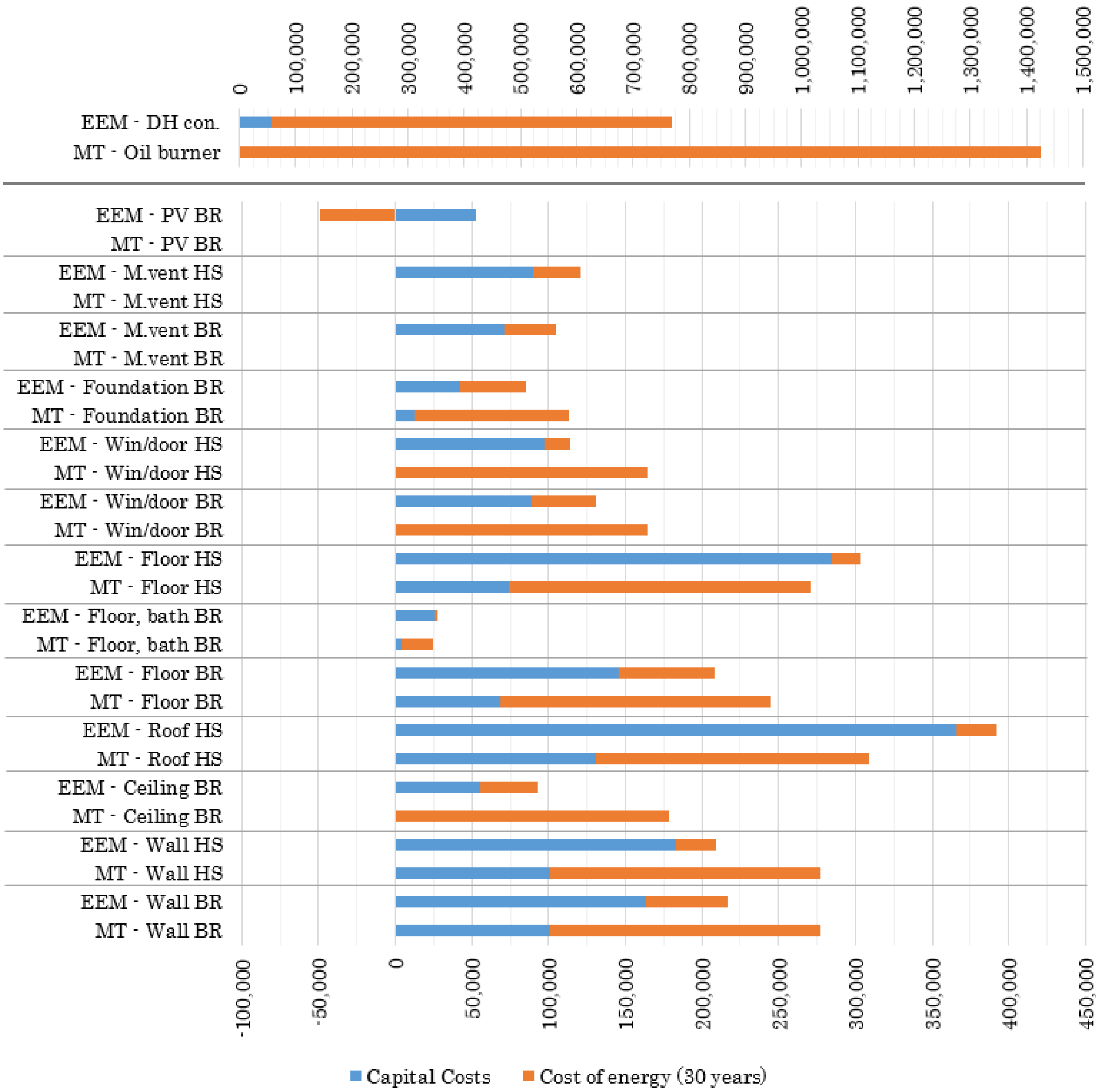


Figure 4.8: Cost of maintenance only and EEM along with their respective energy consumption. EEM = Energy efficient measure; MT = Maintenance; BR = Building Regulations; HS = High Standard

		Capital costs		Yearly cost of Energy cons. (oil)	
	Lifetime	Maint.	EEM	Maint.	EEM
	[years]	[DKK]	[DKK]	[DKK/year]	[DKK/year]
Wall - BR18 - 190 Ins, 20 Brick tiles	30	101,324	163,529	175,759	53,467
Wall - High sta. - 400 Ins, 20 Brick tile	30	101,324	183,198	175,759	25,786
Ceiling - BR18 - 300 Ins	30	-	55,087	178,034	37,162
Roof - High sta. - 360 Ins	30	131,126	366,221	178,034	25,786
Floor - BR18 - 145 Ins	30	68,436	145,338	176,518	62,947
Floor, Bath - BR18 - 250 Ins	30	4,403	25,432	20,098	1,896
Floor - High sta. - 600 Ins	30	74,299	284,525	196,615	18,581
Win/Door - BR18 - Velfac 2 layer	30	-	88,456	164,383	42,091
Win/Door - High sta. - Velfac 3 layer	30	-	97,196	164,383	17,064
Foundation - BR18 - 150 Ins	30	12,206	42,328	100,488	42,850
M.vent - BR18 - Nilan comfort CT200	30	-	71,130	-	33,749
M.vent - High sta. - Nilan Combi 302 P	30	-	90,127	-	30,715
PV - BR18 - Monocrystalline 13.28 m^2	30	-	52,738	- -	49,296
DH, Heat ex. DHW tank	30	0	56,451	1,424,475	712,382

Table 4.7: Table showing the prices used in the previous figure of Simple Payback Time

In all cases of BR standard (except the bathroom floor) it is worth to carry out the measure rather than only maintaining the component. With higher standards, the savings are more, but the investment cost is too expensive. The largest difference between maintenance only and EEM is for the heating source of oil or district heating as this was evaluated for the total heating consumption of the home. These predictions did not consider any price variation over the years (such as discount rate) thus are only a quick estimate. They show that BR18 minimum renovations can be considered financially beneficial.

4.3.3 Component evaluation according to Cost of conserved energy

As said before, financial viability is only a simple calculation. Equation 4.2 was used, which includes a yearly discount rate and also considers the actual lifetime of the component (technical lifetime). The technical lifetime is - in some cases of component renovations - different than the lifetime used for the profitability calculation (economic lifetime). If the component would be in use for longer than it is economically considered, it would still result in savings. The same is true if the component is considered economically for a longer time than it can actually last, thus its replacement should be taken into account. This way, the investment is multiplied by their ratio, which represents real financial costs more accurately. The technical lifetime cannot exceed the remaining lifetime of the whole house. For our calculations this was assumed to be 60 years, as the buildings are already 45 years old. The real interest rate is assumed to be constant 1.93% (Danmarks Nationalbank). The lifetime of the components is based on either ASHRAE standard [4], InterNACHI database [28] or the Molio Pricebook. Each budget item of every component is taken from Molio Prisdata through the use of Sigma, with only a few exceptions [42]. For the detailed description of the components, the cost of energy efficiency and maintenance, see appendix .2.

$$CCE = \frac{a(n,r) \cdot \frac{n}{n_t} \cdot I}{\Delta E} \tag{4.2}$$

Where
CCE = Cost of Conserved Energy [DKK/kWh]
a(n,r) = annuity factor [-]
n = economic lifetime [year]
n_t = technical lifetime [year]
I = Investment cost of the Energy Efficient Measure [DKK]
ΔE = is the difference between the reference energy consumption and the reduced energy consumption due to measure, taken from Be18 calculation

Annuity is calculated by:

$$a(n,r) = \frac{r}{1-(1+r)^{-n}} \tag{4.3}$$

Where
r = real interest rate [%]
n = economic lifetime [year]

Cost of Conserved Energy represents the amount of money it costs to save 1 kWh of energy, considering the lifespan of the component. CCE can be used for different purposes. It can be used to compare different solutions of one component with each other or only certain parts of the structure, such as insulation. It can also be used to see the monetary advantage of each EEM for a building as an overview. The goal with this calculation is to compare components with different U-values and thus their associated savings. Besides this, there is the question of how to consider the cost of "anyway" maintenance for each component. There are two approaches, neither of which are incorrect. If the external wall is taken as an example, the followings need to be considered: The wall would be maintained by renovating only the mortar of the brick facade. However energy efficient renovation (EER) requires the demolition of the brick wall and the reconstruction of new layers. (Not doing anything is not an option.) Thus there are two ways of considering the investment cost:
1) Since the least amount of work that must be done is the maintenance of the wall, its price would have to be payed as a minimum. If solely the price difference of proposals are considered, the maintenance cost is subtracted from the total cost of the energy efficient measure (EEM). The CCE is calculated with this reduced investment cost.
2) The maintenance and the EEM contain budget items (works to be done) that are not the same. By definition this work would not have to be carried out anyway. Thus the full price of the EEM should be taken into consideration for the CCE.
The main difference is that 1) considers the cost regardless of the work it relates to, whereas 2) considers the actual renovation work, whether or not it is carried out along with the energy efficient renovation. The EPBD recast [11] also specifies that it is possible to omit a) costs that are the same for all measures/packages/variants and b) costs related to building elements that have no influence to the energy performance of the building

To show the difference, both considerations are presented in figure 4.9 and table 4.8. On the figure, The legend is understood as follows: HS: Higher Standard; BR: Building Regulation 2018 minimum standard; with or without MT: Maintenance. MT is n/a: not applicable, if there is no maintenance included in the total price. All BR measures are with a black border. The dotted line connects each measure in terms of MT included or excluded from the total price, thus the change is visible.

To identify the worthiness of a certain renovation measure, there would have to be more energy saved than it costs to buy it. In terms of oil for boilers, it costs around 0.9 DKK/kWh (based on a calorific index of 10.98 kWh/l), thus the CCE ought to be lower than this in order to be worthwhile economically (within the set lifetime of the calculation).

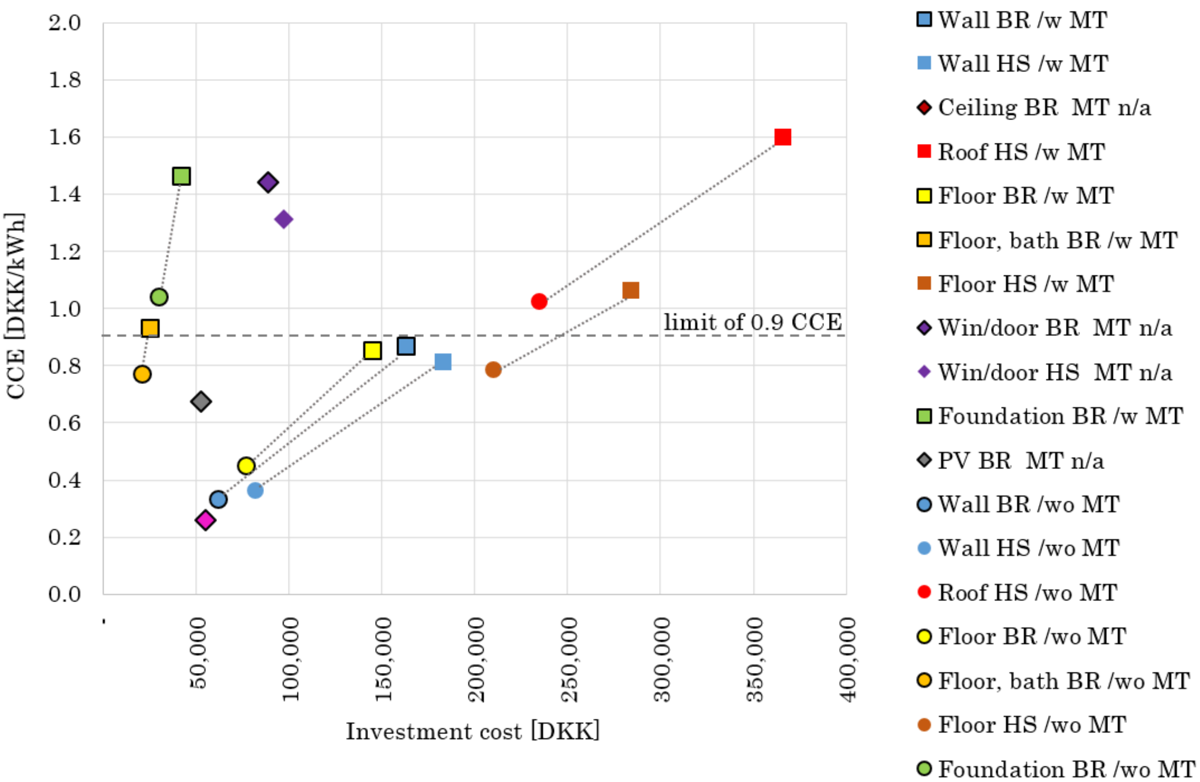


Figure 4.9: The difference in the CCE, if the investment cost is considered as the whole component renovation (left graph) or if only the energy improvement costs are taken into account (right graph)

	Energy consumption		Gross Cost considering anyway renov.		Lifetime		CCE considering anyway renov.	
	Initial	Savings	with	without	Econ.	Tech.	with	without
	[kWh/m².y]	[kWh/m².y]	[DKK]	[DKK]	[years]	[years]	[DKK/kWh]	[DKK/kWh]
Wall - BR18 - 190 Ins, 20 Brick tiles	46.35	32.3	163,529	62,204	30 [a]	60 [b]	0.86	0.33
Wall - High sta. - 400 Ins, 20 Brick tiles	46.35	39.6	183,198	81,874	30 [a]	60 [b]	0.81	0.36
Ceiling - BR18 - 300 Ins	46.95	37.2	55,087	55,087	30 [a]	60 [b]	0.26	0.26
Roof - High sta. - 360 Ins	46.95	40.2	366,221	235,094	30 [a]	60 [b]	1.60	1.02
Floor - BR18 - 145 Ins	46.55	30.0	145,338	76,902	30 [a]	60 [b]	0.85	0.45
Floor(ground) - BR18 - 250 Ins	5.3	4.8	25,432	21,029	30 [a]	60 [b]	0.93	0.77
Floor(ground) - High sta. - 600 Ins	51.85	47.0	284,525	210,226	30 [a]	60 [b]	1.06	0.78
Win/Door - BR18 - Velfac 2 layer	43.35	32.3	88,456	88,456	30 [a]	20 [c]	1.44	1.44
Win/Door - High sta. - Velfac 3 layer	43.35	38.9	97,196	97,196	30 [a]	20 [c]	1.31	1.31
Foundation - BR18 - 150 Ins	26.5	15.2	42,328	30,122	30 [a]	30 [a]	1.46	1.04
DH, Heat ex. DHW tank	-	-	62,444	56,451	20 [a]	20 [c]	-	-
M.vent - BR18 - Nilan comfort CT200	0	-8.9	71,130	71,130	20 [a]	20 [c]	-2.78	-2.78
M.vent - High sta. - Nilan Combi 302 Polar	0	-8.1	90,127	90,127	20 [a]	20 [c]	-5.35	-5.35
PV - BR18 - Monocrystalline 13.28 m²	0	25.0	52,738	52,738	20 [a]	30 [c]	0.68	0.68

a - BR18 Appendix; b - Maximum allowable lifetime due to house; c - InterNACHI database

Table 4.8: Values used for the CCE of components, shown on previous graphs

In case of the external wall, it is seen that depending on how anyway renovation is considered in the investment cost it is either worth or not to invest in a more expensive solution. Nonetheless, walls are one of the most expensive measure which explains why their renovation is so rarely done.

The windows are to be evaluated (acc. to BR18) with an economic lifetime of 30 years, but the technical lifetime of the windows are 20 years [28]. With these consideration the CCE is 1.56 DKK/kWh, which is the highest of all components. If the windows' lifetime is taken as 30 years, the CCE goes down to 1.04 DKK/kWh. There is no maintenance cost considered in case of the windows. Even though their CCE is so high, they have a relatively low cost, which is one reason why they are frequently carried out, besides their short lifetime and necessity to be changed.

In case of the foundation, the CCE is calculated subtracting the necessary maintenance of applying bituminous waterproofing, thus the value changes from 1.58 to 1.12 DKK/kWh. This shows that even with a higher CCE, a low cost could make it more appealing, similar to windows. The difference is that this EEM does not have such obvious benefits as windows.

In case of the district heating the site energy consumption does not reduce, thus CCE does not apply in this case. Nonetheless the price of the new heat source decreases, giving savings.

4.3.4 Whole Renovation solutions

In the following there will be 3 different renovation scenarios presented: 1) Only necessary maintenance, without improving energy performance of the building; 2) Maintenance and EERs up to the BR18 minimum standards; 3) Maintenance and EERs with a higher standard not including renewable energy. The components and their extent of renovation (or maintenance) is based on the previously presented EEMs. These are gathered in a budget sheet as a one-off, extensive renovation in Appendix .3. It is possible to compare the total price difference between the different approaches and their final outcomes in terms of energy savings and indoor comfort. Table 4.9 shows these final prices.

Component	Maintenance	BR18 min	Higher std.
Foundation	9,788	33,862	33,862
Partition floor	60,178	123,439	165,748
Ground floor - bathroom	3,523	16,823	18,962
Externall wall	72,199	125,891	136,451
Ceiling	44,780	88,850	44,780
Roof	76,571	76,571	221,806
Windows and doors	70,899	70,899	77,890
Heating and DHW	68,910	68,910	119,671
Ventilation	-	56,222	72,102
Solar PV cells	-	42,190	-
	406,848	703,657	891,273
VAT	25%	25%	25%
	508,559	**879,571**	**1,114,091**

Table 4.9: Table summarizing the final cost and results of the renovation proposals

All prices are taken from Molio Prisdata using a tool called Sigma. It needs to be noted, that a large part of the budget is to cover labour cost of the craftsmen. As mentioned in the previous chapter of the report, homeowners often carry out maintenance work either by themselves or through friends and family. Because of this, a real life budget of such renovation works would be much cheaper.

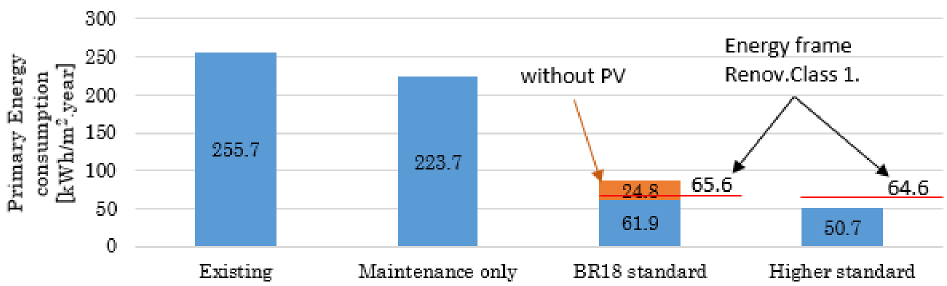


Figure 4.10: Final energy consumption of all scenarios. Red line showing Renovation Class 1 energy frame

Figure 4.10 shows the energy frame calculated by Be18. The contribution from PV cells are also stated for BR18 scenario. Carrying out only maintenance on the building does not result in any energy improvement, but still has a high cost. This amount would have to be spent on the house as a minimum, since the cheapest solution for maintenance was considered in every case in order to show the bare minimum one is required to spend. The choices of EEMs for the BR18 approach are also the cheapest energy efficiency measures that satisfy minimum requirements. The Higher standard would have to be justified by either better economic investment, increased comfort, or personal preference of the homeowner.

For the following steps of the methodology (3, 4, 5) BR18 minimum is chosen for application. The Higher standard solutions will not be considered for these steps. In terms of the Maintenance only scenario, it is used for comparison with the staged result of the BR18 scenario. This is done to see what are the benefits of energy renovation over mere maintenance of the house.

4.4 Step 3: Assigning staging data to renovation works

In this section, step 3 of the methodology is applied. Three tables are created that are needed for the staging process. The tables are - the Measure Summary, the Disruption Evaluation, and the Ordering Restriction.

Additional data (specifically required for staged renovation) is assigned to the individual renovation measures in the Measures Summary table are. These are:

- The remaining lifetime of the existing building component or system, assessed in step 1.
- The individual cost of the renovation measures, estimated in step 2
- The energy saving given by each EEM, evaluated in this step
- The co-benefits of all renovation measures are also evaluated in this step

The last two points of evaluations are presented below.

4.4.1 Energy savings given by the EEMs

The individual energy savings of the EEMs are found using Be18 program. The data is found by applying each EEM at the time to Be18 model of the house in its existing condition. After the implementation of each EEM the new energy consumption of the house is extracted. The difference between before and after the EEM is the energy reduction given by the EEM. This procedure repeats until all the measures are added to the model. This procedure was applied to all the EEM of the case building and is presented in the table 4.10. The energy extracted are the primary and the actual energy savings.

Renovation measure	Energy Saving (kWh/m^2. year)	
	Primary Energy	Actual Energy
CEILING INSULATION	32.00	35.80
EXTERNAL WALL INSULATION	27.00	32.80
FLOOR INSULATION	30.40	34.80
FOUNDATION INSULATION	15.70	14.10
HEAT SOURCE & DHW REPLACEMENT	54.50	20.50
SOLAR CELLS SYSTEM	25.00	13.90
VENTILATION SYSTEM (CAV)	-11.00	-4.20
WINDOWS AND DOORS CHANGES	26.00	25.40

Table 4.10: individual energy savings of the case building EEMs

The table demonstrates that for each of the measures primary and actual energy savings have different values. The biggest difference can be seen in the energy savings attributed to the “heat source & DHW replacement”. That is because the energy source changes from oil boiler to district heating, changing the primary factor attributed to the house heating.

4.4.2 Coupling planned implementation measures with their given co-benefits

The co-benefits were estimated by a qualitative analysis of each renovation measure. This estimation was done by the project group and is presented in the table 4.11. The evaluation can be subjective from people to people. Therefore, in a project done for a homeowner, the evaluation is done first by the building expert and after re-evaluated by the homeowner, after a technical explanations of co-benefits concept from the building expert.

Renovation measure	Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
CEILING INSULATION	2	0	-1	0	0	1	1	0	0	1
EXTERNAL WALL INSULATION	2	-1	-1	0	-1	1	1	0	0	1
FLOOR INSULATION	3	0	0	0	0	1	1	0	0	1
FOUNDATION INSULATION	1	0	0	0	0	1	0	0	0	0
HEAT SOURCE & DHW REPLACEMENT	0	0	0	1	1	2	0	1	3	0
SOLAR CELLS SYSTEM	0	0	0	0	-2	3	0	0	0	3
VENTILATION SYSTEM (CAV)	0	0	2	1	-1	-2	0	-1	1	1
WINDOWS AND DOORS CHANGES	3	0	-2	1	1	1	2	1	1	2
Total:	**12**	**-1**	**-2**	**6**	**1**	**8**	**12**	**1**	**5**	**16**

Table 4.11: Individual energy savings of the EEMS of the case building

The table presents the co-benefits for each renovation measure but also the sum of co-benefits typologies from all measures. The sum of each co-benefits typology values shows the overall potential of the renovation to enhance or diminish the quality of the home concerning the co-benefits typology. For this project, after all stages are implemented, there will be a significant improvement in Thermal Comfort, Aesthetics and Prestige. Most of the Thermal comfort improvement is given by the EEMs. The housing safety and usage will also be improved. However, the daylight and air quality tend to remain unchanged or get worse. The daylight can get worse because the selected windows have slightly lower light transmittance and the wall will be slightly thicker. Regarding air quality, the building will be more airtight, and the ventilation system chosen is not demand controlled.

4.4.3 Measures Summary table

After co-benefits and energy savings by evaluated for the renovation measures, the data is included in the Measure Summary table. Together with the cost and the remaining lifetime of the existing building components and system. The summary table is presented in table 4.12

Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy										
CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
FLOORING REPLACEMENT	10	74,921.98			0	0	0	0	0	0	3	0	0	2
FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
HEATING SYSTEM MAINTENANCE	5	5,993.08			1	0	0	1	2	0	0	0	0	1
KITCHEN RENOVATION		55,775.63			0	0	0	2	1	0	3	0	0	3
ROOF FINISHSING REPLACEMENT	15	95,713.50			0	0	0	0	0	0	1	0	0	1
SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
Total:		879,570.60	199.60	173.10	**12**	**-1**	**-2**	**6**	**1**	**8**	**12**	**1**	**5**	**16**

Table 4.12: Summary table of the case building

4.4.4 Disturbance Evaluation

The estimation of values to the renovation measures about their disturbance location and disturbance level were estimated by the project group as presented in the table 4.13. The evaluation of the location is almost straightforward due to the definition of the external and internal disturbance. However, the evaluation of disturbance level can be subjective from person to person. Therefore, in a project done for a homeowner, the evaluation is done first by the building expert, given his knowledge of house renovation, and after, it is re-evaluated by the homeowner to ensure that he agrees with the expert evaluation.

DISRUPTION EVALUATION		
RENOVATION MEASURES	**PLACE**	**DISTURBANCE**
CEILING INSULATION	EXTERNAL	LOW
EXTERNAL WALL INSULATION	EXTERNAL	MEDIUM
FLOOR INSULATION	EXTERNAL	LOW
FLOORING REPLACEMENT	INTERNAL	HIGH
FOUNDATION INSULATION	EXTERNAL	MEDIUM
HEAT SOURCE & DHW REPLACEMENT	EXTERNAL / INTERNAL	MEDIUM
HEATING SYSTEM MAINTENANCE	INTERNAL	LOW
KITCHEN RENOVATION	INTERNAL	HIGH
ROOF FINISHSING REPLACEMENT	EXTERNAL	MEDIUM
SOLAR CELLS SYSTEM	EXTERNAL	LOW
VENTILATION SYSTEM (CAV)	EXTERNAL / INTERNAL	LOW
WINDOWS AND DOORS CHANGES	EXTERNAL / INTERNAL	MEDIUM

Table 4.13: Summary table of the case building

4.4.5 Ordering Restriction

The attribution of values of predecessor measures and related works were also estimated by the project group, and the evaluation is presented in the table 4.14. The considerations for predecessor measures and related works are not always a straightforward decision. Technological inter-dependency between measures can vary depending on specific aspects of the renovation solutions and the procedure for their installation. Therefore, the evaluation of a renovation measure as a predecessor or related work can be subjective from project to project depending on particular considerations of the building expert.

ORDERING RESTRICTION		
RENOVATION MEASURES	**PREDECESSOR**	**RELATED WORK**
CEILING INSULATION	VENTILATION DUCTING	
EXTERNAL WALL INSULATION	FOUNDATION	WINDOWS AND DOORS
FLOOR INSULATION		
FLOORING REPLACEMENT		
FOUNDATION INSULATION		EXTENRAL WALL
HEAT SOURCE & DHW REPLACEMENT	ENVELOPE INSULATION	HEATING SYSTEM
HEATING SYSTEM MAINTENANCE		HEATING SOURCE
KITCHEN RENOVATION		
ROOF FINISHSING REPLACEMENT		SOLAR PANELS
SOLAR CELLS SYSTEM	ROOF FINISHING	
VENTILATION SYSTEM (CAV)	AIR TIGHTNESS / ENVELOPE	CEILING INSULATION
WINDOWS AND DOORS CHANGES		EXTENRAL WALL

Table 4.14: Attribution of values of predecessor measures and related works by project group

Table 4.14 shows an example of the subjectivity of the evaluation of the measures as a predecessor or related works. In this case, it is the roof, that was considered as a predecessor of solar cells. The roof could be renovated after the solar panels but would mean an extra cost for removal and re-installation of the panels. Therefore, it is considered here as a predecessor in order to test the methodology, but another building expert could consider it as related work. With all the Ordering Restriction table done, all the three tables from step 3 are complete and the staging process can start.

4.5 Step 4: Staging the extensive renovation

In this section, step 4 of the methodology is applied. In this step, the extensive renovation is divided into renovation stages, and it is ordered in a sequence that tries to reflect the homeowner's or any other chosen priority for the renovation. The first part of the step calculates the "Mean Values"; the reference values that guide the building expert in the second part of the step. In the second part, the staging process takes place with its sub-steps.

4.5.1 Calculation of the Mean Values of the staged renovation

The Mean Values used to guide the staging process, as presented in the methodology, is the Mean Stage Cost, the Mean number of stages, and the Mean time interval between stages. Moreover, it is also calculated the earliest implementation year of the stages with mean costs, and the minimum number of years to complete the staged renovation. The calculated numbers are presented in table 4.15.

DESCRIPTION	VALUE	UNIT
Renovation total cost:	879,571	DKK
Value available per year:	48,000	DKK/year
Minimum no. of years:	18.32	year
Most expensive measure:	100,405	DKK
Maximum stage cost:	150,000	DKK
Minimum stage cost:	80,000	DKK
Mean stage cost:	90,203	DKK
Mean number of stages:	7	stage
Mean time interval between stages:	2.7	year

Stage no.	Earliest year
1	3
2	6
3	9
4	11
5	14
6	17
7	19

Table 4.15: "Mean Values" of the case building

The left table presents that the most expensive measure of the case building, costs 100,405 DKK (the floor insulation). Since this cost is lower than 150,000 DKK, 150,000 DKK is used as the maximum limit for the stages cost. The minimum number of years needed to complete the staged renovation is 18,32 years, which actually means that 19 years it need to complete the project. By the mean values, the extensive renovation is divided in 7 stages, which gives a mean time interval between stages of 2.7 years. The right table presents the earliest year to implement each of the seven stages.

4.5.2 Staging process

In this part of the section the staging process of the extensive renovation made for the case building house is presented. The result of this process must be a staged renovation with an implementation order of the renovation measures that reflects the chosen priority. Because the case building is a building from a project already finished, the priority of the homeowner that rules the ordering is hypothetical. Therefore, we considered to be more relevant to present the staging process step by step applied to the reference case "Energy Priority". After that, it will be presented the result of applying the staging process to the extensive renovation prioritizing Aesthetics and Prestige. This hypothetical scenario is considered by the project group the worse scenario energy-wise; a situation where renovation measures that do not improve the house energy efficiency are implemented before, and EEMs are left to the last stages. By applying the staging process to this two extreme situation - in relation to energy improvement - we consider that is the best manner to test the method of staging.

4.5.3 Staging process applied to "Energy Priority" reference case

Ordering implementation measures

The ordering process is done using the Measures Summary table created in step 3, as explained by the methodology. Initially, the measures are randomly placed in the table, as presented in the table 4.16

Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy										
CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
FLOORING REPLACEMENT	10	74,921.98			0	0	0	0	0	0	3	0	0	2
FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
HEATING SYSTEM MAINTENANCE	5	5,993.08			1	0	0	1	2	0	0	0	0	1
KITCHEN RENOVATION		55,775.63			0	0	0	2	1	0	3	0	0	3
ROOF FINISHSING REPLACEMENT	15	95,713.50			0	0	0	0	0	0	1	0	0	1
SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
Total:		879,570.60	199.60	173.10	**12**	**-1**	**-2**	**6**	**1**	**8**	**12**	**1**	**5**	**16**

Table 4.16: Summary table of the case building

The first step in the ordering process consists of ordering the measures by the priority, which is primary energy savings. For that, renovation measures that have higher primary energy savings are placed in the uppermost part of the list, followed in a decreasing manner by the ones that have lower values of primary energy savings, as presented by table 4.17

MEASURES SUMMARY					CO-BENEFITS									
Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy										
CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
HEATING SYSTEM MAINTENANCE	5	5,993.08	0.00	0.00	1	0	0	1	2	0	0	0	0	1
KITCHEN RENOVATION		55,775.63	0.00	0.00	0	0	0	2	1	0	3	0	0	3
FLOORING REPLACEMENT	10	74,921.98	0.00	0.00	0	0	0	0	0	0	3	0	0	2
ROOF FINISHSING REPLACEMENT	15	95,713.50	0.00	0.00	0	0	0	0	0	0	1	0	0	1
VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
Total:		879,570.60	199.60	173.10	**12**	**-1**	**-2**	**6**	**1**	**8**	**12**	**1**	**5**	**16**

Table 4.17: Renovation measures ordered by primary energy savings

Table 4.17 shows that all the measures are ordered in decreasing order by primary energy savings. This initial order is not possible to be maintained because the measures with short life expectancy are placed towards the end, and measures that are a predecessor of others are not placed before its successor. Therefore, the renovation measures that have ordering restrictions must be rearranged in the table.

The first rearrangement that is made because of ordering restriction is considering precedent and related works, as suggested by the methodology. The analysis of predecessor works and related works was done using the table Ordering Restriction table. The result of this first rearrangement is presented by table 4.18. Measures that are the predecessor of another measure were placed just above its successor, and related works were placed next to each other in order to be executed in the same renovation stage.

MEASURES SUMMARY					CO-BENEFITS									
Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m^2. year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy										
VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
ROOF FINISHSING REPLACEMENT	15	95,713.50	0.00	0.00	0	0	0	0	0	0	1	0	0	1
SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
HEATING SYSTEM MAINTENANCE	5	5,993.08	0.00	0.00	1	0	0	1	2	0	0	0	0	1
KITCHEN RENOVATION		55,775.63	0.00	0.00	0	0	0	2	1	0	3	0	0	3
FLOORING REPLACEMENT	10	74,921.98	0.00	0.00	0	0	0	0	0	0	3	0	0	2
Total:		879,570.60	199.60	173.10	12	-1	-2	6	1	8	12	1	5	16

Table 4.18: Renovation measures reordered because of precedence and relation restriction

Table 4.18 shows that the rearrangement brought 'Ventilation System' and "Foundation Insulation" to a higher place in the list. However, the majority of measures with high energy saving are still placed in the upper part of the list.

The second revaluation of the implementation order was made considering the lifetime of the current building components. Renovation measures with restriction in the latest year of implementation because of the remaining lifetime, placed in the bottom part of the list, were placed into a higher position. That ensures that this measures are implemented before the remain lifetime expires. The selection of the position to place the measures is done with the assistance of the "Mean Values" tables that presents the earliest implementation year of the mean cost stages. Table 4.19 presents the order of the measures after the second rearrangement.

MEASURES SUMMARY					CO-BENEFITS									
Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
			Primary Energy	Actual Energy										
HEATING SYSTEM MAINTENANCE	5	5,993.08	0.00	0.00	1	0	0	1	2	0	0	0	0	1
HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
FLOORING REPLACEMENT	10	74,921.98	0.00	0.00	0	0	0	0	0	0	3	0	0	2
FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
ROOF FINISHSING REPLACEMENT	15	95,713.50	0.00	0.00	0	0	0	0	0	0	1	0	0	1
VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
KITCHEN RENOVATION		55,775.63	0.00	0.00	0	0	0	2	1	0	3	0	0	3
Total:		879,570.60	199.60	173.10	12	-1	-2	6	1	8	12	1	5	16

Table 4.19: Renovation measures reordered because of remain lifetime

As presented in table 4.19 remaining lifetime of 'Heating System Maintenance' and 'Flooring Replacement' expires within 5 and 10 years, respectively, which means within the first half of the renovation process that is 19 years. Therefore, these measures were place placed in the upper position of the list.

The implementation order after considering maintenance is entirely different from the first arrangement. On this order, most of the remaining lifetime values are in a crescent order (besides External Wall that is placed early on the list because of its relation with foundation and windows). These two rearrangements due to implementation restriction demonstrates very well the real-life situation of housing - even though energy savings is a high priority, the need for maintenance and restriction because of precedent works forces energy improvement measures to be implemented later.

Presenting stage packages

In this sub-step, the stage packages are formed. Using the last order of the renovation measures, the list is divided into stage packages. As presented by the Mean Values table, the reference cost for the packages are minimum 80,000 DKK and maximum 150,000 DKK. The division of stages packages is shown in table 4.20.

MEASURES SUMMARY						CO-BENEFITS									
Stage	Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
				Primary Energy	Actual Energy										
1	HEATING SYSTEM MAINTENANCE	5	5,993.08	0.00	0.00	1	0	0	1	2	0	0	0	0	1
	HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.50	20.50	0	0	0	1	1	2	0	1	3	0
		Stage package total cost:	**86,137.01**												
2	FOUNDATION INSULATION		42,327.54	15.70	14.10	1	0	0	0	0	1	0	0	0	0
	EXTERNAL WALL INSULATION	15	157,363.60	27.00	32.80	2	-1	-1	0	-1	1	1	0	0	1
	WINDOWS AND DOORS CHANGES	10	88,623.49	26.00	25.40	3	0	-2	1	1	1	2	1	1	2
		Stage package total cost:	**288,314.62**												
3	FLOORING REPLACEMENT	10	74,921.98	0.00	0.00	0	0	0	0	0	0	3	0	0	2
	FLOOR INSULATION		100,405.36	30.40	34.80	3	0	0	0	0	1	1	0	0	1
		Stage package total cost:	**175,327.34**												
4	ROOF FINISHSING REPLACEMENT	15	95,713.50	0.00	0.00	0	0	0	0	0	0	1	0	0	1
		Stage package total cost:	**95,713.50**												
5	VENTILATION SYSTEM (CAV)		70,277.36	-11.00	-4.20	0	0	2	1	-1	-2	0	-1	1	1
	CEILING INSULATION		55,287.06	32.00	35.80	2	0	-1	0	0	1	1	0	0	1
		Stage package total cost:	**125,564.43**												
6	SOLAR CELLS SYSTEM		52,738.06	25.00	13.90	0	0	0	0	-2	3	0	0	0	3
	KITCHEN RENOVATION		55,775.63	0.00	0.00	0	0	0	2	1	0	3	0	0	3
		Stage package total cost:	**108,513.70**												

Table 4.20: Stage renovation packages for the case building

Table 4.20 shows that the external walls, the foundation, and the windows were gathered as stage package in stage 2 - becoming a facade renovation. That is because the three measures were considered as "related works". Stage 2 has now a total cost of 288,315 DKK, which is a much higher cost than the upper limit suggested. Therefore, the implementation of the facade renovation is decided to be divided in two stages, first facades North and East, and later, South and West, as presented in table 4.21.

MEASURES SUMMARY							CO-BENEFITS									
Stage	Year	Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
					Primary Energy	Actual Energy										
1	3	HEATING SYSTEM MAINTENANCE	5	5,993.08	0.0	0.0	1	0	0	1	2	0	0	0	0	1
		HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.5	20.5	0	0	0	1	1	2	0	1	3	0
				86,137.01	**54.5**	**20.5**										
2	6	FOUNDATION INSULATION		19,047.39	7.1	6.3	1	0	0	0	0	1	0	0	0	0
		EXTERNAL WALL INSULATION	15	70,813.62	12.2	14.8	2	-1	-1	0	-1	1	1	0	0	1
		WINDOWS AND DOORS CHANGES	10	39,880.57	11.7	11.4	3	0	-2	1	1	1	2	1	1	2
				129,741.58	**30.9**	**32.5**										
3	9	FOUNDATION INSULATION		23,280.14	8.6	7.8	1	0	0	0	0	1	0	0	0	0
		EXTERNAL WALL INSULATION	15	86,549.98	14.9	18.0	2	-1	-1	0	-1	1	1	0	0	1
		WINDOWS AND DOORS CHANGES	10	48,742.92	14.3	14.0	3	0	-2	1	1	1	2	1	1	2
				158,573.04	**37.8**	**39.8**										
4	12	FLOORING REPLACEMENT	10	74,921.98	0.0	0.0	0	0	0	0	0	0	3	0	0	2
		FLOOR INSULATION		100,405.36	30.4	**34.8**	3	0	0	0	0	1	1	0	0	1
				175,327.34	**30.4**	**34.8**										
5	14	ROOF FINISHSING REPLACEMENT	15	95,713.50	0.0	0.0	0	0	0	0	0	0	1	0	0	1
				95,713.50	**0.0**	**0.0**										
6	17	VENTILATION SYSTEM (CAV)		70,277.36	-11.0	-4.2	0	0	2	1	-1	-2	0	-1	1	1
		CEILING INSULATION		55,287.06	32.0	35.8	2	0	-1	0	0	1	1	0	0	1
				125,564.43	**21.0**	**31.6**										
7	19	SOLAR CELLS SYSTEM		52,738.06	25.0	13.9	0	0	0	0	-2	3	0	0	0	3
		KITCHEN RENOVATION		55,775.63	0.0	0.0	0	0	0	2	1	0	3	0	0	3
				108,513.70	**25.0**	**13.9**										

Table 4.21: Stage renovation packages for the case building

The division of the façade renovation in two stages, besides decrease the package cost, ensures that half of the façade is implemented in an earlier year than with implemented at once. That is because would need more time to save money to pay for a whole façade renovation than to half of it. Thus, energy saving measures are implemented earlier.

The next step was to evaluate the disruption level and place of the stage packages. The evaluation is shown below by Table 4.22.

MEASURES SUMMARY		DISRUPTION EVALUATION	
Stage	RENOVATION MEASURES	INTERNAL OR EXTERNAL WORK	DISTURBANCE
1	FLOOR INSULATION	EXTERNAL	LOW
	HEATING SYSTEM MAINTENANCE	INTERNAL	LOW
2	EXTERNAL WALL INSULATION	EXTERNAL	MEDIUM
	FOUNDATION INSULATION	EXTERNAL	MEDIUM
	WINDOWS AND DOORS CHANGES	EXTERNAL / INTERNAL	MEDIUM
3	EXTERNAL WALL INSULATION	EXTERNAL	MEDIUM
	FOUNDATION INSULATION	EXTERNAL	MEDIUM
	WINDOWS AND DOORS CHANGES	EXTERNAL / INTERNAL	MEDIUM
4	FLOORING REPLACEMENT	INTERNAL	HIGH
	HEAT SOURCE & DHW REPLACEMENT	EXTERNAL / INTERNAL	MEDIUM
5	ROOF FINISHSING REPLACEMENT	EXTERNAL	MEDIUM
6	CEILING INSULATION	EXTERNAL	LOW
	VENTILATION SYSTEM (CAV)	EXTERNAL / INTERNAL	LOW
7	KITCHEN RENOVATION	INTERNAL	MEDIUM
	SOLAR CELLS SYSTEM	EXTERNAL	LOW

Table 4.22: Disturbance evaluation of the case building

Table 4.22 shows that only stage 4 has a high internal disturbance. That may call for moving out during the renovation. Stage 2 and 3 have a Medium disturbance. However, the internal work in these two stages is because of the window replacement, and most of the work can be done from the outside - thus, the internal disturbance is not much. Stage 7 has a medium internal disturbance but is because of the kitchen renovation that is a homeowner which - therefore, it cannot be avoided. The disturbance analysis concludes that there are no excessive problems of disturbance with the current stage packages and no modification is needed.

Earliest Implementation Year of the stages

With the cost of each stage established, the energy consultant can calculate the actual earliest implementation year of the stages. The earliest implementation year of the stages is based on the annual household savings, as said in the methodology. The earliest actual implementation year is the next year where enough money is available to pay for the renovation stage. Figure 4.11 presents the earliest implementation year of the stages with the accumulative savings.

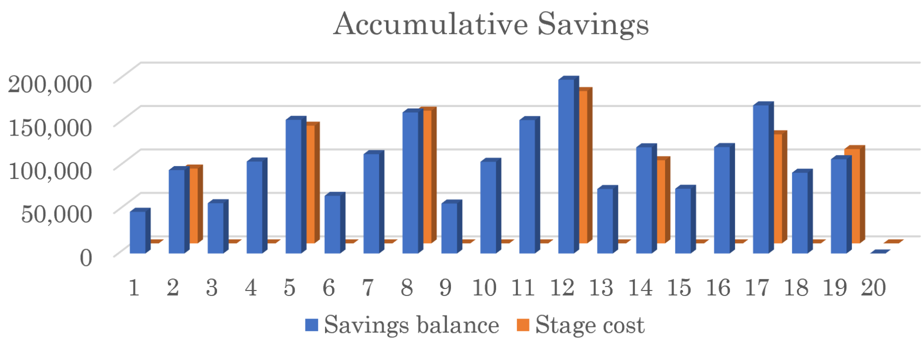


Figure 4.11: Comparison between renovation stages and annual savings for Energy Priority reference case

Figure 4.11 demonstrates that once the saved amount is higher than a stage cost, the renovation is performed, which decreases the savings total. That keeps happening until the last renovation stage is performed. Moreover, the last stage is implemented in year 19, which means that it is within the limit of the maximum time established by the methodology, 20 years.

With the implementation year of the stages known the house energy consumption throughout the staged renovation process was found, as presented by the table 4.12.

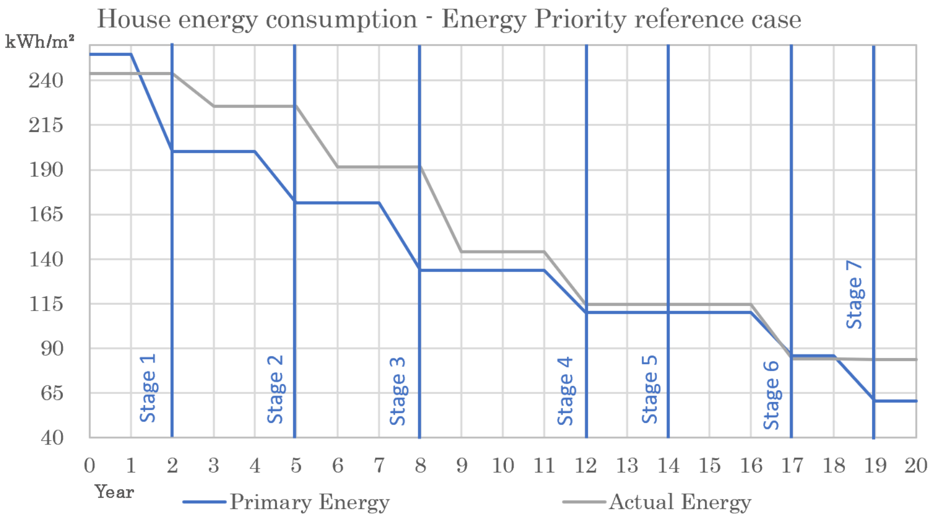


Figure 4.12: Energy consumption of the case building throughout the staged renovation - Energy Priority reference case

The staged renovation for Energy Priority reference case was successively planed using the staged renovation methodology. The number of stages is the same number than suggested by the Mean Values. The cost of the stages respected the minimal limit but the the upper limit was slightly exceeded by stages 3 and 4. The primary energy saving is the biggest in the first stage and has almost an decreasing pattern, which means that primary energy savings is prioritized.

4.5.4 Aesthetics and Prestige as priorities for the staged renovation

As presented by the literature review, many homeowners perform house renovation for better house usability, aesthetics, and prestige, rather than for energy savings. Because of this, it is reasonable to investigate the staged renovation methodology using a co-benefits as a priority - more specifically Aesthetics and Prestige. In this hypothetical scenario, the kitchen renovation must be placed in the first stage as a request from the homeowner. This condition represents the worse scenario regarding energy savings, as mentioned before. However, at the end of the process, the house still achieves Renovation Class 1. Below it is presented the final result after applying the staged renovation having Aesthetics and Prestige as a priority.

MEASURES SUMMARY							CO-BENEFITS									
Stage	Year	Renovation measure	Remain lifetime (years)	Cost (DKK)	Energy Saving (kWh/m². year)		Thermal comfort	Daylight	Air quality	Ease of Use	Maintenance	Low Exposure to energy price	Aesthetics	Acoustics	Safety	Prestige
					Primary Energy	Actual Energy										
1	3	HEATING SYSTEM MAINTENANCE	5	5,993.08	0.0	0.0	1	0	0	1	2	0	0	0	0	1
		FLOORING REPLACEMENT	10	74,921.98	0.0	0.0	0	0	0	0	0	0	3	0	0	2
		KITCHEN RENOVATION		55,775.63	0.0	0.0	0	0	0	2	1	0	3	0	0	3
				136,690.69	**0.0**	**0.0**										
2	6	WINDOWS AND DOORS CHANGES	10	88,623.49	26.0	25.4	3	0	-2	1	1	1	2	1	1	2
		FOUNDATION INSULATION		42,327.54	15.7	14.1	1	0	0	0	0	1	0	0	0	0
		EXTERNAL WALL INSULATION	15	157,363.60	27.0	32.8	2	-1	-1	0	-1	1	1	0	0	1
				288,314.62	**68.7**	**72.3**										
3	9	WINDOWS AND DOORS CHANGES	10	88,623.49	26.0	25.4	3	0	-2	1	1	1	2	1	1	2
		FOUNDATION INSULATION		42,327.54	15.7	14.1	1	0	0	0	0	1	0	0	0	0
		EXTERNAL WALL INSULATION	15	157,363.60	27.0	32.8	2	-1	-1	0	-1	1	1	0	0	1
				288,314.62	**68.7**	**72.3**										
4	12	HEAT SOURCE & DHW REPLACEMENT	12	80,143.94	54.5	20.5	0	0	0	1	1	2	0	1	3	0
		ROOF FINISHSING REPLACEMENT	15	95,713.50	0.0	0.0	0	0	0	0	0	0	1	0	0	1
				175,857.44	**54.5**	**20.5**										
5	17	SOLAR CELLS SYSTEM		52,738.06	25.0	13.9	0	0	0	0	-2	3	0	0	0	3
		FLOOR INSULATION		100,405.36	30.4	34.8	3	0	0	0	0	1	1	0	0	1
				153,143.43	**55.4**	**48.7**										
6	19	CEILING INSULATION		55,287.06	32.0	35.8	2	0	-1	0	0	1	1	0	0	1
		VENTILATION SYSTEM (CAV)		70,277.36	-11.0	-4.2	0	0	2	1	-1	-2	0	-1	1	1
				125,564.43	**21.0**	**31.6**										

Table 4.23: Stage Summary table for staged renovation prioritizing Aesthetics

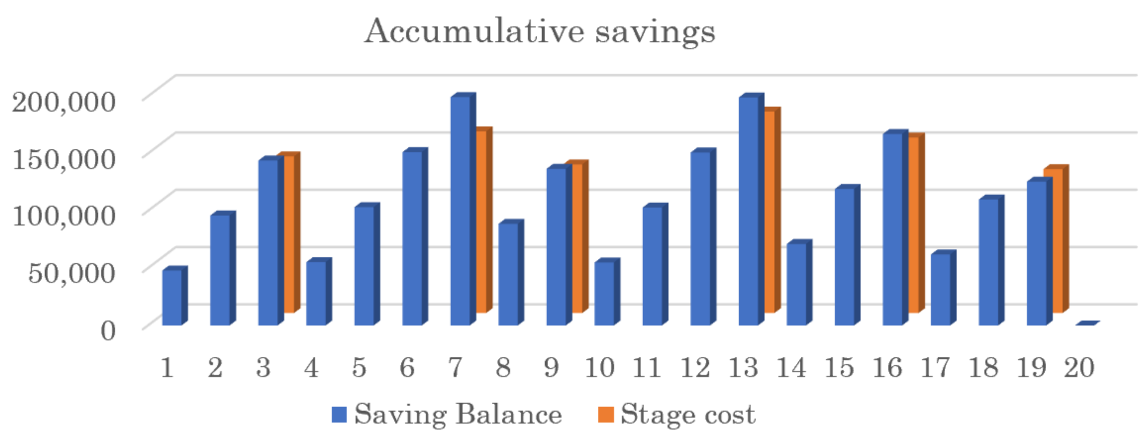


Figure 4.13: Comparison between renovation stages and annual savings for Aesthetic priority

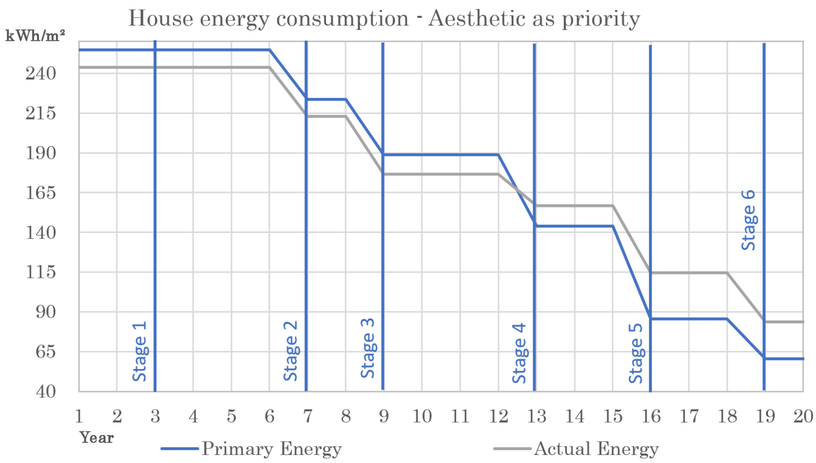


Figure 4.14: Energy consumption of the case building throughout the staged renovation - Aesthetics as priority

Figure 4.14 demonstrates that by prioritizing Aesthetics and Prestige, the more significant energy improvements are left towards the end of the renovation process. Energy reduction starts only after year 6, and the most significant primary energy savings happen in the second half of the renovation process. The co-benefits in stage summary table depicts that the first three stages have the majority of Prestige and Aesthetics points. That demonstrates that the staged renovation methodology is capable to create staged renovations that prioritize co-benefits, reflecting the priority in the implementation order and stage packages.

4.5.5 Sub-conclusion

The application of the staging process in the reference case and the hypothetical scenario showed that the staging process is effective to create a staged renovation that prioritizes benefits and co-benefits. The comparison of the two scenarios showed that the implementation order has a significant influence on the house energy savings over-time. Moreover, it presented to be suitable to be used in a holistic approach that takes into consideration energy renovation, maintenance needs, homeowner wishes, and the homeowner's financial capacity.

The comparison of the three scenarios showed that the implementation order has a significant influence on the decreasing of energy consumption over time. Finally, the co-benefits table proved to be a great help throughout the process.

4.6 Step 5: Life Cycle Cost assessment of the staged renovation

In this section step 5 of the methodology is applied to the study case project. The staged renovation that prioritizes the Aesthetics and Prestige is financially evaluated considering the Life Cycle Cost of the project, and compared with the two reference cases. Afterward, the staged renovation is also financially compared with the one-off renovation.

The financial evaluation of the staged renovation has the purpose of presenting to the homeowner the economic aspects of his house renovation, in a life cycle perspective. As mentioned in the methodology the life cycle cost analysis is made for 30 years. To test the staged renovation methodology, the hypothetical staged renovation made in step 4 is used as the staged renovation made for the homeowner. Moreover, as mentioned in the methodology, two reference cases are presented together in the accumulative graph (figure 4.15) to give a reference to the LCC result of the staged renovation. The two reference cases are the reference case Anyways and reference case Energy Priority. The procedure to calculate the life cycle cost of each scenario is presented in the following part of this section.

4.6.1 Parameters for the LCC calculation

The LCC analysis of a building renovation involves a dynamic consideration of money in time, the price of energy, and the prediction of future energy prices. The parameters used for LCC calculation are demonstrated in table 4.24

Energy price	
Electricity (DKK/kWh)	2.36
Heating oil (DKK/kWh)	0.92
District heating Aarhus average 2018 (DKK/kWh)	0.45
District heating Aarhus annual subscription fee 2018 (DKK)	710.00
District heating Aarhus annual power constribution 2018 (DKK/m²)	352.99

Rates		Reference
Real discount rate	1.93%	Danmarks Natinalbank; average last 20 years
Electricity escalation rate	6.82%	Energinet's analysis assumptions 2017; average prediction next 20 years
Heating Oil escalation rate	2.50%	Statista.com; average last 7 years
District Heating escalation rate	2.00%	Assumption
Loan interest rate	2.30%	Finance Denamark; average last 15 years

Table 4.24: Parameters for life cycle cost calculations

4.6.2 LCC analysis of the staged renovation made for the homeowner

The life cycle cost analysis considers the costs spent on the renovation and the cost of running the building. The running costs are the cost of energy for space heating and electricity used by the building systems — derived from Be18. Therefore the energy consumption of the building after each stage was calculated using Be18 program. The result of the energy consumption after each stage is presented in table 4.25.

STAGE SUMMARY			ENERGY CONSUMPTION (kWh/m2)					
STAGE	YEAR	MEASURE	Electric.	Oil	D.H.	PV cells	Primary Energy	% Primary Energy
0	0	EXISTING CONDITION	5.8	243.8	0.0	0.0	254.7	1.0
1	3	HEATING SYSTEM MAINTENANCE FLOORING REPLACEMENT KITCHEN RENOVATION	5.8	243.8	0.0	0.0	254.7	100.0%
2	6	WINDOWS AND DOORS CHANGES (N/E) FOUNDATION INSULATION EXTERNAL WALL INSULATION	5.6	213.0	0.0	0.0	223.7	87.8%
3	9	WINDOWS AND DOORS CHANGES (S/W) FOUNDATION INSULATION EXTERNAL WALL INSULATION	5.4	176.5	0.0	0.0	188.7	74.1%
4	12	HEAT SOURCE & DHW REPLACEMENT ROOF FINISHSING REPLACEMENT	4.5	0.0	156.8	0.0	143.8	56.5%
5	17	SOLAR CELLS SYSTEM FLOOR INSULATION	4.5	0.0	114.6	-13.0	85.5	33.6%
6	19	CEILING INSULATION VENTILATION SYSTEM (CAV)	6.1	0.0	83.6	-13.0	60.5	23.8%

Table 4.25: Energy consumption of the house after each stage for staged renovation prioritizing aesthetics

The annual energy consumption is the actual annual energy consumption of the building multiplied by the energy price of its energy source. The energy price of each energy source varies differently in time. Thus the annual running cost for each year was corrected to its predicted future price using the "future cost" formula presented in the Methodology considerations. The costs for the renovation are accounted for by the annual savings, which means that it is accounted every year until it sums up the total cost of the renovation. The savings are 48,000 DKK for 18 years, and 15,571 DKK saved in year 19, as presented in table 4.26. The "future" annual energy cost was summed up with the annual savings to become the annual recurring cost. To the recurring costs is applied the NPV formula (the result of this calculation is presented in column NPV in table 4.26). Finally, the Life Cycle Cost of the staged renovation project for 30 years is the sum of NPV values. The LCC for the renovation project for the years before its end is represented by the accumulative costs (NPV accumulated column). This calculation is presented in table 4.26.

STAGED RENOVATION - AESTHETICS AND PRESTIGY AS PRIORITY																		
Renovation cost				Electricity			Oil			District heating			Solar cells			LCC values		
Year	Stage	Stage cost	Annual Savings	Electr. Consump.	Electr. Cost	FUTURE Electr. Cost	Oil consump. (kWh)	Oil cost	FUTURE Oil cost	DH consump.	DH cost (DKK)	FUTURE DH cost (DKK)	Solar cell produc.	Solar cell savings (DKK)	FUTURE Solar cell savings (DKK)	FUTURE Annual recurring cost	NPV	NPV Accumulated
1			48,000	727	1,717	1,834	30,792	28,232	28,938							78,772	77,281	77,281
2			48,000	727	1,818	6,801	30,792	28,232	29,661							84,462	81,296	158,578
3	1	136,691	48,000	727	1,717	2,093	30,792	28,232	30,403							80,496	76,012	234,590
4			48,000	727	1,717	2,235	30,792	28,232	31,163							81,398	75,410	310,001
5			48,000	727	1,717	2,388	30,792	28,232	31,942							82,330	74,830	384,831
6			48,000	727	1,717	2,551	30,792	28,232	32,741							83,291	74,272	459,103
7	2	158,573	48,000	727	1,717	2,724	30,792	28,232	33,559							84,284	73,735	532,837
8			48,000	707	1,669	2,829	26,902	24,665	30,052							80,882	69,420	602,257
9	3	129,742	48,000	707	1,669	3,022	26,902	24,665	30,804							81,826	68,901	671,158
10			48,000	682	1,610	3,113	22,292	20,439	26,163							77,276	63,839	734,998
11			48,000	682	1,610	3,325	22,292	20,439	26,817							78,143	63,333	798,331
12			48,000	682	1,610	3,552	22,292	20,439	27,488							79,040	62,848	861,179
13	4	175,857	48,000	682	1,610	3,794	22,292	20,439	28,175							79,969	62,384	923,564
14			48,000	568	1,341	3,377				19,804	10,028	13,232				64,610	49,449	973,013
15			48,000	568	1,341	3,608				19,804	10,028	13,497				65,105	48,885	1,021,897
16	5	153,143	48,000	568	1,341	3,854				19,804	10,028	13,767				65,621	48,340	1,070,237
17			48,000	568	1,341	4,116				14,474	7,614	10,661	- 1,646	- 3,885	- 11,922	50,856	36,755	1,106,992
18			48,000	568	1,341	4,397				14,474	7,614	10,875	- 1,646	- 3,885	- 12,734	50,537	35,833	1,142,825
19	6	125,564	15,571	568	1,341	4,697				14,474	7,614	11,092	- 1,646	- 3,885	- 13,603	17,757	12,352	1,155,177
20				770	1,818	6,801				10,559	5,840	8,679	- 1,646	- 3,885	- 14,530	949	648	1,155,825
21				770	1,818	7,265				10,559	5,840	8,852	- 1,646	- 3,885	- 15,521	596	399	1,156,224
22				770	1,818	7,760				10,559	5,840	9,029	- 1,646	- 3,885	- 16,579	210	138	1,156,362
23				770	1,818	8,289				10,559	5,840	9,210	- 1,646	- 3,885	- 17,709	- 211	- 136	1,156,227
24				770	1,818	8,854				10,559	5,840	9,394	- 1,646	- 3,885	- 18,917	- 669	- 423	1,155,804
25				770	1,818	9,458				10,559	5,840	9,582	- 1,646	- 3,885	- 20,207	- 1,167	- 724	1,155,080
26				770	1,818	10,103				10,559	5,840	9,773	- 1,646	- 3,885	- 21,584	- 1,708	- 1,040	1,154,041
27				770	1,818	10,792				10,559	5,840	9,969	- 1,646	- 3,885	- 23,056	- 2,295	- 1,371	1,152,670
28				770	1,818	11,527				10,559	5,840	10,168	- 1,646	- 3,885	- 24,628	- 2,932	- 1,718	1,150,952
29				770	1,818	12,313				10,559	5,840	10,372	- 1,646	- 3,885	- 26,307	- 3,622	- 2,082	1,148,871
30				770	1,818	13,153				10,559	5,840	10,579	- 1,646	- 3,885	- 28,101	- 4,369	- 2,463	1,146,408
																LCC:	**1,146,408**	

Table 4.26: Life cycle calculation for staged renovation prioritizing aesthetics

The table demonstrates that the price of electricity is very high in the last years of the project when corrected to its future price (column "FUTURE Electr. Cost"). The future price for electricity also has a high influence on the price of electricity generated by the PV cells. Therefore, the energy cost in the last years of the project becomes negative. It is important to remember that running cost only takes into account the energy for space heating and electricity to rum the building systems. Energy cost for appliances and lighting is not included.

4.6.3 LCC analysis of the reference case Energy Priority

The costs for the reference case Energy Priority was accounted exactly, in the same manner, accounted to the staged renovation made for the homeowner. Therefore the energy consumption of the building after each stage was also calculated using Be18 program. The result of the energy consumption after each stage is presented in table **??**.

STAGE SUMMARY			ENERGY CONSUMPTION (kWh/m2)					
STAGE	YEAR	MEASURE	Electric.	Oil	D.H.	PV cells	Primary Energy	% Primary Energy
0	0	EXISTING CONDITION	5.8	243.8	0.0	0.0	254.7	100%
1	2	HEAT SOURCE & DHW REPLACEMENT HEATING SYSTEM MAINTENANCE	4.5	0.0	225.6	0.0	200.3	78.6%
2	5	EXTERNAL WALL INSULATION (N/W) WINDOWS AND DOORS CHANGES (N/W) FOUNDATION INSULATION (N/W)	4.5	0.0	191.5	0.0	171.3	67.3%
3	8	EXTERNAL WALL INSULATION (S/E) WINDOWS AND DOORS CHANGES (S/E) FOUNDATION INSULATION (S/E)	4.5	0.0	144.2	0.0	133.6	52.5%
4	12	FLOOR INSULATION FLOORING REPLACEMENT	4.5	0.0	114.6	0.0	110.0	43.2%
5	14	ROOF FINISHSING REPLACEMENT	4.5	0.0	114.6	0.0	110.0	43.2%
6	17	VENTILATION SYSTEM (CAV) CEILING INSULATION	6.1	0.0	84.2	0.0	85.8	33.7%
7	19	SOLAR CELLS SYSTEM KITCHEN RENOVATION	6.1	0.0	83.6	-13.0	60.5	23.8%

Table 4.27: Energy consumption of the house after each stage for staged renovation prioritizing energy savings

The costs for the renovation were also accounted for by the annual savings. The total and annual renovation cost is the same as the staged renovation for the homeowner since only the implementation order of the measures is changed and the cost is accounted for by the annual savings. The calculation of the costs of the LCC analysis is presented by table 4.28

REFERENCE CASE - ENERGY PRIORITY																		
Renovation cost				Electricity			Oil			District heating			Solar cells			LCC values		
Year	Stage	Stage cost	Annual Savings	Electr. Consump.	Electr. Cost	FUTURE Electr. Cost	Oil consump. (kWh)	Oil cost	FUTURE Oil cost	DH consump.	DH cost (DKK)	FUTURE DH cost (DKK)	Solar cell produc.	Solar cell savings (DKK)	FUTURE Solar cell savings (DKK)	FUTURE Annual recurring cost	NPV	NPV Accumulated
1			48,000	727	1,717	1,834	30,792	28,232	28,938							78,772	77,281	77,281
2	1	86,137	48,000	727	1,717	1,959	30,792	28,232	29,661							79,620	76,636	153,917
3			48,000	568	1,341	1,635				28,493	13,965	14,820				64,454	60,865	214,782
4			48,000	568	1,341	1,746				28,493	13,965	15,116				64,862	60,091	274,873
5	2	135,508	48,000	568	1,341	1,865				28,493	13,965	15,418				65,284	59,337	334,210
6			48,000	568	1,341	1,993				24,186	12,014	13,529				63,522	56,643	390,853
7			48,000	568	1,341	2,128				24,186	12,014	13,800				63,929	55,927	446,780
8	3	152,807	48,000	568	1,341	2,274				24,186	12,014	14,076				64,350	55,230	502,011
9			48,000	568	1,341	2,429				18,212	9,308	11,123				61,552	51,830	553,841
10			48,000	568	1,341	2,594				18,212	9,308	11,346				61,940	51,170	605,010
11			48,000	568	1,341	2,771				18,212	9,308	11,573				62,344	50,529	655,539
12	4	175,327	48,000	568	1,341	2,960				18,212	9,308	11,804				62,764	49,907	705,446
13			48,000	568	1,341	3,162				14,474	7,614	9,850				61,011	47,595	753,041
14	5	95,714	48,000	568	1,341	3,377				14,474	7,614	10,047				61,424	47,010	800,052
15			48,000	568	1,341	3,608				14,474	7,614	10,247				61,855	46,445	846,497
16			48,000	568	1,341	3,854				14,474	7,614	10,452				62,306	45,898	892,395
17	6	125,564	48,000	568	1,341	4,116				14,474	7,614	10,661				62,778	45,371	937,765
18			48,000	770	1,818	5,960				10,634	5,875	8,391				62,351	44,210	981,975
19	7	108,514	15,571	770	1,818	6,367				10,634	5,875	8,558				30,496	21,214	1,003,189
20				770	1,818	6,801				10,559	5,840	8,679	-1,646	-3,885	-14,530	949	648	1,003,837
21				770	1,818	7,265				10,559	5,840	8,852	-1,646	-3,885	-15,521	596	399	1,004,236
22				770	1,818	7,760				10,559	5,840	9,029	-1,646	-3,885	-16,579	210	138	1,004,374
23				770	1,818	8,289				10,559	5,840	9,210	-1,646	-3,885	-17,709	-211	-136	1,004,238
24				770	1,818	8,854				10,559	5,840	9,394	-1,646	-3,885	-18,917	-669	-423	1,003,815
25				770	1,818	9,458				10,559	5,840	9,582	-1,646	-3,885	-20,207	-1,167	-724	1,003,092
26				770	1,818	10,103				10,559	5,840	9,773	-1,646	-3,885	-21,584	-1,708	-1,040	1,002,052
27				770	1,818	10,792				10,559	5,840	9,969	-1,646	-3,885	-23,056	-2,295	-1,371	1,000,682
28				770	1,818	11,527				10,559	5,840	10,168	-1,646	-3,885	-24,628	-2,932	-1,718	998,964
29				770	1,818	12,313				10,559	5,840	10,372	-1,646	-3,885	-26,307	-3,622	-2,082	996,882
30				770	1,818	13,153				10,559	5,840	10,579	-1,646	-3,885	-28,101	-4,369	-2,463	994,419
																LCC:	**994,419**	

Table 4.28: Life cycle calculation for staged renovation prioritizing energy savings

4.6.4 LCC analysis of the reference case Anyways

The costs for the reference case Anyways is accounted differently from the previous renovation scenarios. The energy consumption (used for the running costs) is the energy consumption of the house in its current conditions. This value was already calculated in the first step of the methodology, Mapping Phase. However, two of the maintenance works had improved the house energy efficiency because of the Building Regulation restrictions. These maintenance works are the windows replacement and the heat source replacement. Therefore, the energy consumption of the house after these maintenances be performed must be calculated. The calculation was done using Be18 program. The results are presented in table 4.29.

		ENERGY CONSUMPTION (kWh/m2)				
YEAR	MEASURE	Electric.	Oil	D.H.	Primary Energy	% Primary Energy
0		5.8	243.8		254.7	100%
5	HEATING SYSTEM MAINTENANCE	5.8	243.8		254.7	100.0%
10	WINDOWS AND DOORS CHANGES (N/W) FLOORING REPLACEMENT	5.6	217.4		228.1	89.6%
12	HEAT SOURCE & DHW REPLACEMENT	4.5		198.7	177.5	69.7%
15	EXTERNAL WALL MAINTENANCE ROOF FINISHSING REPLACEMENT	4.5		198.7	177.5	69.7%
20	KITCHEN RENOVATION	4.5		198.7	177.5	69.7%
25	FOUNDATION INSULATION (N/W)	4.5		198.7	177.5	69.7%

Table 4.29: Energy consumption of the house after maintenance works

Table 4.29 shows that the change of the windows and the heat source (with DHW) impacts in a primary energy reduction of 30,3% on the house. The actual energy reduction is lower, around 20%.

For the reference case Anyways, the cost for renovation is actually the costs for the maintenance works, calculated by the second budget in step 2. The cost of each maintenance work was accounted in the year that it takes place and not by regular savings as the previous ones. The calculation of the costs of the LCC analysis is presented by table 4.30

REFERENCE CASE - ENERGY PRIORITY																		
Renovation cost				Electricity			Oil			District heating			Solar cells			LCC values		
Year	Stage	Stage cost	Annual Savings	Electr. Consump.	Electr. Cost	FUTURE Electr. Cost	Oil consump. (kWh)	Oil cost	FUTURE Oil cost	DH consump.	DH cost (DKK)	FUTURE DH cost (DKK)	Solar cell produc.	Solar cell savings (DKK)	FUTURE Solar cell savings (DKK)	FUTURE Annual recurring cost	NPV	NPV Accumulated
1			48,000	727	1,717	1,834	30,792	28,232	28,938							78,772	77,281	77,281
2	1	86,137	48,000	727	1,717	1,959	30,792	28,232	29,661							79,620	76,636	153,917
3			48,000	568	1,341	1,635				28,493	13,965	14,820				64,454	60,865	214,782
4			48,000	568	1,341	1,746				28,493	13,965	15,116				64,862	60,091	274,873
5	2	135,508	48,000	568	1,341	1,865				28,493	13,965	15,418				65,284	59,337	334,210
6			48,000	568	1,341	1,993				24,186	12,014	13,529				63,522	56,643	390,853
7			48,000	568	1,341	2,128				24,186	12,014	13,800				63,929	55,927	446,780
8	3	152,807	48,000	568	1,341	2,274				24,186	12,014	14,076				64,350	55,230	502,011
9			48,000	568	1,341	2,429				18,212	9,308	11,123				61,552	51,830	553,841
10			48,000	568	1,341	2,594				18,212	9,308	11,346				61,940	51,170	605,010
11			48,000	568	1,341	2,771				18,212	9,308	11,573				62,344	50,529	655,539
12	4	175,327	48,000	568	1,341	2,960				18,212	9,308	11,804				62,764	49,907	705,446
13			48,000	568	1,341	3,162				14,474	7,614	9,850				61,011	47,595	753,041
14	5	95,714	48,000	568	1,341	3,377				14,474	7,614	10,047				61,424	47,010	800,052
15			48,000	568	1,341	3,608				14,474	7,614	10,247				61,855	46,445	846,497
16			48,000	568	1,341	3,854				14,474	7,614	10,452				62,306	45,898	892,395
17	6	125,564	48,000	568	1,341	4,116				14,474	7,614	10,661				62,778	45,371	937,765
18			48,000	770	1,818	5,960				10,634	5,875	8,391				62,351	44,210	981,975
19	7	108,514	15,571	770	1,818	6,367				10,634	5,875	8,558				30,496	21,214	1,003,189
20				770	1,818	6,801				10,559	5,840	8,679	-1,646	-3,885	-14,530	949	648	1,003,837
21				770	1,818	7,265				10,559	5,840	8,852	-1,646	-3,885	-15,521	596	399	1,004,236
22				770	1,818	7,760				10,559	5,840	9,029	-1,646	-3,885	-16,579	210	138	1,004,374
23				770	1,818	8,289				10,559	5,840	9,210	-1,646	-3,885	-17,709	-211	-136	1,004,238
24				770	1,818	8,854				10,559	5,840	9,394	-1,646	-3,885	-18,917	-669	-423	1,003,815
25				770	1,818	9,458				10,559	5,840	9,582	-1,646	-3,885	-20,207	-1,167	-724	1,003,092
26				770	1,818	10,103				10,559	5,840	9,773	-1,646	-3,885	-21,584	-1,708	-1,040	1,002,052
27				770	1,818	10,792				10,559	5,840	9,969	-1,646	-3,885	-23,056	-2,295	-1,371	1,000,682
28				770	1,818	11,527				10,559	5,840	10,168	-1,646	-3,885	-24,628	-2,932	-1,718	998,964
29				770	1,818	12,313				10,559	5,840	10,372	-1,646	-3,885	-26,307	-3,622	-2,082	996,882
30				770	1,818	13,153				10,559	5,840	10,579	-1,646	-3,885	-28,101	-4,369	-2,463	994,419
																LCC:	**994,419**	

Table 4.30: Life cycle calculation for the house without renovation

Table 4.30 shows that the change of heat source has a great impact on the energy cost. That is attributed to the big price difference between energy sources but also because of the high heat demand of the house. It is also seen in the table that the energy consumption after year 13 is always constant impacting in a high energy cost.

4.6.5 LCC analysis result

The values in column NPV Accumulated for the three scenarios were plotted in a graphic for better visualization of the LCC analysis over time. The graphic is presented in figure 4.15

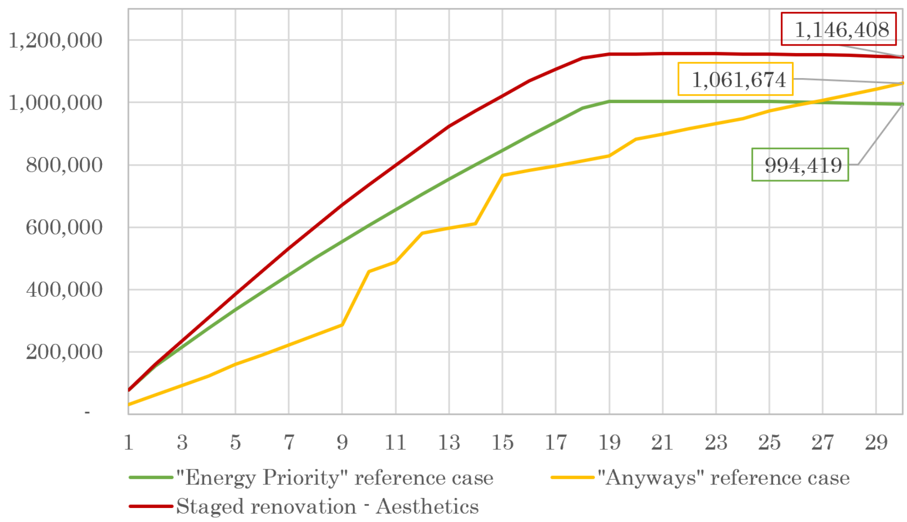


Figure 4.15: Accumulative graph showing the life cycle cost of the staged renovation with the two reference cases

Figure 4.15 shows that prioritizing aesthetics resulted in the highest LCC over the 30 years and prioritizing energy savings resulted in the lowest. It also shows that maintain the house in its original condition after 26 years becomes more expensive than renovate prioritizing energy savings. That is because the high cost for the running the house in its original conditions after 19 years still high, while for the other one is very low due to the renovation.

4.6.6 Sub-conclusion

The life cycle cost assessment over the study case demonstrates to be efficient. The finances of the staged renovation project over 30 years are easy to understand. The reference cases demonstrated to be helpful to give a better perspective of the financial impact of the staged renovation over time - It becomes clear the financial impact of maintain the house in its original conditions or prioritizing energy efficiency in the staged renovation. Moreover, the financial analysis demonstrated to be comprehensive because it considers not only the cost for renovation but also for running the house.

4.6.7 Financial comparison between staged renovation and one-off renovation

A financial evaluation between staged renovation and one-off renovation was performed using the study case project. This evaluation considers the same parameters and method used in the previous section.

To make this comparison, two one-off hypothetical scenarios where created. The one-off renovations scenarios created were very different from each other. They represent two extreme approaches of current practices of one-off renovations.

In one case, a bank loan is taken to renovate the house in the first year. The loan is paid by constant annual payments over 30 years – the maximum period possible to pay off a loan, which means that the payments are the minimal possible. This renovation is advantageous because the house energy consumption from year 2 is already the final one from the staged renovation. Take a loan has recently shown to be advantageous in Denmark that is because of low interest rates in the last five years. However, this same low interest rates cannot be considered for a 30 years loan since the economic scenario can change in the future. The drawback of this renovation approach is that building components that are far from its end of life are renovated early.

In the other case, the homeowner does not take a bank loan but saves money every year to have money available to pay for the whole house renovation, which means that the renovation is only carried out after several years of annual savings. The annual savings are the same amount considered for annual saving by the stage renovation methodology. The disadvantage of this approach is that the house energy consumption it remains high for all the saving period, which is 22 years. Moreover, during the period maintenance needs occur, consuming the money saved for the extensive renovation.

The annual recurring cost for this two scenario is presented in table 4.16.

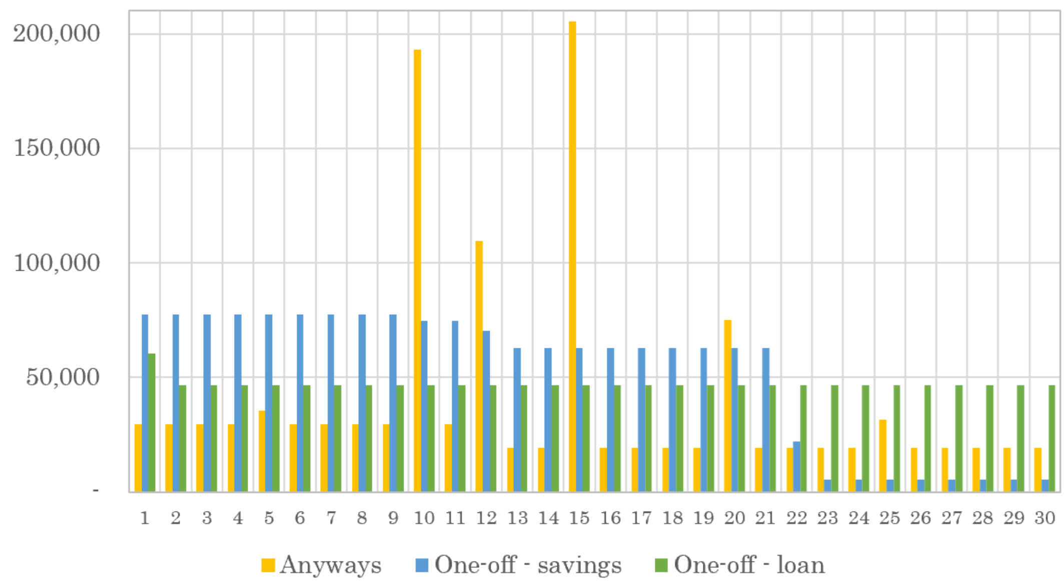


Figure 4.16: Annual recurring cost of the two one-off scenarios and the Anyways scenario

The LCC for these two scenarios were calculated in the same fashion than to the staged renovation. The tables of the calculations are presented in appendix .4. The annual recurring costs corrected to the present values were plotted in the accumulative chart together with the Anyways reference case, as presented by table 4.17

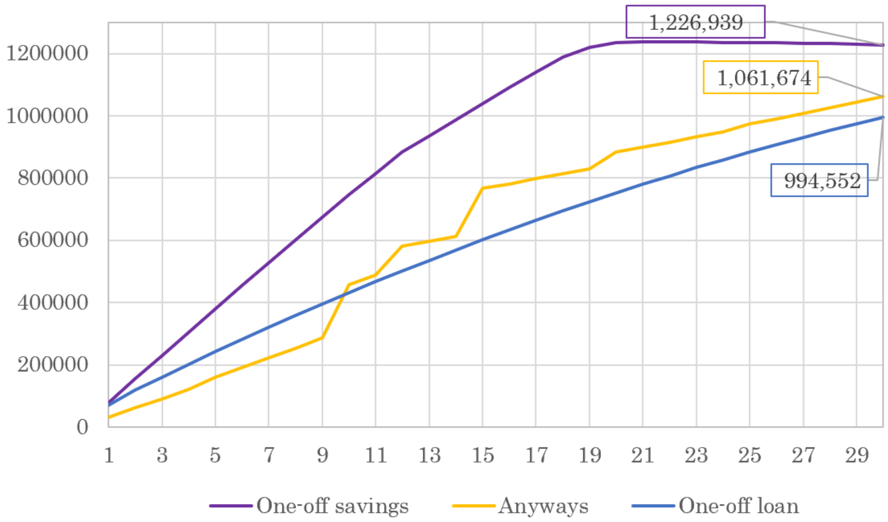


Figure 4.17: Accumulative graphic showing the life cycle cost of the two one-off renovation scenarios and Anyways scenario

FIgure 4.17 shows that the accumulated cost of a one-off approach by a bank loan is lower than maintain the house in its original conditions and the turning point is after ten years. However, renovating the house with personal savings showed not to be beneficial and has higher costs all over the 30 years. That shows that, in 30 years consideration, it is more financially advantageous to renovate the house using a bank loan than maintain it in its current condition.

The next step was to compare the one-off renovation with the staged renovation scenarios. The comparison is presented in figure 4.18.

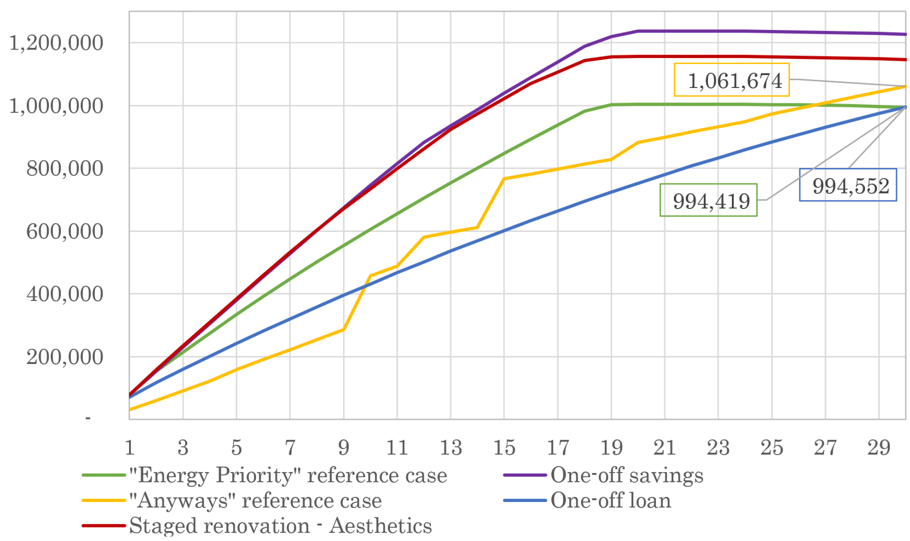


Figure 4.18: Accumulative graphic showing the life cycle cost of the two one-off renovation scenarios, reference case Anyways and Energy Priority, and the staged renovation scenario

The comparison demonstrated by figure 4.18 shows that one-off renovation by a loan and stage renovation prioritizing energy efficiency has similar LCC costs at the end of 30 years. However, over the years the one-off renovation is significantly cheaper. One-off renovate by savings is the most costly option; it has similar costs than staged renovation prioritizing aesthetics, but after 16 years the difference becomes significant.

This analysis concludes that if energy efficiency is the priority when staged renovating, the staged renovation can have similar cost in 30 years than one-off renovation by a loan. However, the annual costs in the staged renovation would be higher in the early years, which means that one-off renovation by a loan is the most advantageous option. Moreover, one-off renovation by annual savings is the least advantageous scenario having higher cost throughout the whole period.

Ownership interrupted before 30 years

The comparison between staged renovation and one-off renovation approaches showed that one-off renovation is the most advantageous financial option. However, this result does not reflect the current practices of house renovation. The current practices, as presented by the literature review, shows that staged renovation is the approach most used by homeowners. Also, homeowners prefer to renovate by savings than to take a bank loan.

One motive that can justify this current practice is if the homeowner wants to sell the house before the total period of the loan, he would need to pay off the loan at once when selling the house. Thus, this cost would be subtracted from the selling price of the house, which could transform the house renovation by loan not advantageous anymore. Based on this supposition new comparisons between staged renovation and one-off renovation was made considering the house been sold before 30 years, which is the period considered for the loan in the one-off scenario.

However, compare straightforward the staged renovation and one-off renovation would not be correct because of the property value increase of a house after a renovation. In one-off renovation the house is totally renovated after year 2 while in the staged renovation the renovation is complete only at year 19. Therefore, in the one-off renovation, if the house is sold in 10 years, for example, the house would have higher selling price than in the staged renovation scenario since in the staged renovation scenario the house renovation would be in the middle of the renovation process. Therefore the concept of property value gain because of house renovation must be introduced to have a more valuable comparison.

The value increase is difficult to predict; it depends on many aspects, energy improvement, aesthetics, functional improvements, location [5]. However, the result of an SBi research demonstrates that the selling price of a house increase when the EPC label of the house improves. Therefore, an estimation of property value increase based on this research was applied to the study case house. The value of the selling price increase is added in the LCC calculation as a residual value on the LCC formula. The calculation and considerations of the house property value increase made for the study cause project considering both renovation approaches are presented in appendix .4.

The comparison was made for the two least costly scenarios of the one-off and staged renovation (staged renovation prioritizing energy efficiency and one-off by a loan) and considering the house been sold after 10, 15, and 20 years. The LCC analysis of these scenarios are presented in figure 4.19.

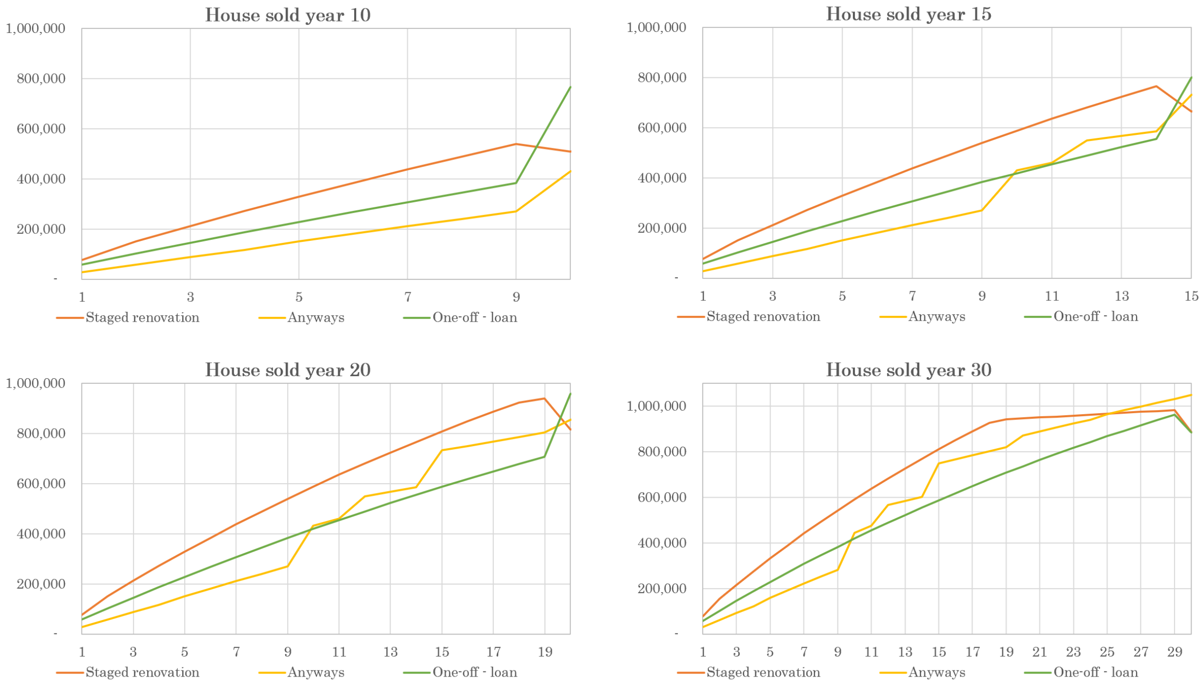


Figure 4.19: Accumulative graphic showing the life cycle cost of one-off renovation staged renovation considering the house been sold after 10, 15, 20, and 30 years

The four graphics in figure 4.19 show that, for all the cases, after selling the house it is more advantageous to stage renovate than to one-off renovate by a loan. Because there is no debt when stage renovating, the price gain from EPC improvement becomes a monetary gain to the homeowner, while for the one-off approach it becomes only a reduction of the total debt. The graphics also show that after 15 years it is less costly to stage renovate than to only maintain the house.

In conclusion, the result of this analysis confirms the hypothesis that it is not financially advantageous to one-off renovate if the house is sold before the loan is totally paid off. Moreover, this justifies the current behavior of homeowners in staged renovation using personal savings.

4.7 Simulation results of the Staged renovation

This section describes the improvements of the indoor environmental quality for each renovation stage. The results are primarily viewed in relation to each other, emphasizing the difference from stage to stage, rather than the absolute, measured conditions.

4.7.1 Tools used for the evaluation of the building's performance

This section will describe the tools used to evaluate the performance of the building in terms of energy consumption and indoor environmental quality.

BE18 is a single zone simulation tool for energy frame calculation of buildings [Sbi, 2008], that is used on a national level to compare buildings' energy consumption. Also it is used for assigning an energy label in connection with the EPC of buildings. The purpose of using this tool is to get the final energy consumption of both the house. It was used to evaluate the existing, staged and final conditions.

The building was modelled according to the following inputs:
The energy frame of the building was calculated in Be06 by the university and this file was modified to reflect the conditions defined by the project group. The thermal envelope was reevaluated, and U-values based on the previously described constructions were used. Natural ventilation during winter was defined by only taking infiltration into account as 0.3 $l/s/m^2$. Summer natural ventilation was taken as standard 1.2 $l/s/m^2$. Heat gains from people was defined as standard 1.5 W/m^2 and from appliances as 3.5 W/m^2. The heating pipes in the crawlspace were taken as 30m with a linear heat loss of 0.14 W/mK. The heat circulation pump was defined with constant operation of 60W. The hot water tank was taken as a 100l, without electrical heater and a hat loss of 1.1 W/K. The 20 kW boiler was defined with 93% efficiency, 70°C, at maximum laod and 95% efficiency, 50°C at 30% nominal load. Auxiliary energy for operation was defined as 105W. With the above input the final, primary energy consumption was 255.7 $kWh/m^2/year$.

Design Builder is a dynamic simulation tool, based on the simulation engine Energy Plus. In this project it is used to evaluate both the indoor climate and the energy consumption of the building. The tool was used with simplified input, as the detailed option was considered to be too complex to be worthwhile for this project. Input parameters were based on available information from the measurements and previous BE18 setup to reflect similar input. Besides the living room (which is comparable with the measurements), bedroom3 (North) will also be evaluated in terms of IEQ as these rooms can give a representative condition for the building.

Each room is considered a different zone, with heat exchange between them, but without air mixing. Occupancy is based on 3 people throughout the whole project. The profile is built up with general assumptions, as hourly use and occupation of individual rooms. For each model (existing and renovations) the same profile was used and rebound effect was not considered. The usage profile is available in appendix .6 figure .35. Domestic hot water consumption was modelled in the same manner is in BE18, to reflect general conditions and to allow for comparison. For all stages, a full year is simulated. For each stage the heating is simulated with constant operation of 20.5°C to avoid unnecessary under-heating (below 20°C). This was also chosen in order for the energy consumption results to be comparable with Be18. In order to avoid excessive overheating, external shading had to be applied on the East and West windows at stage 2 and 3. The stages were in the following order show in table **??**. Infiltration for existing conditions was defined according to measurements, but for the renovations, assumptions were made as to which component would cause improvements and by how much. In Design Builder infiltration is modelled dynamically, thus depends on the current weather conditions: wind speed, direction, outdoor temperature. The amount of infiltration possible depends on the individual building components, which is defined by a "crack-template", quantifying the area for infiltration. Because of these reasons, during winter, it often happens, that high wind speed and low outdoor temperatures cause the building to cool down below comfort conditions. This is discussed in more detail in further chapters. The base model will be validated, by comparing them with the measured data in the following section. Afterwards the model will be used to set up a stage 0, which will be continuously improved according to the chosen stage renovation scenario. For each stage, indoor climate and energy consumption is noted and analyzed to see the quality of improvements. The result of energy consumption from Design Builder are compared with that of BE18.

4.7.2 Design Builder base model and validation

The validation of the Design Builder model is based on the measurements taken in the living room. Indoor climate will be compared between the measured and simulated conditions, by looking into shorter time periods. The weather file used for the simulations was a 2002 DRY weather file based on Aalborg, adapted to be used by Design Builder. As this weather file is different from the outdoor conditions during the measurement period, the validation is based on getting similar peaks of indoor temperature and average trend-line and not to have the exact same variation of the temperature.

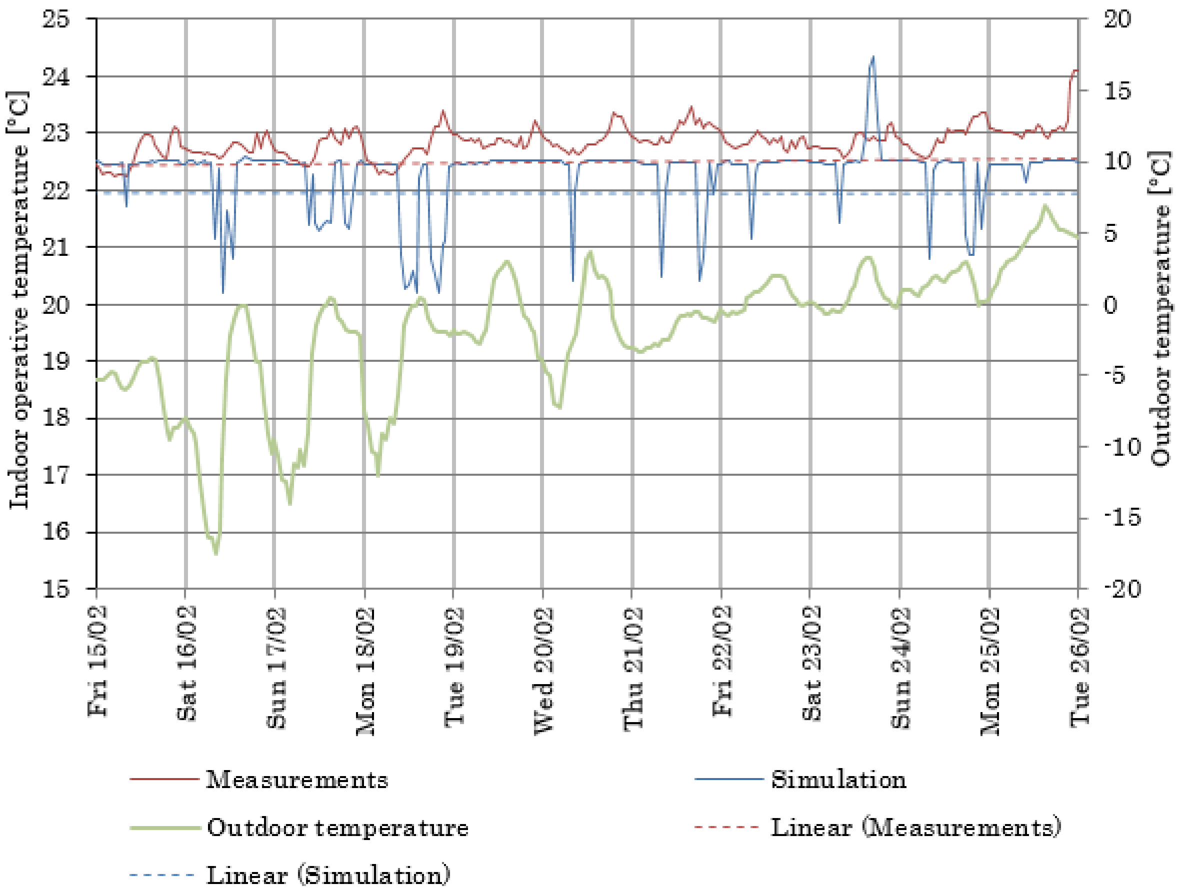


Figure 4.20: Operative temperature during a 2 week period in February for measurements and simulation

Seen on figure 4.20 the simulations were run with a heating set-point of 22.5°C, which is derived from the mean measured indoor temperatures during the heating period. From the measurements a daily rise and fall of indoor temperature is observed, which is due to the time lag of the heating system's temperature sensor and the internal gains in the room. On the other hand, simulated conditions are kept constant and the temperature only drops due to the increased infiltration. Since during the heating period for simulations, this trend continues, the time when heating is turned off is further evaluated.

In April, it is seen from the measurements that the heating is turned off in the living room. Simulations reflect this, thus the indoor temperature varies much more as seen on figure 4.21. This is due to the varying outdoor temperature throughout the day, and solar gains and occupancy in the afternoon. The simulated daily temperature profiles show similar conditions to the measured ones. The average linear trend-line has a difference of 1.6°C.

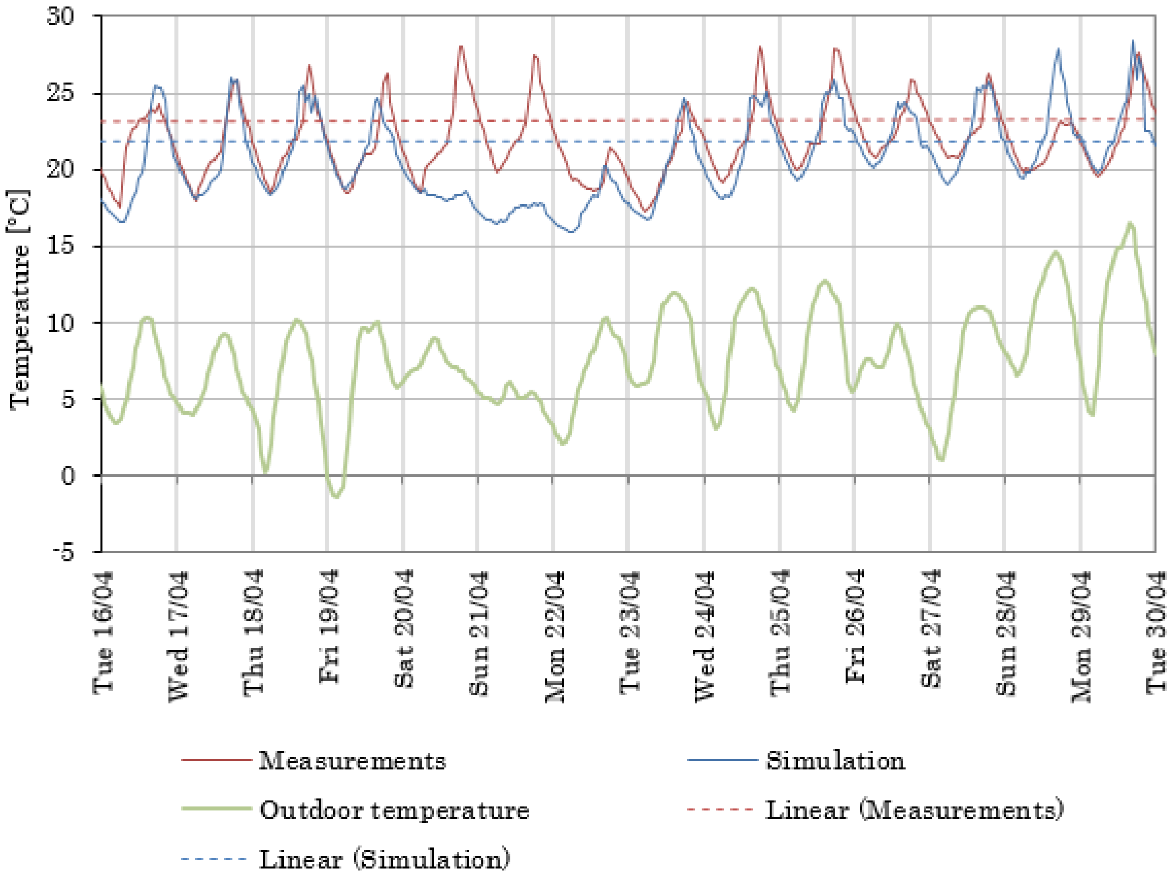


Figure 4.21: Operative temperature during a 2 week period in April for measurement and simulation

Table 4.31 shows the percentage of overall hours in each comfort class for the measured and simulated conditions, until the 30^{th} of June. The simulations show less hours of overheating compared to the measurements. If the heating is left operational for the whole simulation period, thermal comfort is better in terms of minimum temperatures kept. However, due to this, there is also more overheating.

	Cat. I	Cat. II	Cat. III	T>26°C [h]	T>27°C [h]
Measurement	79 %	89 %	95 %	317	184
Simulation heating til April	71 %	84 %	89 %	106	65
Simulation heating allways on	93 %	96 %	99 %	256	79

Table 4.31: Thermal comfort in the living room for measurements and simulation

In terms of air quality, the same 2 week period is evaluated in February. Figure 4.22 shows similar peaks as pollution rises, but due to the increased infiltration, the pollution decreases much faster, which is not the same for the measurements. Since the accumulation of CO_2 causes similar peaks, the model reflects similar building characteristics and occupant definition (pollution source)

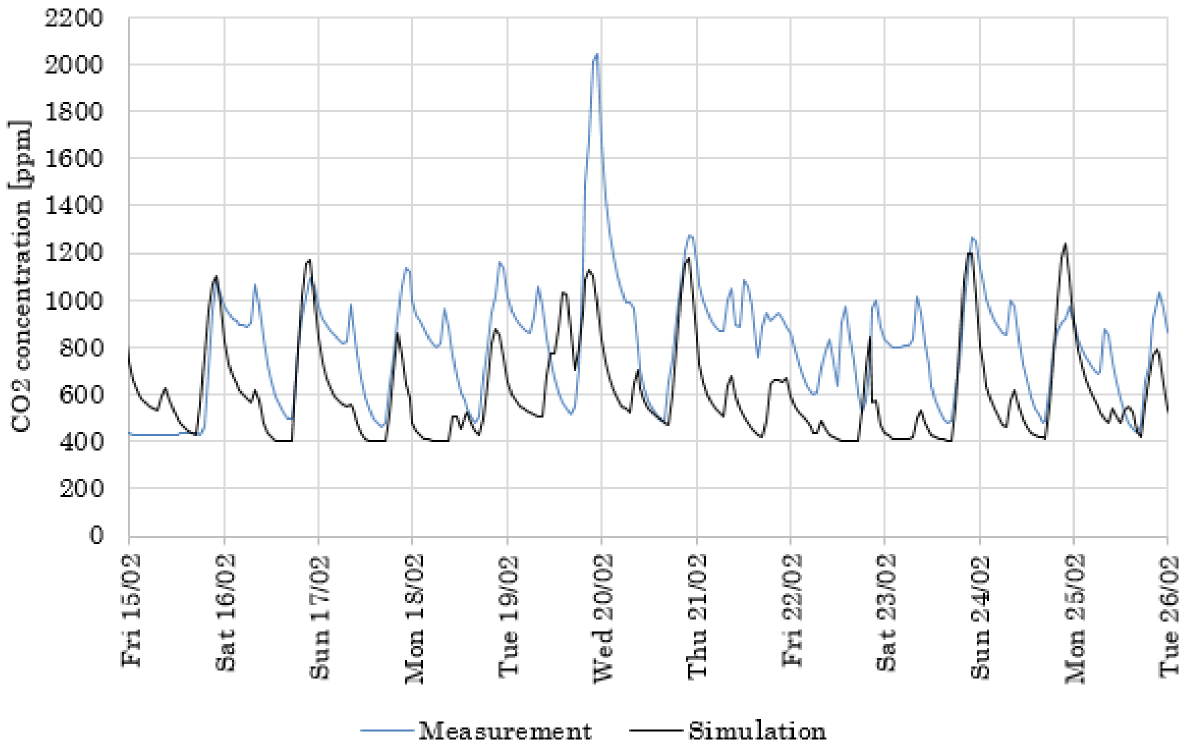


Figure 4.22: Air quality in the living room for a 2 week period in February for measurement and simulation

Table 4.32 summarizes the hours within each of the categories for measured and simulated conditions. Due to the more frequent ventilation due to infiltration, the air quality is much better for the simulation.

	Cat I		Cat II		Cat III	
	[h]	[%]	[h]	[%]	[h]	[%]
Measurements	1377	32%	2272	52%	3665	85%
Simulation	3488	80%	3899	90%	4283	99%

Table 4.32: Comfort categories for air quality in the living room for measurements and simulations

4.7.3 Thermal comfort during the stages

To show the improvement in thermal comfort, each category is shown, over the progress of the stage renovation. Figures 4.23 and 4.24 show that improvement in category II is observed. Seen from table 4.33 after the floor and wall part of the envelope is insulated, the thermal comfort significantly improves in terms of reduced under-heating, detailed yearly simulations can be seen in appendix ??. This is further elaborated in the next paragraph. On the other-hand, overheating becomes a bigger issue as the building keeps the summer gains for a longer time. For this reason, to keep comfortable summer temperatures inside the building, shading is applied. Category I is not reached more due to the heating set-point of the simulation is 20.5°C which is outside of category 1.

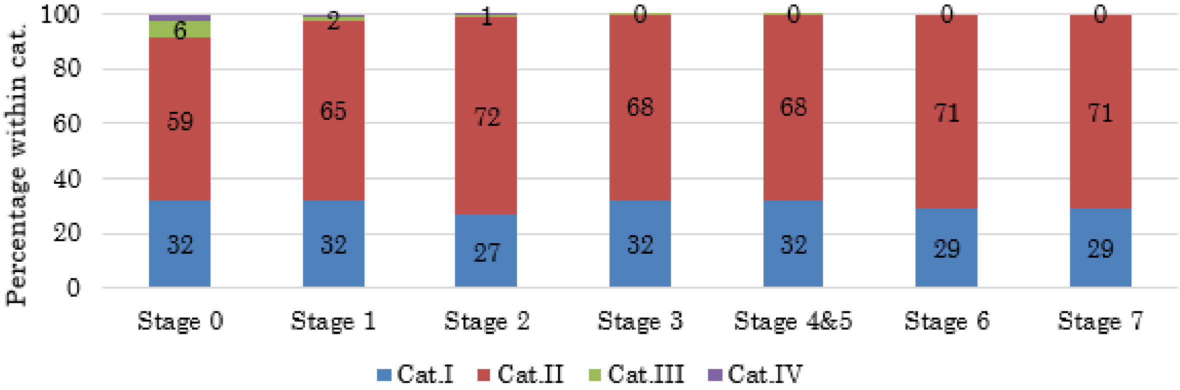


Figure 4.23: Bedroom3: Thermal comfort shown for each renovation stage

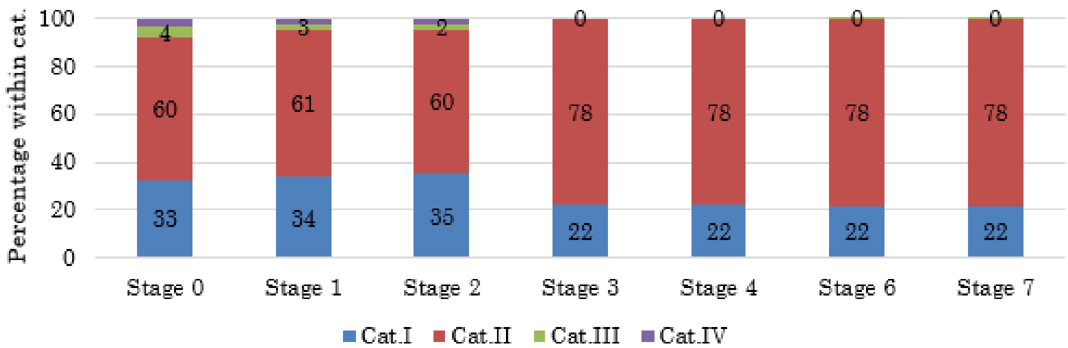


Figure 4.24: Living room: Thermal comfort shown for each renovation stage

	Living room			Bedroom3		
	<20	>26	>27	<20	>26	>27
Stage 0	415	262	157	728	43	16
Stage 1	152	285	159	173	44	17
Stage 2	101	312	175	73	19	3
Stage 3	0	0	0	1	0	0
Stage 4-7	0	0	0	0	0	0

Table 4.33: Hours at specific temperatures during a full year of simulation

Addressing under-heating: On figure 4.25 two graphs show a day in February from stage 0 and 6. For the existing conditions, high wind speed causes external air to enter the building and indoor temperature to drops. For stage 6, the same weather conditions do not cause this drop, as the building envelope is improved and infiltration is lower.

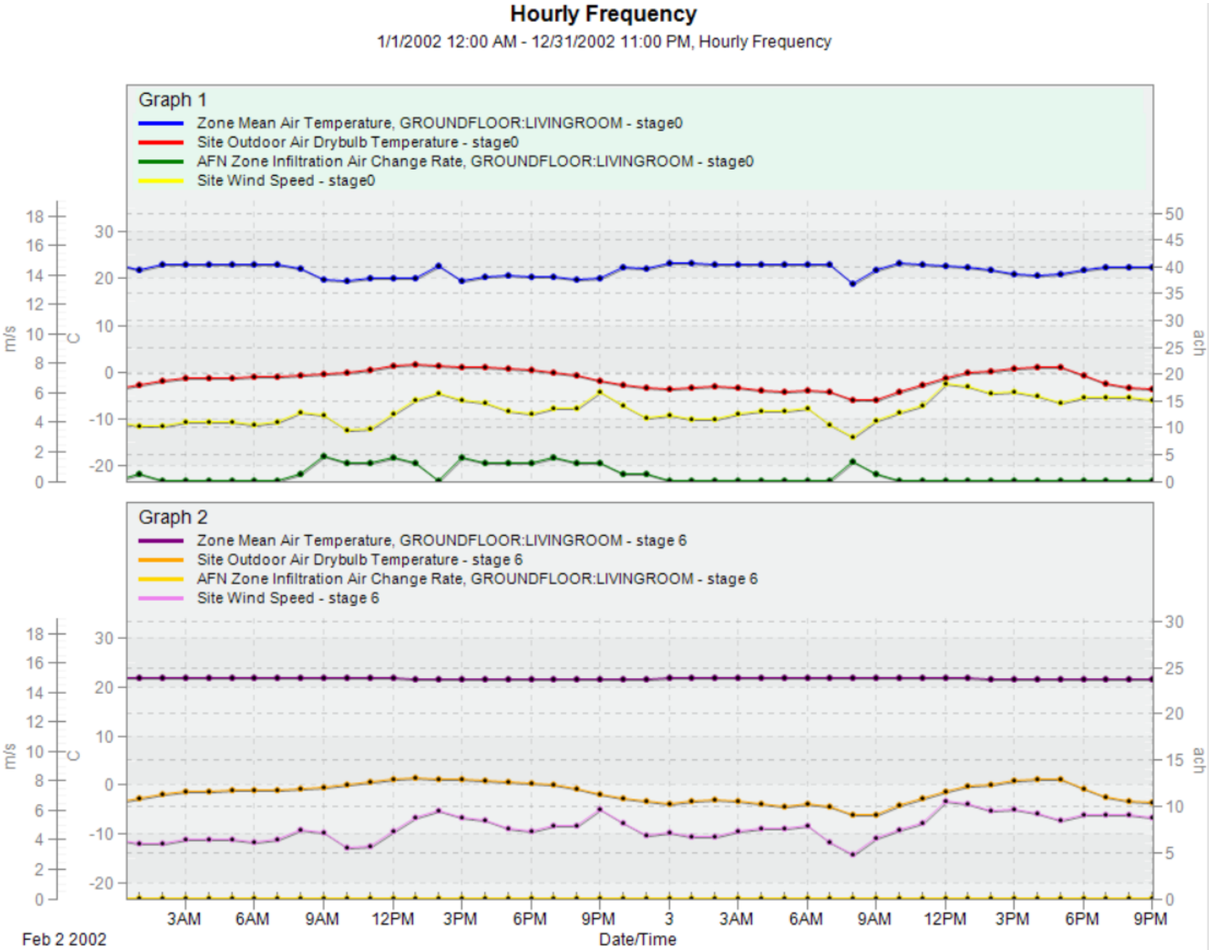


Figure 4.25: Extract from ResultViewer, showing the outdoor and indoor climate conditions, which drives infiltration. Graph above showing Existing conditions, Graph below showing final stage conditions.

As the building is undergoing the different steps of renovation and the envelope gets more insulated and airtight, keeping stable indoor operative temperatures and reducing fluctuations for radiant and air temperature is easier for the heating system. The high variation of radiant and air temperature in stage 0 is due to the poor insulation and air-tightness on the external surfaces. This can be seen in figure 4.26. Detailed yearly simulations can be seen in appendix **??**

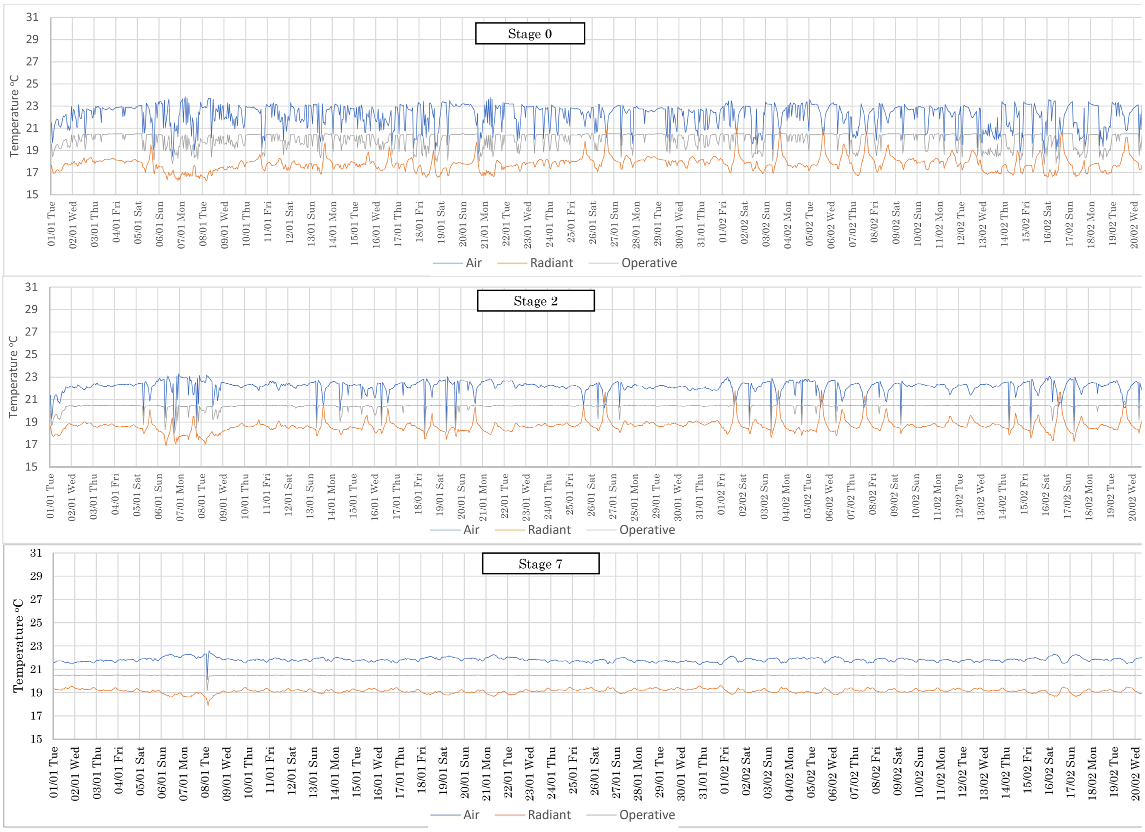


Figure 4.26: Living room: Air, radiant, and operative temperature fluctuations, for stage 0, 2 and 7

On the following figure 4.27 below, the average temperatures in January are shown for each stage. Air temperature (Air), radiant temperature (Rad) and Operative temperature (Op) are shown. Operative temperature increases and the difference between the radiant and air temperatures are decreasing. The polynomial trend-lines (Poly.) aid in seeing this. Improvement is most distinguishable until stage 3, when the envelope is almost fully renovated except for the ceiling. Detailed yearly simulations can be seen in appendix **??**

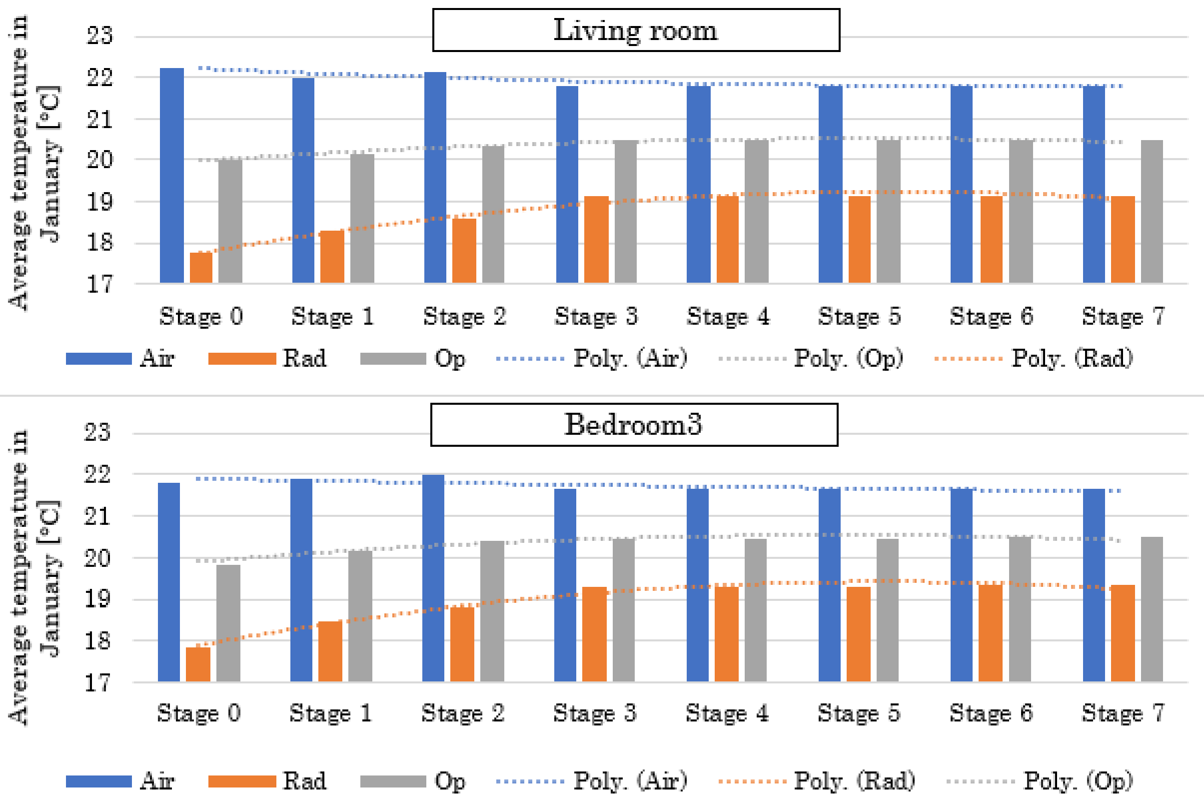


Figure 4.27: Living room and Bedroom 3: Heating set-point of 20.5°C kept during the heating season with different margins. Progress shown for each renovation stage

Local discomfort was evaluated in the living room and bedroom3 by taking the internal surface temperatures of external wall, internal wall, floor and windows, seen on figure 4.28. Simulations were run with a heating set-point of 20.5°C. Radiant asymmetry is not an issue for the opaque surfaces as the difference between the surface temperatures never exceeds 4°C. The windows on the other hand have, on average, a much lower temperature. Table 4.34 shows the hours for the whole year, when the surface temperature difference between the window (coldest) and internal wall (warmest) is larger than 10°C. Conditions improve, when the windows are changed to better ones at stages 2 and 3. Looking at the floor, the amount of insulation proposed still cannot significantly improve surface temperatures. Local discomfort of cold feet (less than 19°C is experienced until stage 3. Detailed yearly simulations for the living room can be seen in appendix **??**

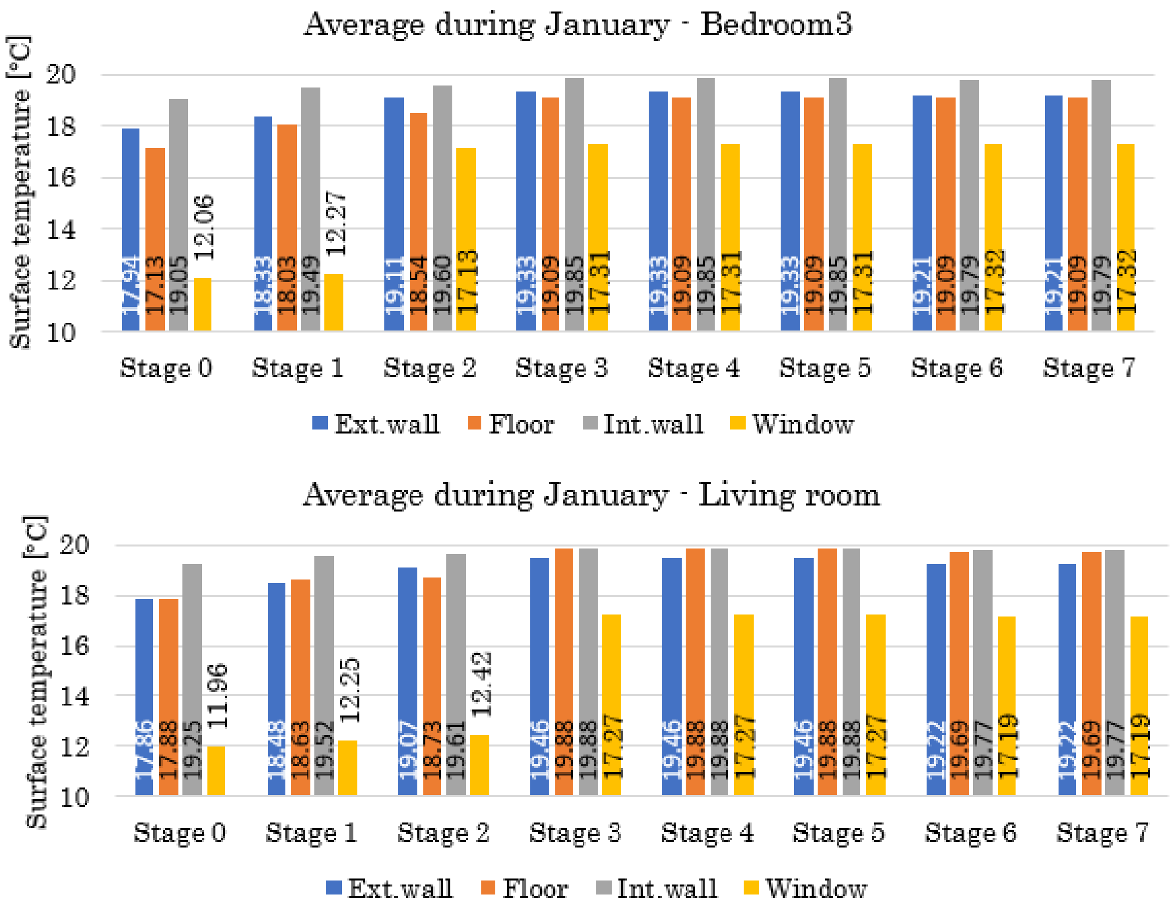


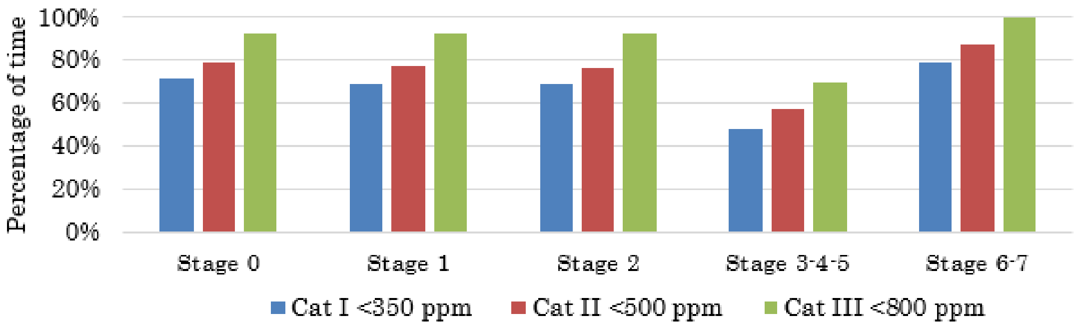
Figure 4.28: Internal surface temperature of different components of the living room and bedroom3, throughout the renovations. Average during January.

	Living room		Bedroom3	
	[h]	[%]	[h]	[%]
Stage 0	100	1.14%	66	0.75%
Stage 1	101	1.15%	97	1.11%
Stage 2	87	0.99%	0	0.00%
Stage 3	0	0.00%	0	0.00%
Stage 4	0	0.00%	0	0.00%
Stage 5	0	0.00%	0	0.00%
Stage 6	0	0.00%	0	0.00%
Stage 7	0	0.00%	0	0.00%

Table 4.34: Hours for a difference in internal surface temperature higher than 10°C, for window and internal wall over the whole year.

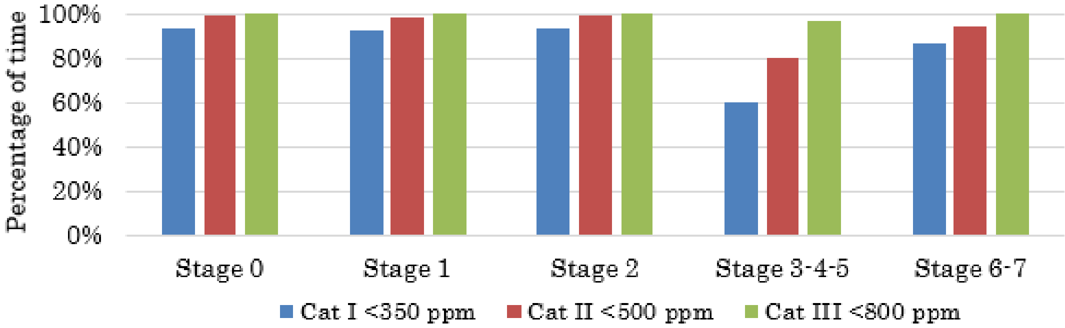
4.7.4 Air quality during the stages

Air quality is evaluated throughout the renovation stages in the living room and bedroom3 on figures 4.30 and 4.29. Due to no change in the conditions over stages 3 4 and 5, and stages 6 and 7, these are shown together for simplicity. For the whole year, simulations are run with the same occupant behaviour and set-point for natural venting. Due to this, infiltration influences air quality the most. At stage 3, infiltration is modelled to be reduced and air quality decreases severely. Mechanical ventilation is installed at stage 6, thus air quality is increased. The design airflow rates are according to BR18 minimum standard (0.5 air change per hour), but this is still not sufficient to satisfy category II in the bedroom due to the small size and high occupancy during nighttime. Detailed yearly simulations for living room and bedroom 3 can be seen in appendix **??**.



DS/EN 15251	Cat I <350 ppm		Cat II <500 ppm		Cat III <800 ppm	
Stage 0	6228	71%	6898	79%	8088	92%
Stage 1	6044	69%	6753	77%	8057	92%
Stage 2	6000	68%	6713	77%	8055	92%
Stage 3-4-5	4179	48%	4967	57%	6094	70%
Stage 6-7	6909	79%	7664	87%	8705	99%

Figure 4.29: Bedroom3: Comfort categories for air quality over the whole year



DS/EN 15251	Cat I <350 ppm		Cat II <500 ppm		Cat III <800 ppm	
Stage 0	8202	94%	8670	99%	8760	100%
Stage 1	8151	93%	8665	99%	8760	100%
Stage 2	8165	93%	8673	99%	8760	100%
Stage 3-4-5	5291	60%	6996	80%	8500	97%
Stage 6-7	7592	87%	8230	94%	8760	100%

Figure 4.30: Living room: Comfort categories for air quality over the whole year

Seen on figures 4.31 and 4.32 Stages 0, 1 and 2 have similar conditions, and as infiltration is modelled to reduce at stage 3, air quality worsens. Mechanical ventilation improves this after stage 6, when pollution cannot rise as much as it used to in previous stages. Although during certain days, there is still a higher concentration, which shows that the 0.5 air change per hour for mechanical ventilation cannot make up for the reduced infiltration, therefore a higher ventilation rate would be suggested. Detailed yearly simulations for CO_2 in living room and bedroom 3 can be seen in appendix **??**.

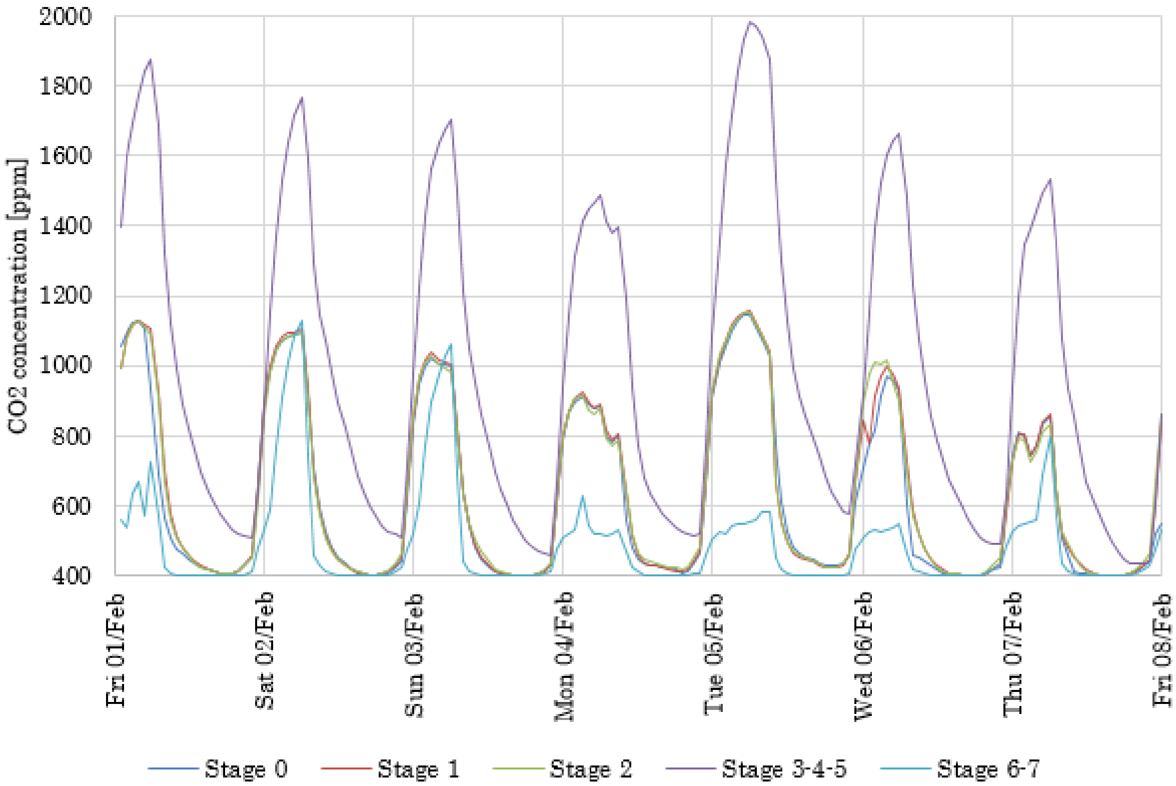


Figure 4.31: bedroom3: 1 week period in February showing the CO_2 concentration in the air for each stages

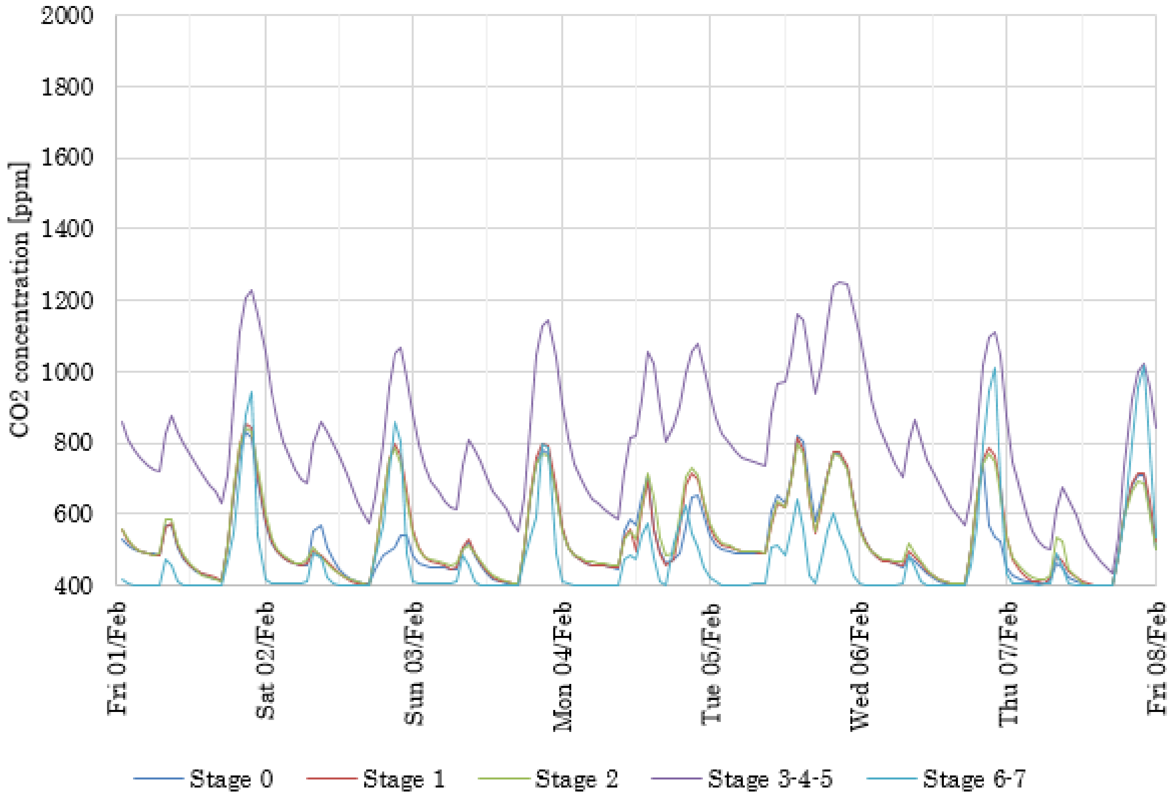


Figure 4.32: living room: 1 week period in February showing the CO_2 concentration in the air for each stages

Sub-conclusion

The purpose of this evaluation was to confirm the predicted improvements and to see their extent. Having said this, it is beneficial to include such an evaluation prior to renovation planning, to aid decision making and help to communicate to the homeowner the extent of comfort improvements. This is prominent to justify certain renovation measures.

For example, wall insulation is a generally undesirable and rarely carried out, but thermal comfort improvements are closely related to this EEM. It is seen that insulating the envelope, indoor climate during winter is enhanced, although, summer time overheating is increasing.

Unwanted (or uncontrolled) infiltration is also an issue that is solved by the renovation of the envelope. However this reduction of fresh air decreases indoor air quality, which would have to be compensated by other means, which is not accounted for in the model. In practice, if there is a reduction of infiltration and thus energy conserved, there should be an increase in natural ventilation via windows and thus energy lost. Ultimately the energy balance is (theoretically) the same. However there will be a need to operate windows manually throughout the winter, which can be considered a nuisance and there would be short periods of discomfort due to cold air. To receive the benefits of reduced energy consumption, mechanical ventilation has to be installed. Shown by the results, even with that, air quality can be compromised.

Whether the positive effects are predominant in contrast to the negative ones is a complex question that could be answered by future research. Quantifying the value of IEQ improvement was not part of this thesis. Moreover the homeowner (and occupants) can nonetheless have a perception of comfort and other personal preferences of lifestyle that overrules general assumptions.

4.7.5 Energy consumption

The energy consumption from Design Builder was taken as the total energy use for room heating [kWh] for one year and was converted to show the primary energy consumption per heated floor area for each stage. The results are compared with that of BE18 in figure 4.33, with the percentage of reduction achieved at each stage in table 4.35. It is seen that dynamic simulations give lower values than that of semi-steady state, despite the similar setup. Due to the infiltration defined to reduce at stage 3 in the DB model, the reduction in energy consumption shows to be much more sudden.

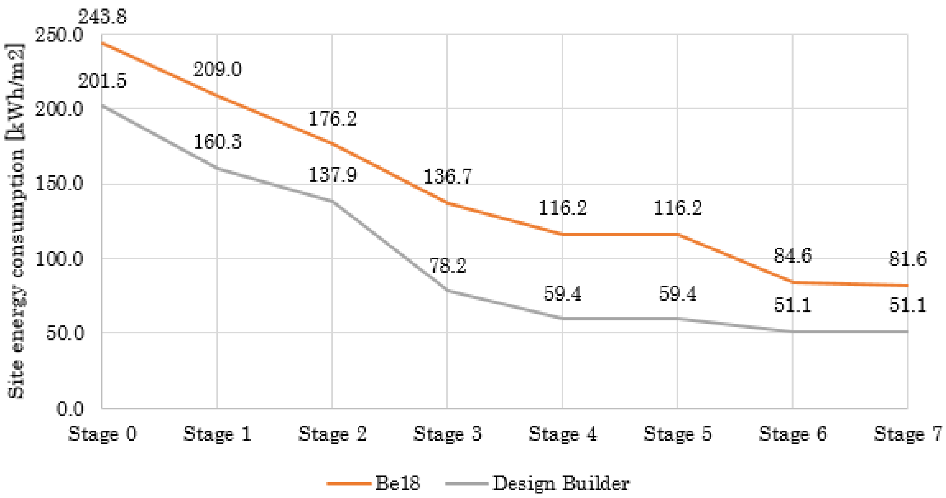


Figure 4.33: Comparison of Primary energy consumption between Design Builder results and Be18

Compering the results for steady state (BE18) to a dynamic (Design Builder) simulation can not give a straightforward conclusion. Because the two software have different calculation methods, comparison is not valid. Moreover how most of the input parameters are defined and used in the calculations also differ. It is assumed that the different weather file is responsible for most of the discrepancies between the two simulation results.

Although relative difference from stages to stages have similar tendencies, some stages still differ. For example, reduction from stage 1 to stage 2 gave a 14% and 16% reduction (compared to previous stage) for the two software, but from stage 5 to 6 is much more different. The purpose with the dynamic simulations were not to extract energy usage, thus this is not evaluated further.

	Energy consumption [kWh/m^2.year]		Reduction in terms of previous stage [%]	
	DB	Be18	DB	Be18
Stage 0	201.5	243.8	0%	0%
Stage 1	160.3	209.0	20%	14%
Stage 2	137.9	176.2	14%	16%
Stage 3	78.2	136.7	43%	22%
Stage 4	59.4	116.2	24%	15%
Stage 5	59.4	116.2	0%	0%
Stage 6	51.1	84.6	14%	27%
Stage 7	51.1	81.6	0%	4%

Primary energy consumption for room heating only

Table 4.35: Comparison of Primary energy consumption between Design Builder results and Be18

5 Discussion

Many previous works[13] [5] [21] presented house renovation implemented over time with a holistic approach as a way to overcome common barriers that slow down the number of energy renovations in single-family houses in Denmark and Europe. This project intended to give one step further and create a methodology of renovating houses that combine theses characteristic to investigate what are the specific characteristics that a overtime renovation with a holistic approach should have to be more appealing for homeowners and contribute to their adoption to energy renovation.

As a result, based on the latest research and surveys within this field, first, a methodology for staged renovation was created and afterward, tested on a case building. The staged renovation methodology was created as complementary to already well-established methods of designing one-off renovations.It considers aspects of home renovations that are generally overlooked, such as the remaining lifetime of components or wishes of the homeowner regarding non-energy efficiency measures.

The holistic approach of the methodology included other considerations than energy reduction and efficient solution for the renovation, meaning aesthetic, functional, technical, and homeowner economics. The staged renovation can have a flexible implementation sequence that best suits the homeowner priorities to the renovation, respecting the restrictions on the implementation order and trying to combine with necessary maintenance. Moreover, the stage packages of the renovation stages are created with the intention to have a total cost that the average of the homeowner is used to spend in house renovation. Finally, the renovation has a high potential to energy improve the house and avoid future lock-outs. The methodology considered to first plan the renovation as one-off renovation considering renovation for 20 years and aims to achieve high energy efficiency, to avoid lock-outs, and then divide the renovation into stages implemented over time.

Even though the methodology considerations were based on various surveys of large sample sizes, the surveys did not directly address the issues relevant for stage renovation. Due to this, the assumptions to create the methodology may be arguable. Therefore, further investigation and specific surveys should be carried out to substantiate the assumptions used to create the methodology.

The staged renovation methodology was successfully applied to a typical three bedroom Danish single-family house from the 60s and 70s. The renovation was designed to achieve energy efficiency Renovation Class 1, which shown to be to the case building an energy reduction of 76%. Moreover, the renovation included a wished kitchen renovation and maintenance works (an opportunity to renovate the house). The cost of the renovation was 880,00 DKK and showed to be a reasonable price for a renovation of this extent.

Given the similarities of the Danish single-family houses from the 60s and 70s and that the renovation energy efficient measures applied were cost-efficient measures based on energy renovation packages developed specially for this housing segment **??**, the renovation solution can be considered as common renovation solution for 3 bedroom houses from the 60s and 70s. Therefore, it can be assumed, within the boundaries of the project, that the methodology is applicable for this type of houses.

The application of the methodology in the case building showed that is possible to plan a house renovation over time with a holistic approach to a homeowner with a relative low household income and achieve high energy efficiency (Renovation Class 1 energy frame). Meaning that the methodology can be considered suitable for homeowners with a household income of 300,000 and above.

5.1 Discussion of the application of the Methodology

Staged renovation methodology was applied to a case building in order to:

- test its application;
- investigate if it is possible to stage renovate with a holistic approach;
- see the outcomes compared to a one-off renovation in terms of energy savings, financial benefits, indoor climate, and other co-benefits;

Financial barriers to energy efficient renovations are one of the most cited and prevailing issues. It was a question if a household with a not so high income of 300.000 DKK/years would be capable of financing a staged renovation process and still reaching Renovation Class 1 energy frame at the end of the renovation process. The staged renovation methodology suggested to reserve 15% of the total household income (chapter 3.1.3), and to complete the staged renovation in maximum 20 years. The study case showed that it is possible and with such an income the staged renovation is concluded in 19 years, including one desired functional improvement and three necessary maintenance works. Thus, the staged renovation has the potential to help increase the number of staged renovations in Denmark. Moreover, to help the house renovations to achieve higher energy efficiency than when are one-off renovated.

Tina Fawcett pointed out that some of the benefits of a renovation over time that the disruption and costs could be spread over time. By creating the staged renovation methodology and applying on a study case, it was possible to evaluate whether spreading the disruption and costs was a real benefit. The evaluation showed that spread the cost over time is a benefit. The extensive renovation could be divided into many smaller stages, paid by reasonable annual savings to perform a extensive renovation that achieved high energy consumption, implemented wished renovations and reformed necessary renovations for 20 years. However, spreading the disruption over time showed not to be a real benefit. That is because, renovation interventions occur more often, disturbing the homeowner many times, which is a disadvantage. Moreover, the level of disturbance is ruled by the renovation measures, and because of the restrictions on the implementation order, high disturbing renovation measures can occur several times during the process of a renovation.

It was also shown from the literature review that home renovations are, by majority, performed to improve aspects of the house other than energy efficiency. A kitchen renovation was implemented in the case study as a functional measure wished by the homeowner to represent such a desire. Moreover, three maintenance work was included as heating system maintenance, flooring replacement, and roof finishing replacement. Even though this works contributed substantially to the total budget, it was possible to achieve the set-out goal of Renovation Class 1. However, it is reasonable to assume that a homeowner would desire more than one functional improvement over 20 years. Therefore, as a future work more non-EEMs could be applied to the renovation process in the case building to identify the point where non-EEMs start to restrict the implementation of energy improvements, which means that the total time length and cost of the stage renovation would reach its limits restricting Renovation Class 1 to be achieved.

The Life Cycle Cost analysis was performed using the "full cost" approach. As suggested by the approach, house costs that were the same for the staged renovation and the reference case should be omitted. That included electricity from lighting and appliances. Due to this, the recurrent annual values have negative value at future, in the last years of the analysis. That is because of the production of electricity from the PV cells that are accounted in the calculation, and also high price increase of electricity. In actuality, appliances consume the electricity provided by the PV cells and the energy consumption of the house is not negative. Therefore, even though that the financial analysis is technically correct, this can be confusing for the homeowner and may lead to a miss understanding of the results.

Further comparison of the life cycle cost of a staged renovation and one-off renovation, not included in the methodology, considered scenarios where the house is sold before 30 years. In the one-off renovation scenario, a bank loan is taken to pay the house renovation performed in the first year. Therefore, when the house is sold the remaining amount of the loan must be fully paid, which becomes a deficit in the sale price of the house. However, even though that the house is not fully renovated, that does not happen in the staged renovation since there is no loan. Therefore, the staged renovation becomes more financially beneficial. This analysis showed to be more comprehensive than the analysis suggested by the methodology. Therefore, it should be used when comparing building renovations performed over time.

Indoor climate was evaluated with dynamic simulations that showed both improvements and declines. The survey 3.1 showed that insulating the envelope would only have positive benefits for thermal comfort, but dynamic simulation showed, that this is only true for the heating period, for the summer season it will increase the hours of overheating as it can be seen in table 4.33. While making the building more airtight would decrease the heating energy required, but at the same time it would make indoor air quality poorer because the ventilation system is not yet installed, to compensate the reduced neutral air change rate through infiltration. Conditions of air quality were improved only after the mechanical ventilation was installed, which was only after stage 6 — that meaning several years of air quality worse than planned to be, which is not acceptable. These results showed that it is necessary to use dynamic simulations to assess the IEQ of the house after each stage and improve upon the staging order if necessary. Moreover, the co-benefits table 3.1 was used to evaluate the renovation measures during the step of creating an extensive one-off renovation. This evaluation represented the co-benefits given by the renovation measure at the end of the process. However, it is only mentioned the co-benefits delivered by the measures after each stage varies, which means that for staged renovation, the co-benefits were not fully assessed. Thus, it is suggested to include on the staging process a re-evaluation of the co-benefits after the stage packages are created. That is to avoid incorrect implementation order

5.2 Discussion of the Methodology

The stage renovation methodology was created with a holistic approach, that includes aesthetic, functional, technical, and economic considerations. This way, drivers of home renovations, as presented by the literature review, are addressed by the methodology, which motivates the homeowners to initiate the renovation process of their houses.

The holistic approach also ensured that lock-out does not happen, due to the high energy reduction goal (Renovation Class 1). That means, having renovation measures that would not prevent the house to achieve high energy efficiency in the future if the homeowner would like to. For example, if the homeowner does not want to invest his/her money in having low energy consumption at the beginning of the process, the measures applied will not refrain him from doing it afterward.

Combining maintenance works with energy efficiency measures showed to be efficient, which was presented by the literature review as one of the best ways to engage homeowners in energy renovations. Moreover, the methodology presents to the homeowner an assessment of the necessary maintenance for the next 20 years (including their costs), as the "Anyways" reference case. That gives a clear and comprehensive overview of the works and costs involved with not improving the house in the long term and thereby has the potential to overcome the barriers for lack of information.

On the other hand, the estimation of the remaining lifetime of the building components showed to be also a weak point in the staged renovation methodology since predicting the remaining lifetime for long periods is not straightforward and can lead to incorrect assumptions that can affect the original planning. For example, if some building component happens to have a shorter lifetime, for unexpected reasons, the original plan of the stage renovation will need to be changed.

The process of staging a one-off renovation (step 4 of the methodology) showed to be efficient in selecting the implementation order according to a chosen priority of benefit or co-benefit. The implementation order can be quite flexible with the implementation sequence allowing homeowners to invest their money in house improvements that they consider as a priority and possibly engage them in energy renovations throughout the process.

The staged renovation methodology showed that it is possible to implement an extensive renovation over time with costs that, according to the surveys, homeowners are used to spending. By that, the homeowners have an option to renovate their house to a high energy efficiency level, without spending a large sum of money at once, which they would otherwise refrain from.

The financial evaluation included in the methodology showed to overcome barriers to information and finances. The life cycle cost analysis gives a long-term perspective of the staged renovation and the economics of the house, even if the homeowner decides not the perform the renovation. It can also be assumed to be a great tool to convince homeowners to engage in the energy renovation process. The reference case of “Anyways” presented along with the staged renovation scenario demonstrates that, in the long term, the costs of maintaining the house in its original conditions can be close or even higher than having an improved house. Moreover, the “Energy Priority” reference case demonstrates the financial benefits of implementing EEMs, which can convince homeowners to implement EEMs sooner than they were willing to at the beginning of the process; or to convince them to keep renovating after their desired improvements are implemented.

However, there are some improvements to be done to the financial evaluation. The life cycle cost of the renovations is very sensitive to considerations of the present and future economic situations. Therefore, the LCC analysis should be presented as a range from the best to the worst economic scenario. The financial comparison between staged renovation and one-off renovation showed to clarify the differences of choosing one approach or another. Since many projects of energy renovation are presented as one-off renovation, this comparison should be included in the methodology to be presented to the homeowner. The concept of considering the house to be sold before 30 years showed to give light to the benefits of stage renovation. Therefore, it should be further developed and also be included in step 5 of the methodology. Finally, to better present the results to the homeowner, it is suggested to include the energy consumption of appliances and lighting. The "Full cost approach" of the LCC analysis suggests not to include it to simplify the calculation. However, if they are not included, it may be difficult by the homeowner to understand the full extent of the results presented.

The evaluation of the co-benefits for the staged renovation showed to be a crucial tool in the implementation order of the renovations. However, the co-benefits analysis should be adapted to be used in the staged renovation. It is suggested that Thermal Comfort typology should be divided into two categories, "Thermal Comfort for the heating season" and "Thermal Comfort for the cooling season". By doing this it becomes more clear the impact of each renovation measure for both seasons, and mistakes on thermal comfort evaluation are avoided.

6 Conclusion

Previous works presented house renovation implemented over time with a holistic approach manner to overcome common barriers that slow down the number of energy renovations in single-family houses in Denmark, and Europe. This project intended to give one step further and create a methodology of renovating houses that combine theses characteristic to investigate what are the specific characteristics that an overtime renovation with a holistic approach should have to be more appealing for homeowners and contribute to their adoption to energy renovation. For this reason, the research question is *How does a holistic staged renovation need to be built up so that homeowners would consider it beneficial and appealing?*. To find the answer for the question first a methodology for staged renovation was created and afterward tested on a case building.

The staged renovation methodology was created as a complementary methodology to current methods of designing one-off renovation. The holistic approach of the methodology included other considerations than energy reduction and efficient solution for the renovation. The staged renovation can have a flexible implementation sequence that best suits the homeowner priorities, respecting the restrictions on the implementation order and trying to combine with necessary maintenance. Moreover, the stage packages of the renovation stages are created with the intention to have a total cost that the average of the homeowner is used to spend in house renovation. The renovation has a high potential to energy improve the house and avoid future lock-outs. For that, the methodology considered to first plan the renovation as one-off renovation considering renovation for 20 years and aims to achieve high energy efficiency (Be18 Renovation Class 1), to avoid lock-outs, and then divide the renovation into stages implemented over time. The methodology includes a life cycle evaluation of the staged renovation that intends to inform the homeowner the homeowner the financial considerations of energy improve the house.

The creation of the methodology was based in researches and Danish surveys that did not directly address the issues relevant for stage renovation. For this reason, the assumptions to create the methodology are arguable. Therefore, further investigation and specific surveys should be carried out to substantiate the assumptions used to create the methodology.

The staged renovation methodology was successfully applied to a typical three-bedroom Danish single-family house from the 60s and 70s. The renovation was designed to achieve energy efficiency Renovation Class 1, which shown to be to the case building an energy reduction of 76%. The renovation included assumed functional renovation and the necessary maintenance for 20 years. The cost of the renovation was 880,00 DKK and showed to be a reasonable price for a renovation of this extent.

Given the similarities of the Danish single-family houses from the case building age and the cost-efficient considerations of the renovation measures, it can be assumed, within the boundaries of the project, that the methodology is applicable for Danish single-family houses from 1960-1979.

The application of the methodology in the case building showed that is possible to plan a house renovation over time with a holistic approach to a homeowner with a relatively low household income and achieve high energy efficiency (Renovation Class 1 energy frame) with reasonable yearly savings (15% of the household income). That means that the methodology can be considered suitable for homeowners with a household income of 300,000 and above.

Bibliography

[1] European commissioning, retrieved from website.

[2] Statistics denmark (http://www.statbank.dk).

[3] Bolius boligejerundersøgelse. Technical report, Bolius Boligejernes in collaboration with TNS Gallup, 2014-2018.

[4] Ashrae. 19 March 2018.

[5] M. G. Bjørneboe. *Method for planning extensive energy renovation of detached single-family houses*. PhD thesis, Danmarks Tekniske Universitet, 2017.

[6] M. G. Bjørneboe, S. Svendsen, and A. Heller. Initiatives for the energy renovation of single-family houses in denmark evaluated on the basis of barriers and motivators. *Energy & Buildings*, 30.12.2017.

[7] B. Boligejeranalyse. Bolius boligejeranalyse 2017. Maj 2017.

[8] BYG-ERFA. Risiko ved udeluftventilerede krybekaeldre, 2009.

[9] T. H. Christensen, K. Gram-Hanssen, M. de Best-Waldhober, and A. Adjei. Energy retrofits of danish homes: is the energy performance certificate useful? *Routledge*, 25 Apr 2014.

[10] C. W. L. C. G. Chryssochoidis. Why do people decide to renovate their homes to improve energy efficiency? June 2014.

[11] T. E. COMMISSION. Regulations. of 16 January 2012.

[12] M. de Almeida, M. Ferreira, A. Rodrigues, and et. al. Methodology for cost-effective energy and carbon emissions optimization in building renovation (annex 56). Technical report, International Energy Agency, 2017.

[13] T. Fawcett. Exploring the time dimension of low carbon retrofit: owner-occupied housing. *Building Research & Information*, 2013.

[14] P. Femenías, K. Mjornell, and L. Thuvander. Rethinking deep renovation: The perspective of rental housing in sweden. *Energy & Buildings*, 30 August 2016.

[15] Ferreira, A. M., and R. A. Impact of co-benefits on the assessment of energy related building renovation with a nearly-zero energy target. *Energy and Buildings 152, 587–601*, 2017.

[16] C. Focus. What's in it for me - using the benefits of energy efficiency to overcome the barriers, 2012.

[17] C. V. e. a. Forsingdal. Build up skills denmark national roadmap. Technical report, BUILD UP Skills, May 2013.

[18] J. Friege and E. Chappin. Modelling decisions on energy-efficient renovations. *Energy & Buildings*, 2014.

[19] H. Fyhn and N. Baron. The nature of decision making in the practice of dwelling: A practice theoretical approach to understanding maintenance and retrofitting of homes in the context of climate change. *Society & Natural Resources*, 30.12.2017.

[20] N. Galiotto. *The Integrated Renovation Process A Holistic Methodology Towards Nearly Zero Energy Buildings*. PhD thesis, May 2014.

[21] N. Galiotto, P. P. Heiselberg, , and M.-A. Knudstrup. Integrated renovation process: Overcoming barriers to sustainable renovation. 2016.

[22] R. Galvin. Why german homeowners are reluctant to retrofit. *Building Research & Information*, 2014.

[23] Gram-Hanssen. Existing buildings – users, renovations and energy policy. *Renewable Energy, 61, 136–140. http://doi.org/10.1016/j.renene.2013.05.004*, 2014.

[24] K. Gram-Hanssen. Retrofitting owner-occupied housing: remember the people. *Building Research & Information*, 2014.

[25] K. Gram-Hanssen. Existing buildings e users, renovations and energy policy. *Energy & Buildings*, 25 May 2013.

[26] K. Gram-Hanssen, F. Bartiaux, O. Jensen, and M. Cantaert. Do homeowners use energy labels? a comparison between denmark and belgium,. *Energy Policy 35*, 2007.

[27] K. Gram-Hanssen, J. O. Jensen, and F. Friis. Local strategies to promote energy retrofitting of single-family houses. *Cross Mark*, 19 March 2018.

[28] InterNACHI. Standard estimated life expectancy chart for homes, extracted from website, 2018.

[29] E. P. Judson and C. Maller. Housing renovations and energy efficiency: insights from homeowners' practices. *Building Research & Information*, 2014.

[30] N. K., H. Amecke, A. Novikova, and K. Stelmakh. Thermal efficiency retrofit of residential buildings: The german experience. 2011.

[31] Karvonen. Towards systemic domestic retrofit: a social practices approach. *Building Research and Information, 41*, 2013.

[32] Klöckner. Psychological determinants of intentions to upgrade the energy standards of privately-owned buildings: results from a norwegian survey. *J. Sustain. Build. Technol. Urb. Dev. 5*, 2014.

[33] C. A. Klöckner and A. Nayum. Specific barriers and drivers in different stages of decision-making about energy efficiency upgrades in private homes. *Frontiers in Psychology*, 08 September 2016.

[34] H. Knudsen and O. Jensen. Indoor climate perceived as improved after energy retrofitting of single-family houses. *Scopus*, 2014.

[35] U. C. O. B. I. T. London. Behaviour change and energy use. 2011.

[36] D. Loveday and K. Vadodaria. Project calebre, consumer appealing low energy technologies for building retrofitting. 2014.

[37] R. M. Quality in architecture: A disputed concept. considering research: Reflection upon current themes in architectural research. Technical report, Lawrence Technological University, 2011.

[38] K. Mahapatra, L. Gustavsson, T. H. and; Synnøve Aabrekk, S. Svendsen, L. Vanhoutteghem, S. Paiho, and M. Ala-Juusela. Business models for full service energy renovation of single family houses in nordic countries. *Applied Energy*, 2013, December.

[39] K. Mahapatra, L. Gustavsson, T. Haavik, S. Aabrekk, S. Svendsen, L. Vanhoutteghem, and M. A.-J. S. Paiho. Business models for full service energy renovation of single-family houses in nordic countries. *Appl. Energy*, 2014.

[40] A. e. a. Mortensen. *Energy renovation of Danish single-family houses Economy, barrier, motivation and limit.* PhD thesis, DCE Technical reports, No. 190, 2015.

[41] M. Pomianowski, Y. I. Antonov, and P. Heiselberg. Development of energy renovation packages for danish residential single family houses - "parcel houses". Technical Report DCE Technical Report No 244, Aalborg University, Department of Civil Engineering, 2018.

[42] M. Pomianowski, Y. I. Antonov, and P. Heiselberg. Development of energy renovation packages for danish residential single family houses - "parcel houses". 2018.

[43] S. S. Energy-led domestic retrofit: impact of the intervention sequence. *Building Research and Information, 44(1)*, 08 January 2015,.

[44] SBi. Renovation of danish parcel house - existing knowledge and new experiences (in danish). Technical report, SBi, Statens Byggeforskningsinstitut, Aalborg Universitet, 2015.

[45] SBi. Renovation of danish parcel house - existing knowledge and new experiences (in danish). Technical report, SBi, Statens Byggeforskningsinstitut, Aalborg Universitet, 2015.

[46] M. Sunikka-Blank and R. Galvin. Introducing the prebound effect: the gap between performance and actual energy consumption. *Building Research & Information*, 2012.

[47] E. S. Trust. Trigger points: a convenient truth promoting energy efficiency in the home. 2014.

[48] P. Tuominen, K. Klobut, A. Tolman, A. Adjei, and M. de Best-Waldhober. Energy savings potential in buildings and overcoming market barriers in member states of the european union. *Energy Build. 51*, 2012.

[49] P. Tuominen, K. Klobut, A. Tolman, and A. A. M. Energy savings potential in buildings and overcoming market barriers in member states of the european union,. *Energy Build. 51*, 2012.

[50] Urge-Vorsatz, Petrichenko, and Butcher. How far can buildings take us in solving climate change? a novel approach to building energy and related emission forecasting. 2011.

[51] L. Vanhoutteghem, H. Tommerup, S. Svendsen, K. Mahapatra, L. Gustavsson, T. Haavik, S. Aabrekk, S. Paiho, and M. Ala-juusela. Analysis of promising sustainable renovation concepts,. 2010.

[52] L. Vanhoutteghem, H. Tommerup, S. Svendsen, K. Mahapatra, L. Gustavsson, T. Haavik, S. Aabrekk, S. Paiho, and M. Ala-Juusela. Deliverable 1.2 analysis of promising sustainable renovation concepts, 2010.

[53] L. Vlasova and K. Gram-Hanssen. Incorporating inhabitants' everyday practices into domestic retrofits, building research & information. *Routledge*, 29 Apr 2014.

[54] C. Watts, M. Jentsch, and P. James. Evaluation of domestic energy performance certificates in use. *Build. Res. Inf*, 2011.

[55] J. Weiss, E. Dunkelberg, and T. Vogelpohl. Improving policy instruments to better tap into homeowner refurbishment potential: lessons learned from a case study in germany. *Energy Policy 44*, 2012.

[56] Wilson and Dowlatabadi. Models of decision-making and residential energy use. *Annu.Rev.Environ.Resour, 32:169-203*, 2007.

[57] C. Wilson, L. Crane, and G. Chryssochoidis. Why do homeowners renovate energy efficiently, contrasting perspectives and implications for policy. *Energy Res. Soc. Sci.*, 2015.

[58] C. Wilson, L. Crane, and G. Chryssochoidis. Why do homeowners renovate energy efficiently? contrasting perspectives and implications for policy. *Energy & Buildings*, 24 March 2015.

[59] www.iha.dk/HomeAutomation. Deliverable 1.2 analysis of promising sustainable renovation concepts.

[60] S. Zundel and I. Stieß. Beyond profitability of energy-saving measures-attitudes towards energy saving,. *Consum. Policy. 34*, 2011.

[61] D. Ürge Vorsatz, A. Novikova, and M. Sharmina. Counting good: Quantifying the co-benefits of improved efficiency in buildings. 2014.

.1 Appendix 1 - Heat transmittance calculations

.1.1 Study case house - current components

External wall	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Gypsum Plastering	0.013	0.4	0.033
	Concrete Block (Medium)	0.11	0.51	0.216
	Rockwool - unbounded	0.07	0.047	1.489
	Brick	0.108	0.84	0.129
	Extenal resistance			0.040
	Assembly thickness (m) =	0.301		2.036
			U' (W/m2.K)	0.491
	DS418 p. 59		Ug - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.491**

Ceiling	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, 6.2.1	Internal resistance			0.100
	Plasterboard	0.0125	0.25	0.050
	Plasterboard	0.0125	0.25	0.050
	Inhomogeneous layer:	0.100	0.059	1.682
	Hard wood	0.015	0.130	
	Rockwool	0.085	0.047	
	Inhomogeneous layer:	0.100	0.162	0.619
	Wood - pine, pitch pine Dry	0.015	0.170	
	2010 NCM Air layer unventilated-roof	0.085	0.16	
DS418, pg. 25,	Extenal resistance			0.040
table 6.5.1	Assembly thickness (m) =	0.125		2.541
			U' (W/m2.K)	0.394
	DS418 p. 59, table A.1		; - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.394**
			U-value DB	0.441

Roof	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Rafter (wood)			n/a
	Battens (wood)			n/a
	Internal resistance (DS 418 pg 23, 6.2.1)			0.100
	Asphalt / Asbestos roofing	0.005	0.370	0.014
	Inhomogeneous layer:	0.030	0.162	0.185
	Wood - pine, pitch pine Dry	0.006	0.170	
	2010 NCM Air layer unventilated-roof	0.024	0.16	
	Extenal resistance (DS 418 pg 23, 6.2.1)			0.040
	Assembly thickness (m) =	0.065		0.339
			U' (W/m2.K)	2.952
	DS418 p. 59, table A.1		; - air-cracks (W/m2.K)	0.040
			U total (W/m2K)	**2.992**
			U-value DB	2.827

Figure .1: U value Existing

Wooden strip	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Gypsum Plastering	0.013	0.4	0.033
	Gas Concrete	0.11	0.59	0.186
	Rockwool	0.07	0.047	1.489
	Wooden clapboard	0.0127	0.18	0.071
	Extenal resistance			0.040
	Assembly thickness (m) =	0.206		1.949
			U' (W/m2.K)	0.513
	DS418 p. 59		; - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.513**
			U-value DB	

Internal wall	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Gypsum Plastering	0.005	0.72	0.007
	Concrete Block (Lightweight)	0.1	0.19	0.526
	Gypsum Plastering	0.005	0.72	0.007
	Extenal resistance			0.040
	Assembly thickness (m) =	0.110		0.710
			U' (W/m2.K)	1.408
	DS418 p. 59		; - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**1.408**
			U-value DB	1.250

Floor (suspended)	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, table	Internal resistance			0.170
	Timber flooring	0.02	0.12	0.167
	Inhomogeneous layer:	0.050	0.047	1.059
	wooden battons	0.005	0.130	
	Rockwool	0.045	0.038	
DS 418 pg 23, table	Extenal resistance			0.040
	Assembly thickness (m) =	0.070		1.436
			U' (W/m2.K)	0.696
	DS418 p. 59		; - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.696**
			U-value DB	0.679

Figure .2: U value Existing

Floor (ground)	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, table	Internal resistance			0.170
	Ceramic glazer	0.02	1.4	0.014
	Cement/plaster/mortar - cement plaster	0.010	0.72	0.014
	Cast concrete	0.040	1.130	0.035
	Cast concrete	0.040	1.130	0.035
	Cast concrete (lightweight)	0.200	0.380	0.526
DS418 pg 37, table	Extenal resistance			1.500
	Assembly thickness (m) =	0.260		2.295
			U' (W/m2.K)	0.436
	DS418 p. 59		; - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.436**
			U-value DB	1.197

External wall (light	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Plaster 1	0.013	0.25	0.052
	Plaster 2	0.012	0.25	0.048
	Inhomogeneous layer:	0.050	0.051	0.977
	Hard wood	0.005	0.170	
	Rockwool	0.045	0.038	
	Wooden cladding	0.015	0.12	0.125
	Extenal resistance			0.040
	Assembly thickness (m) =	0.090		1.372
			U' (W/m2.K)	0.729
	DS418 p. 59		; - air-cracks (W/m2.K)	0.010
			U total (W/m2K)	**0.74**
			U-value DB	0.803

Figure .3: U value Existing

.1.2 Renovated components - BR18 minimum

External wall	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Gypsum Plastering	0.013	0.400	0.033
	Concrete Block (Medium)	0.110	0.510	0.216
	Rockwool - unbounded	0.190	0.036	5.278
	Brick	0.020	0.840	0.024
	Extenal resistance			0.040
	Assembly thickness (m) =	0.333		5.720
			U' (W/m2.K)	0.175
	DS418 p. 59		Ug - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.175**
			U-value DB	0.491

Ceiling	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.100
	Plasterboard	0.013	0.250	0.050
	Plasterboard	0.013	0.250	0.050
	Construction wood	0.013	0.180	0.071
	Vapour barrier			
	Inhomogeneous layer:	0.100	0.059	1.682
	Hard wood	0.015	0.130	
	Rockwool	0.085	0.047	
	Blown-in insulation	**0.300**	0.040	7.500
	Extenal resistance			0.040
	Assembly thickness (m) =	0.138		9.493
			U' (W/m2.K)	0.105
	DS418 p. 59, table A.1		Ug - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.105**
			U-value DB	0.441

Roof	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Rafter (wood)			n/a
	Battens (wood)			n/a
	Internal resistance			0.100
	Chosen roof covering	0.005	0.370	0.014
	Inhomogeneous layer:	0.030	0.162	0.185
	Wood - pine, pitch pine Dry	0.006	0.170	
	2010 NCM Air layer unventilated-roof	0.024	0.160	
	Extenal resistance			0.040
	Assembly thickness (m) =	0.065		0.339
			U' (W/m2.K)	2.952
	DS418 p. 59, table A.1		Ug - air-cracks (W/m2.K)	0.040
			U total (W/m2K)	**2.992**
			U-value DB	2.827

Figure .4: U value BR18

~~Wooden strip~~	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
changed to: External	Internal resistance			0.130
	Gypsum Plastering	0.013	0.400	0.033
	Gas Concrete	0.110	0.590	0.186
	Rockwool	0.070	0.047	1.489
	Wooden clapboard	0.013	0.180	0.071
	Extenal resistance			0.040
	Assembly thickness (m) =	0.206		1.949
			U' (W/m2.K)	0.513
	DS418 p. 59		Ug - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.513**
			U-value DB	

Floor (Crawl space)	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
Changed to ground	Internal resistance			0.170
supported floor	Timber flooring	0.020	0.120	0.167
	Inhomogeneous layer:	0.125	0.047	2.648
	wooden battons	0.013	0.130	
	Rockwool	0.113	0.038	
	Rockwool	0.025	0.038	0.658
	Extenal resistance			0.040
	Assembly thickness (m) =	0.145		3.683
			U' (W/m2.K)	0.272
	DS418 p. 59		Ug - air-cracks (W/m2.K)	0.000
			U total (W/m2K)	**0.272**
			U-value DB	

Floor - Ground sup.	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, table 6.:	Internal resistance			0.17
	Ceramic tiles + glue	0.03	1	0.030
	Concrete + reinforcement	0.1	1.2	0.083
	EPS insulation	**0.25**	0.035	7.143
	Gravel	0.2	0.52	0.385
DS418 pg 37, table 6.9	Extenal resistance			1.5
	Assembly thickness (m) =	0.271		9.311
			U' (W/m2.K)	0.107
		DS418 p. 59	Ug - air-cracks (W/m2.K)	0
			U total (W/m2K)	**0.107**

Windows			
	Eref >	-17.000	
	U-value:	1.100	
	g-value	0.420	(at least)

$$E_{ref} = 196.4 \times g_w - 90.36 \times U_w.$$

Figure .5: U value BR18

.1.3 Renovated components - Higher standard

External wall	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
	Internal resistance			0.130
	Gypsum Plastering	0.013	0.400	0.033
	Gas Concrete	0.110	0.590	0.186
	EPS insulation	**0.400**	0.035	11.429
	Brick Tiles	**0.020**	0.840	0.024
	Extenal resistance			0.040
	Assembly thickness (m) =	**0.543**		11.841
			U' (W/m2.K)	0.084
	DS418 p. 59		Jg - air-cracks (W/m2.K)	0
			U total (W/m2K)	**0.084**

Ceiling	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, 6.2.1	Internal resistance			0.13
	Plasterboard	0.0125	0.25	0.050
	Plasterboard	0.0125	0.25	0.050
	Wooden cladding	0.02	0.09	0.222
	Inhomogeneous layer:	0.1	0.05345	1.871
	Hard wood	0.015	0.09	
	Rockwool	0.085	0.047	
DS418, pg. 25, table 6	Extenal resistance			0.04
	Assembly thickness (m) =	**0.545**		2.363
	DS418 p. 59, table A.1		U' (W/m2.K)	0.423
			Jg - air-cracks (W/m2.K)	0
			U total (W/m2K)	**0.423**

Roof	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, 6.2.1	Internal resistance			0.13
page 186	**Inhomogeneous layer:**	0.15	0.0441	3.401
D88	Hard wood	0.0225	0.09	
	Rockwool	0.1275	0.036	
	OSB layer	**0.018**	**0.14**	**0.129**
	Vapour Barrier	**0**	**0**	**0.000**
	Inhomogeneous layer:	**0.36**	**0.0441**	**8.163**
	Hard wood	**0.054**	**0.090**	
	Rockwool	**0.306**	**0.036**	
	OSB layer	**0.018**	**0.14**	**0.129**
	PE-foil, vapour permeable	**0**	**0**	**0.000**
	Batten, counter batten	**0.05**		**0.000**
	Roofing tiles of fibre cement			**0.000**
	Extenal resistance			0.04
	Assembly thickness (m) =	**0.596**		11.992
DS418, pg. 25, table 6	DS418 p. 59, table A.1		U' (W/m2.K)	0.083
			Jg - air-cracks (W/m2.K)	0
			U total (W/m2K)	**0.083**

Figure .6: U value Ambitious

Ceiling hatch to attic		U-value
	Assumed to be the same as the ceiling U-value, after its improvement	0.423

Insulation of the floor above crawl space: max 150mm to avoid moisture issues [M&Y report]. Vapour barrier underneath f
Ventilation of crawl space is required to avoid condensation and moisture damage. Additional ventilation bore holes in foo
Height requirement for crawl space can limit insulation thickne

Floor - Ground sup.	Layer	Thickness	Thermal conductivity λ (W/mK)	R = d/λ(thermal resistance) m2K/W
DS 418 pg 23, table 6.	Internal resistance			0.17
	Ceramic tiles + glue	0.03	1	0.030
	Concrete + floor heating + reinforcemer	0.15	1.2	0.125
	EPS insulation	**0.6**	0.035	17.143
	Concrete sub-floor	0.05	0.5	0.100
				0
				0.000
DS418 pg 37, table 6.9	Extenal resistance			1.5
	Assembly thickness (m) =	0.271		19.06785714
			U' (W/m2.K)	0.052
			DS418 p. 59 Jg - air-cracks (W/m2.K)	0
			U total (W/m2K)	**0.052**

Windows

	Eref >	-17.000		
U-value:		0.790		
g-value		0.530		
$E_{ref} = 196.4 \times g_w - 90.36 \times U_w$.		#REF!	(at least)	54.38

Case Nr.	Window type	U_{window} [W/m^2.K]	Solar Transmittance g	Light Transmittance	Energy Gain - E_{ref} [kWh/m^2/year]
5	Low-Energy, 3-layers glass	0,79	0,53	0,74	32,71
6	Standard, 2-layers glass	1,29	0,64	0,82	9,13
7	Standard, 2 layers glass	1,32	0,63	0,80	4,46

Figure .7: U value Ambitious

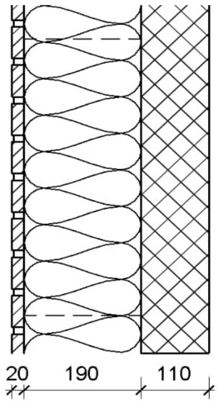
.2 Appendix 2 - Renovation proposals

.2.1 Description of the renovation measures

Renovation of component - BR18 minimum standard

Exterior wall

Drawing/sketch



Specificiation	
Inside	
0.013 Plaster finish	Existing
0.110 Gas concrete blocks	Existing
0.190 Mineral wool unbonded	New
0.020 Brick tiles	New
Outside	

Renovation	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Removal/Demolition				
Removal of Insulation - 70 mm	104.85	m²	13.20	1,384.02
Demolition of brick façade - 108 mm	104.85	m²	74.42	7,802.94
Demolished material removal - transportation to final destination (10 km average distance)	22.65	m²	207.22	4,693.04
Lightweight wall next to windows	7.00	m²	207.22	1,450.54
Construction				
Rockwool with 190mm - insulation thickness 380 mm	104.85	m²	169.92	17,816.11
Brick tiles - 20 mm	104.85	m²	931.58	97,676.16

Necessary maintenance, otherwise	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Changing mortar between bricks	104.85	m²	773.10	81,059.54

Calculations	
Energy Savings [kWh/m².year]	27.4
Energy Savings [kWh/year]	3463.36
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	101,324
Gross Energy Renovation cost [DKK]	163,529
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.64
CCE /wo Maintenance [DKK/kWh]	0.43
CCE /w Maintenance [DKK/kWh]	1.13

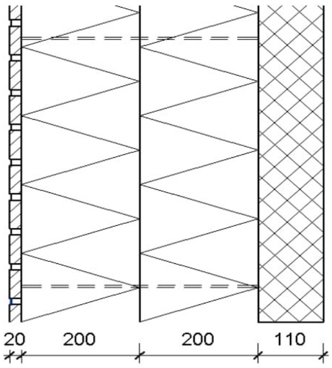
Characteristics	
U-value (incl. surface R)	0.175

Figure .8: BR18 standard, Renovation of the external wall

Renovation of component - Higher standard

Exterior wall

Drawing/sketch



Specificiation	
Inside	
0.013 Plaster finish	Existing
0.110 Gas concrete blocks	Existing
0.400 EPS insulation boards	New
0.020 Brick tiles	New
Outside	

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal/Demolition				
Removal of Insulation - 70 mm	104.85	m²	13.20	1,384.02
Demolition of brick façade - 108 mm	104.85	m²	74.42	7,802.94
Demolished material removal - transportation to final destination (10 km average distance)	22.65	m²	207.22	4,693.04
Lightweight wall next to windows	7.00	m²	207.22	1,450.54
Construction				
200mm EPS100	209.70	m²	160.00	33,552.00
Brick tiles - 20 mm	104.85	m²	931.58	97,676.16

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Changing mortar between bricks	104.85	m²	773.10	81,059.54

Calculations	
Energy Savings [kWh/m².year]	34.7
Energy Savings [kWh/year]	4386.08
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	101,324
Gross Energy Renovation cost [DKK]	183,198
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.72
CCE /wo Maintenance [DKK/kWh]	0.45
CCE /w Maintenance [DKK/kWh]	1.00

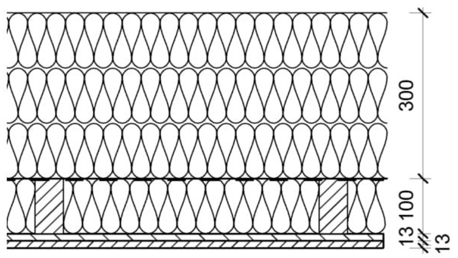
Characteristics	
U-value (incl. surface R)	0.084

Figure .9: Higher standard, Renovation of the external wall

Renovation of component - BR18 minimum standard

Ceiling partition

Drawing/sketch



Specificiation	
Inside	
0.013 Wooden ceiling boarding	Existing
0.013 Wooden plank	Existing
0.001 Vapour barrier	Existing
0.100 Structural ceiling joists	Existing
Insulation between joists	Existing
0.300 Mineral wool batts	New
Unheated space	

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Construction				
Vapour barrier	127.50	m²	28.00	3,570.00
Mineral wool granulate kl.40, blown-in - 300 mm	124.40	m²	325.56	40,499.66

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*

Calculations	
Energy Savings [kWh/m².year]	32.3
Energy Savings [kWh/year]	4082.72
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	55,087
Real interest rate [%]	1.93%
BR18 financial viability [kWh/DKK]	2.22
CCE /wo Maintenance [DKK/kWh]	0.30
CCE /w Maintenance [DKK/kWh]	0.30

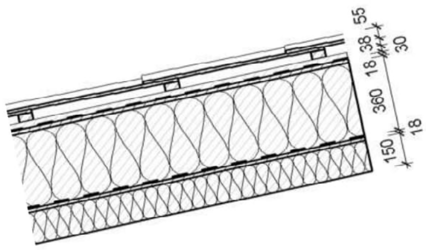
Characteristics	
U-value (incl. surface R)	0.105

Figure .10: BR18 standard, Insulation of the ceiling partition

Renovation of component - Higher standard

Pitched roof

Drawing/sketch



Specificiation	
Unheated space	
0.150 Structural rafters	Existing
Insulation between rafters	New
0.018 OSB	New
0.001 Vapour Barrier	New
0.360 Rafter extensions	New
Insulation between rafters	New
0.018 OSB	New
0.001 Waterproofing PE foil	New
0.030 Counter battens	New
0.038 Battens	New
0.050 Fiber-cement sheets	New
Outside	

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Construction				
OSB board (plywood in Sigma) - 18 mm	150.00	m²	72.00	10,800.00
Vapour barrier	150.00	m²	16.71	2,506.50
Adding extra rafters, 2x 50x180 - 360	539.00	m	188.37	101,531.43
Rockwool insulation (245 mm)	139.80	m²	296.47	41,446.51
Rockwool insulation (120 mm)	139.80	m²	150.15	20,990.97
OSB board (plywood in Sigma) - 18 mm	150.00	m²	72.00	10,800.00

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal				
Removal of Roof cladding (Fibercement sheet)	150.00	m²	196.92	29,538.00
Removal of battens	450.00	m	8.91	4,009.50
Construction				
Wooden battens - 38 x 56 mm	450.00	m	54.26	24,417.00
Fibercement sheet - 0,5 cm thichness	150.00	m²	285.69	42,853.50
Water proof sheet - PE- foil	150.00	m²	27.22	4,083.00

Calculations	
Energy Savings [kWh/m².year]	30.9
Energy Savings [kWh/year]	3905.76
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	131,126
Gross Energy Renovation cost [DKK]	235,094
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.50
CCE /wo Maintenance [DKK/kWh]	1.44
CCE /w Maintenance [DKK/kWh]	2.24

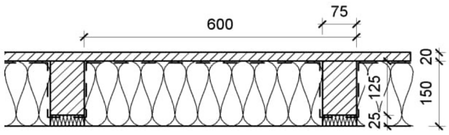
Characteristics	
U-value (incl. surface R)	0.083
Fibrecement - Technical lifetime [years]	25
OSB - Technical lifetime [years]	60

Figure .11: Higher standard, Insulation of the pitched roof

Renovation of component - Best practice

Floor above crawl space

Drawing/sketch



Specificiation	
Inside	
0.020 Floor boards	Existing
0.001 Vapour barrier	New
0.125 Floor joists	Existing
Insulation between joists	New
0.025 Insulation under joists	New
Crawl space	

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal/Demolition				
Insulation removal - 50 mm	124.60	m²	81.00	10,092.60
Construction				
Rockwool insulation - 150 mm	124.60	m²	396.04	49,346.58

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal/Demolition				
Removal of existing floor covering	124.60	m²	85.00	10,591.00
Demolished material removal - transportation to final destination (10 km average distance)	4.49	m³	53.50	240.22
Construction				
New floor covering - Wooden planks on joists	124.60	m²	352.47	43,917.76

Calculations	
Energy Savings [kWh/m².year]	25.1
Energy Savings [kWh/year]	3172.64
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	68,436
Gross Energy Renovation cost [DKK]	74,299
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	1.28
CCE /wo Maintenance [DKK/kWh]	0.56
CCE /w Maintenance [DKK/kWh]	1.07

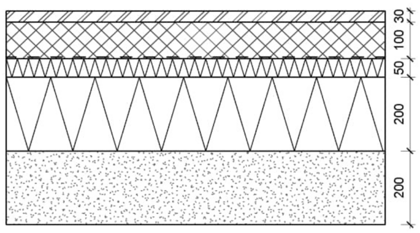
Characteristics	
U-value (incl. surface R)	0.27
Fibrecement - Technical lifetime [years]	25
OSB - Technical lifetime [years]	60

Figure .12: BR18 standard, Insulation of the floor above the crawl space

Renovation of component - BR18 minimum standard

Bathroom floor

Drawing/sketch



Specificiation	
Inside	
0.030 Tiles and glue	New
0.100 Concrete screed	New
0.001 Vapour barrier (PE foil)	New
0.050 EPS insulation	New
0.200 EPS insulation	New
0.200 Gravel capillary breaking layer	New
Soil	

Renovation	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Removal/Demolition				
Demolition of existing floor	5.75	m²	102.22	587.77
Removing insulation	5.75	m²	81	465.75
Hand excavation	2.30	m³	630.81	1,450.86
Demolished material removal - transportation to final destination	2.47	m³	53.5	131.89
Construction				
Gravel capillary breaking layer - 200 mm	5.75	m²	121.51	698.68
Insulation EPS80 - 200 mm	5.75	m²	229.68	1,320.66
Insulation EPS80 - 50 mm	5.75	m²	87.35	502.26
Concrete - 100 mm - 12.46 m3	0.58	m³	1721.07	989.62
PE foil	5.75	m²	16.71	96.08
Bathroom floor ceramic tiles - 20 mm	5.75	m²	1839.95	10,579.71

Necessary maintenance, otherwise	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Removal/Demolition				
Linoleum removal	5.75	m²	59.00	339.25
Demolished material removal - transportation to final destination	0.07	m³	53.50	3.69
Construction				
Linoleum 2.5 mm including surface treatment	5.75	m²	553.00	3,179.75

Calculations	
Energy Savings [kWh/m².year]	4.8
Energy Savings [kWh/year]	606.72
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	4,403
Gross Energy Renovation cost [DKK]	21,029
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.87
CCE /wo Maintenance [DKK/kWh]	0.83
CCE /w Maintenance [DKK/kWh]	1.00

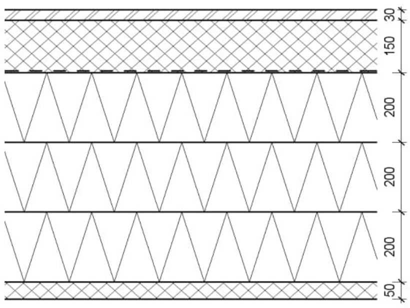
Characteristics	
U-value (incl. surface R)	0.107
Linoleum - Technical lifetime [years]	25

Figure .13: BR18 standard, Reconstruction of the ground supported floor in the wetrooms

Renovation of component - Higher standard

Ground supported floor

Drawing/sketch



Specificiation	
Inside	
0.030 Tiles and glue	New
0.150 Concrete screed /w reinforc.	New
0.001 Vapour barrier (PE foil)	New
0.200 EPS insulation	New
0.200 EPS insulation	New
0.200 EPS insulation	New
0.050 Concrete screed	New
Soil	

Renovation	Quantity	Unit	Unit Cost	Total Cost
Removal/Demolition				
Demolition of existing floor	124.60	m²	102.22	12,736.61
Removing insulation	124.60	m²	81.00	10,092.60
Hand excavation - 200 mm deep	24.92	m³	630.81	15,719.79
Demolished material removal - transportation to final destination (10	35.39	m³	53.50	1,893.17
Construction				
Concrete screed sub-floor - 50 mm	6.23	m³	1,636.76	10,197.01
Insulation EPS80 (200 mm x3) - 600 mm	373.80	m²	211.78	79,163.36
PE-folie, 0,2 mm, Terrain deck	124.60	m²	16.71	2,082.07
Reinforcement 1%	118.85	m²	59.88	7,116.74
Concrete floor - 150 mm	17.83	m³	1,636.76	29,179.34

Necessary maintenance, otherwise	Quantity	Unit	Unit Cost	Total Cost
Removal/Demolition				
Removal of existing floor covering	124.60	m²	81.00	10,092.60
Construction				
New floor covering - Wooden planks	124.60	m²	396.04	49,346.58

Calculations	
Energy Savings [kWh/m².year]	42.1
Energy Savings [kWh/year]	5321.44
Economic lifetime [years]	30
Technical lifetime [years]	60
Gross Maintenance cost [DKK]	74,299
Gross Energy Renovation cost [DKK]	210,226
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.76
CCE /wo Maintenance [DKK/kWh]	0.94
CCE /w Maintenance [DKK/kWh]	1.28

Characteristics	
U-value (incl. surface R)	0.052
Lifetime of Floor tiles [years]	50+

Figure .14: Higher standard, Reconstruction to ground supported floor

Renovation of component - BR18 minimum standard

Windows and Doors

Drawing/sketch

Specificiation	
Inside	
Velfac Ribo Alu 2 layer	New
Outside	
Wooden frame with Alu ext. finishing	
4-24-4 Clear - Argon - Energy Xtra WE Grey	

Renovation	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Removal/Demolition				
Labor cost - Removing window	14.00	hour	401.00	5,614.00
Construction				
Kitchen	1.00	unit	5,664.00	5,664.00
Kitchen	1.00	unit	3,540.00	3,540.00
Door - Entrance	1.00	unit	3,840.00	3,840.00
Toilet	1.00	unit	1,543.00	1,543.00
Bath	1.00	unit	1,543.00	1,543.00
Door - Service room	1.00	unit	3,840.00	3,840.00
Living window	1.00	unit	3,540.00	3,540.00
Living door	1.00	unit	3,840.00	3,840.00
Living window	2.00	unit	5,373.00	10,746.00
Bedroom 3	2.00	unit	3,459.72	6,919.44
Bedroom 2	1.00	unit	3,540.00	3,540.00
Bedroom 1	1.00	unit	3,122.00	3,122.00
Labor cost - windows instalation	33.60	hours	401.00	13,473.60

Necessary maintenance, otherwise	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***

Calculations	
Energy Savings [kWh/m².year]	27.4
Energy Savings [kWh/year]	3463.36
Economic lifetime [years]	30
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	88,456
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	1.17
CCE /wo Maintenance [DKK/kWh]	1.83
CCE /w Maintenance [DKK/kWh]	1.83

Characteristics	
U-value (incl. surface R)	1.21
Solar heat gain coefficient	0.73
Light transmittance	0.82
E_ref [kWh/m².year]	-12.3

Figure .15: BR18 standard, Velfac windows and doors, 2 layers

Renovation of component - Higher standard

Windows and Doors

Drawing/sketch

Specificiation	
Inside	
Velfac Ribo Alu 3 layer	New
Outside	
Wooden frame with Alu ext. finishing	
4-20-4-20-4 Std, Clear, Energy Std WE Grey with Argon	

Renovation	Quantity	Unit	Unit Cost	Total Cost
Removal/Demolition				
Labor cost - Removing window	14.00	hour	401.00	5,614.00
Construction				
Kitchen	1.00	unit	6,132.00	6,132.00
Kitchen	1.00	unit	3,882.00	3,882.00
Door - Entrance	1.00	unit	4,131.00	4,131.00
Toilet	1.00	unit	2,043.00	2,043.00
Bath	1.00	unit	2,043.00	2,043.00
Door - Service room	1.00	unit	4,131.00	4,131.00
Living window	1.00	unit	5,009.00	5,009.00
Living door	1.00	unit	4,131.00	4,131.00
Living window	2.00	unit	5,718.00	11,436.00
Bedroom 3	2.00	unit	3,763.00	7,526.00
Bedroom 2	1.00	unit	4,823.00	4,823.00
Bedroom 1	1.00	unit	3,382.00	3,382.00
Labor cost - windows instalation	33.60	hours	401.00	13,473.60

Necessary maintenance, otherwise	Quantity	Unit	Unit Cost	Total Cost

Calculations	
Energy Savings [kWh/m².year]	34
Energy Savings [kWh/year]	4297.6
Economic lifetime [years]	30
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	97,196
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	1.33
CCE /wo Maintenance [DKK/kWh]	1.62
CCE /w Maintenance [DKK/kWh]	1.62

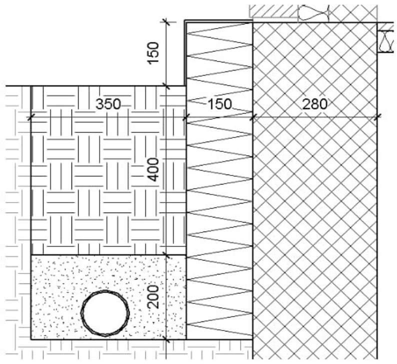
Characteristics	
U-value (incl. surface R)	0.79
Solar heat gain coefficient	0.53
Light transmittance	0.74
E_ref [kWh/m².year]	5.6

Figure .16: Higher standard, Velfac windows and doors, 3 layers

Renovation of component - Best practice

Foundation

Drawing/sketch



Specificiation	
Inside (crawl space)	
0.280 Concrete foundation	Existing
0.150 XPS insulation	New
Gravel around pipe	New
Perimeter Drain	New
Outside	

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal/Demolition				
Excavation - machine, 0.5m wide - 480 mm deep	12.192	m^3	606.37	7,392.86
Excavation - hand, 0.5m wide - 120 mm deep	3.048	m^3	2106.98	6,422.08
Escavation material removal - transportation to final destination	15.24	m^3	53.5	815.34
Construction				
Insulation XPS 0.6m wide	30.48	m^2	320	9,753.60
Alu drip cap (perimeter drain pipe)	50	m	153.11	7,655.50
Gravel capillary breaking layer depth = 200 mm	15	m^2	121.51	1,822.65

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Excavation machine 30 cm deep	6.00	m^3	606.37	3,638.22
Refilling and compressing	6.00	m^3	574.35	3,446.10
Applying bitumen to the footing 450mm heigh	22.50	m^3	119.12	2,680.20

Calculations	
Energy Savings [kWh/m².year]	15.2
Energy Savings [kWh/year]	1921.28
Economic lifetime [years]	30
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	12,206
Gross Energy Renovation cost [DKK]	42,328
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	1.36
CCE /wo Maintenance [DKK/kWh]	1.12
CCE /w Maintenance [DKK/kWh]	1.58

Characteristics	
ψ-value (incl. surface R)	0.31

Figure .17: Insulation of the exterior side of the foundation

Renovation of component - BR18 minimum standard

Heat source and system components

Drawing/sketch

Specification	
Substation containing:	New
Heat exchanger (for DH)	New
Ciculation pump (heating)	New
Expansion tank	New
Pressure regulation valves	New
Hot water tank 100l	New
Temp. and operation control panel	New
Heat and DHW distribution pipes	Existing
Radiators	Existing
Thermostatic valves	New
District Heating Connection	New

Renovation	Quantity	Unit	Unit Cost	Total Cost
Removal				
Removal of the boiler	1.00	unit	421.13	421.13
Construction				
Substation - District heating substation for indirect heating with primary connected tank for domestic hot water preparation and with thermostatic or electronic control. - Termix BVX T/E 1-1 with cover and ECL Comfort 110*	1.00	unit	14,920.00	14,920.00
Labor cost - instalation of substation	4.00	hour	455.00	1,820.00
District Heating				
Connection fee	1.00	unit	14,900.00	14,900.00
Conduction in the footing	1.00	unit	-	-
Connection pipe (10m)	1.00	unit	10,370.00	10,370.00
Meter assembly and test	1.00	unit	-	-
Main consumption meter 1.5 m3/h	1.00	unit	2,729.66	2,729.66

Necessary maintenance, otherwise	Quantity	Unit	Unit Cost	Total Cost
Thermostatic valves	11.00	unit	435.86	4,794.46

Calculations	
Primary Energy Savings [kWh/m².year]	54.4
Primary Energy Savings [kWh/year]	6876.16
Economic lifetime [years]	20
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	5,993
Gross Energy Renovation cost [DKK]	56,451
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	2.44
CCE /wo Maintenance [DKK/kWh]	-
CCE /w Maintenance [DKK/kWh]	-

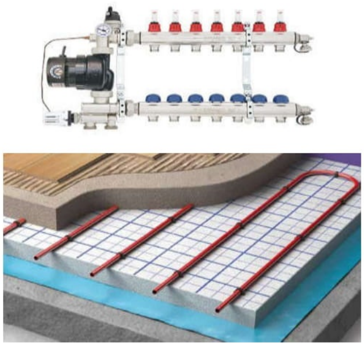
Characteristics	
DH connection - Tech. lifetime [years]	80
Thermostat - Technical lifetime [years]	35

Figure .18: Change of heat source to District Heating

Renovation of component - Higher standard

Heating system, floor heating

Drawing/sketch



Specificiation	
Radiators	Removed
Heating distribution pipes	Removed
Floor heating system	New
Manifold	New
DHW distribution pipes - old	Removed
DHW distribution pipes	New

Renovation	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*
Removal				
Removal of the boiler	1.00	unit	421.13	421.13
Removal of old radiators	8.00	unit	223.65	1,789.20
Removal of old pipes	35.00	m	41.93	1,467.55
Demolished material removal - transportation to final destination (10	3.00	m³	53.50	160.50
Construction				
Piping, AluPex, 16 mm c/c 300mm	124.60	m^2	189.59	23,622.91
Distribution unit with Manifold 2 ways - 2 loops - with shunt, pump, thermometer, regulation valve, distribution pipe with by-pass, wireless electrical regulation with room thermostat	1.00	unit	11,101.00	11,101.00
Distribution unit with Manifold 2 ways - 5 loops - with shunt, pump, thermometer, regulation valve, distribution pipe with by-pass, wireless electrical regulation with room thermostat	1.00	unit	17,415.00	17,415.00

Necessary maintenance, otherwise	*Quantity*	*Unit*	*Unit Cost*	*Total Cost*

Calculations	
Energy Savings [kWh/m².year]	11
Energy Savings [kWh/year]	1390.4
Economic lifetime [years]	30
Technical lifetime [years]	30
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	69,972
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	0.60
CCE /wo Maintenance [DKK/kWh]	2.40
CCE /w Maintenance [DKK/kWh]	2.40

Characteristics

Figure .19: Higher standard, Floor heating system

Renovation of component - BR18 minimum standard

Mechanical ventilation

Drawing/sketch

Specificiation	
Nilan Comfort CT200	New
Counterflow heat exchanger	
Bypass damper	
Filter, class G4	
Condensation drain and piping	
Preheater (freeze protection)	
Supply & Extraction ducts	New
Supply & Extraction diffusers	New
Intake & Outtake ducts (roof)	New

Renovation	Quantity	Unit	Unit Cost	Total Cost
Construction				
AHU - Nilan Comfort CT200	1.00	unit	20,502.79	20,502.79
Installation for ventilation unit	1.50	hour	455.00	682.50
Ducts - Flexible silencing - circular flexiable tubes, 125 mm.	50.00	m	316.14	15,807.00
Air supply difuser	4.00	unit	1,524.96	6,099.84
Air extraction diffuser	4.00	unit	1,524.96	6,099.84
External in/out take diffuser	2.00	Unit	3,856.21	7,712.42

Necessary maintenance, otherwise	Quantity	Unit	Unit Cost	Total Cost

Calculations	
Energy Savings [kWh/m².year]	-12.3
Energy Savings [kWh/year]	-1554.72
Economic lifetime [years]	20
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	71,130
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	-0.44
CCE /wo Maintenance [DKK/kWh]	-2.93
CCE /w Maintenance [DKK/kWh]	-2.93

Characteristics	
Heat recovery (dry) [%]	89%
Specific Fan Power [J/m³]	800
Designed Volume flow [m³/h]	180

Figure .20: BR18 standard, Centralized mechanical ventilation, Nilan Comfort CT200

Renovation of component - Higher standard

Mechanical ventilation

Drawing/sketch

Specificiation	
Nilan Combi 302 Polar	New
Counterflow heat exchanger	
(passive and active heat recovery)	
Bypass damper	
Filter, class G4	
Condensation drain and piping	
Comfort heating	
Comfort cooling	
Supply & Extraction ducts	New
Supply & Extraction diffusers	New
Intake & Outtake ducts (roof)	New

Renovation	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***
Construction				
AHU - Nilan Comfort CT200	1.00	unit	35,700.00	35,700.00
Installation for ventilation unit	1.50	hour	455.00	682.50
Ducts - Flexible silencing - circular flexiable tubes, 125 mm.	50.00	m	316.14	15,807.00
Air supply difuser	4.00	unit	1,524.96	6,099.84
Air extraction diffuser	4.00	unit	1,524.96	6,099.84
External in/out take diffuser	2.00	Unit	3,856.21	7,712.42

Necessary maintenance, otherwise	***Quantity***	***Unit***	***Unit Cost***	***Total Cost***

Calculations	
Energy Savings [kWh/m².year]	-8.1
Energy Savings [kWh/year]	-1023.84
Economic lifetime [years]	20
Technical lifetime [years]	20
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	90,127
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	-0.23
CCE /wo Maintenance [DKK/kWh]	-5.65
CCE /w Maintenance [DKK/kWh]	-5.65

Characteristics	
Heat recovery (dry) [%]	91%
Specific Fan Power [J/m³]	800
Designed Volume flow [m³/h]	200
CO2 controlled	
Coil coil	
Heating coil	
Active heat recovery via heat pump	

Figure .21: Higher standard, Centralized mechanical ventilation, Nilan Combi 302 Polar

Renovation of component - Best practice

PV cells

Drawing/sketch


Specificiation	
PV panels 1.66 m^2 x 8	New
All ancillary system components	New

Renovation	Quantity	Unit	Unit Cost	Total Cost
PV panels - Monocrystalline - VISION 60M STYLE, 1.66 m2 per panel - with inverters, cables, installation support, HPFI- circuit breaker and group circuit breaker (EnergiMidt).	8.00	unit	5,273.81	42,190.45

Necessary maintenance, otherwise	Quantity	Unit	Unit Cost	Total Cost

Calculations	
Energy Savings [kWh/m².year]	25
Energy Savings [kWh/year]	3160
Economic lifetime [years]	20
Technical lifetime [years]	30
Gross Maintenance cost [DKK]	0
Gross Energy Renovation cost [DKK]	52,738
Real interest rate [%]	2.5%
BR18 financial viability [kWh/DKK]	1.20
CCE /wo Maintenance [DKK/kWh]	0.71
CCE /w Maintenance [DKK/kWh]	0.71

Characteristics	
Peak Power [kW/m²]	0.1805

Figure .22: Photovoltaic solar panels, monocrystalline

.3 Appendix 3 - Budget of the renovation proposals

.3.1 Budget for "BR18 minimum" renovation

Item	Data base code	Description	Quant.	Unit	Unit cost (DKK)	Total cost (DKK)
1		**FOUNDATION**				
		Removal				
	(10)21.25,02	Excavation - machine, 0.5m wide - 480 mm deep	12.19	m3	606.37	7,392.86
	(10)21.25,01	Excavation - hand, 0.5m wide - 120 mm deep	3.05	m3	2106.98	6,422.08
	02.40.10,02	Escavation material removal - transportation to final destination (10 km average distance)	15.24	m3	53.5	815.34
		Construction				
	M & Y	Insulation XPS 0.75m height 0.15 width	30.48	m2	320	9,753.60
	03.25.06,01	Alu drip cap (perimeter drain pipe)	50.00	m	153.11	7,655.50
	03.20.26,02	Gravel capillary breaking layer depth = 200 mm	15.00	m2	121.51	1,822.65
2		**PARTITION FLOOR**				
		Removal/Demolition				
	(43)10.30,02	Removal of existing floor covering	124.60	m²	85	10,591.00
	page 62 table 17	Insulation removal - 50 mm	124.60	m²	81	10,092.60
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	10.72	m3	53.5	573.28
		Construction				
	page 64, Table 17	New floor covering - Wooden planks	124.60	m2	396.04	49,346.58
	03.20.21,03	Vapor barrier	124.60	m2	28	3,488.80
	(23)16.05,10	Rockwool insulation - 150 mm	124.60	m2	396.04	49,346.58
3		**GROUND FLOOR - BATHROOM / TOILET**				
		Removal/Demolition				
	(23)20.20,01	Demolition of existing floor	5.75	m2	102.22	587.77
	page 62 table 17	Removing insulation	5.75	m2	81	465.75
	(10)21.05,01	Hand excavation	2.30	m3	630.81	1,450.86
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.47	m3	53.5	131.89
		Construction				
	03.20.26,02	Gravel capillary breaking layer - 200 mm	5.75	m2	121.51	698.68
	03.20.45,08	Insulation EPS80 - 200 mm	5.75	m2	229.68	1,320.66
	03.20.45,04	Insulation EPS80 - 50 mm	5.75	m2	87.35	502.26
	03.20.13,02	Concrete - 100 mm - 12.46 m3	0.58	m3	1721.07	989.62
	03.20.21,01	PE foil	5.75	m2	16.71	96.08
	04.19.65,07	Bathroom floor ceramic tiles - 20 mm	5.75	m2	1839.95	10,579.71
4		**EXTERNAL WALL**				
		Removal/Demolition				
	Estimate	Removal of Insulation - 70 mm	104.85	m²	13.20	1,384.02
	page 56 table 13	Demolition of brick façade - 108 mm	104.85	m²	74.42	7,802.94
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	22.65	m3	53.50	1,211.65
		Construction				
	(21)36.60,07	Rockwool with 190mm - insulation thickness 380 mm	104.85	m²	169.92	17,816.11
	(41)36.50,01	Brick tiles - 20 mm	104.85	m²	931.58	97,676.16
5		**KITCHEN RENOVATION**				
		Removal and installation of new kitchen furniture	16.00	m2	2,798.75	44,780.00
6		**CEILING**				
		Construction				
	page 60 table 16	Vapour barrier	127.50	m²	28.00	3,570.00
	(27)16.97,06	Mineral wool batts - 300 mm	124.40	m²	325.56	40,499.66
7		**ROOF**				
		Removal				
	(47)10.12,01	Removal of Roof cladding (Fibercement sheet)	150.00	m²	196.92	29,538.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	1.80	m3	53.50	96.30
		Construction				
	(47)13.06,01	Fibercement sheet - 0,5 cm thichness	150.00	m²	285.69	42,853.50
	04.22.50,03	Water proof sheet - PE- foil	150.00	m²	27.22	4,083.00

Figure .23: Budget for Be18 renovation

8		**WINDOWS AND DOORS**				
		Removal				
	(31) 45.20	Labor cost - Removing window	14.00	hour	401.00	5,614.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.50	m3	53.50	133.75
		Only material price from Velfac				
	Velfac	kitchen	1.00	unit	5,664.00	5,664.00
	Velfac	kitchen	1.00	unit	3,540.00	3,540.00
	Velfac	Door - Entrance	1.00	unit	3,840.00	3,840.00
	Velfac	Toilet	1.00	unit	1,543.00	1,543.00
	Velfac	Bath	1.00	unit	1,543.00	1,543.00
	Velfac	Door - Service room	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	1.00	unit	3,540.00	3,540.00
	Velfac	Living door	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	2.00	unit	5,373.00	10,746.00
	Velfac	Bedroom 3	2.00	unit	3,459.72	6,919.44
	Velfac	Bedroom 2	1.00	unit	3,540.00	3,540.00
	Velfac	Bedroom 1.2	1.00	unit	3,122.00	3,122.00
	(31) 45.20	Labor cost - windows instalation	33.60	unit	401.00	13,473.60
9		**DHW & HEATING**				
		Removal				
	(56)10.10,01	Removal of the boiler	1.00	unit	421.13	421.13
		Construction				
	elogvvslageret.dk	Substation - District heating substation for indirect heating with primary connected tank for domestic hot water preparation and with thermostatic or electronic control. - Termix BVX T/E 1-1 with cover and ECL Comfort 110*	1.00	unit	33,874.36	33,874.36
	(56) 12.15,01	Labor cost - instalation of substation	4.00	hour	455.00	1,820.00
	(56)34.10,15	Regulation valve - radiator temp. sensor	11.00	unit	435.86	4,794.46
10		**District heating connection**				
		Connection fee	1.00	unit	14,900.00	14,900.00
		Conduction in the footing	1.00	unit	-	-
		Connection pipe (10m)	1.00	unit	10,370.00	10,370.00
		Meter assembly and test	1.00	unit	-	-
	(56)13.20,01	Main consumption meter 1.5 m3/h	1.00	unit	2,729.66	2,729.66
11		**VENTILATION SYSTEM**				
	(57)11.15,01	AHU Comfort CT200, with CTS150 control.	1.00	unit	20,502.79	20,502.79
	05.35.01,02	Ducts - Flexible silencing - cicular flexiable tubes, 125 mm.	50.00	m	316.14	15,807.00
	05.35.30,01	Air supply difuser	4.00	unit	1,524.96	6,099.84
	05.35.30,01	Air extraction diffuser	4.00	unit	1,524.96	6,099.84
	05.35.60,03	External in/out take diffuser	2.00	Unit	3,856.21	7,712.42
12		**SOLAR CELLS SYSTEM**				
	05.55.75,01	PV panels - Monocrystalline - VISION 60M STYLE, 1.66 m2 per panel - with inverters, cables, installation support, HPFI-circuit breaker and group circuit breaker (EnergiMidt).	8.00	unit	5,273.81	42,190.45
					TOTAL W/O INDIRECT COSTS	DKK 703,656.25
					% OF INDERECT COSTS	25.00
					TOTAL WITH INDIRECT COSTS	DKK 879,570.31

Figure .24: Budget for Be18 renovation

.3.2 Budget for Higher standard renovation

Item	Data base code	Description	Quant.	Unit	Unit cost (DKK)	Total cost (DKK)
1		FOUNDATION				
		Removal				
	(10)21.25,02	Excavation - machine, 0.5m wide - 480 mm deep	12.19	m3	606.37	7,392.86
	(10)21.25,01	Excavation - hand, 0.5m wide - 120 mm deep	3.05	m3	2106.98	6,422.08
	02.40.10,02	Escavation material removal - transportation to final destination (10 km average distance)	15.24	m3	53.5	815.34
		Construction				
	page 62 table 17	Insulation XPS 0.75m height 0.15 width	30.48	m2	320.00	9,753.60
	03.25.06,01	Alu drip cap (perimeter drain pipe)	50.00	m	153.11	7,655.50
	03.20.26,02	Gravel capillary breaking layer - depth 200 mm	15.00	m2	121.51	1,822.65
2		PARTITION FLOOR				
		Removal/Demolition				
	(23)20.20,01	Demolition of existing floor	118.85	m2	102.22	12,148.85
	page 62 table 17	Removing insulation	118.85	m2	81.00	9,626.85
	(10)21.05,01	Hand excavation - 200 mm deep	23.77	m3	630.81	14,994.35
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	33.75	m3	53.50	1,805.81
		Construction				
	03.20.13,02	Concrete screed sub-floor - 50 mm	5.94	m3	1,636.76	9,726.45
	03.20.45,08	Insulation EPS80 (200 mm x3) - 600 mm	373.80	m2	211.78	79,163.36
	03.20.21,01	PE-folie, 0,2 mm, Terrain deck	118.85	m2	16.71	1,985.98
	(13)21.17,01	Reinforcement 1%	118.85	m2	59.88	7,116.74
	03.20.13,02	Concrete floor - 150 mm	17.83	m3	1,636.76	29,179.34
3		GROUND FLOOR - BATHROOM / TOILET				
		Removal/Demolition				
	(23)20.20,01	Demolition of existing floor	5.75	m2	102.22	587.77
	page 62 table 17	Removing insulation	5.75	m2	81.00	465.75
	(10)21.05,01	Hand excavation	2.30	m3	630.81	1,450.86
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.47	m3	53.50	131.89
		Construction				
	03.20.26,02	Gravel capillary breaking layer - 200 mm	5.75	m2	121.51	698.68
	03.20.45,08	Insulation EPS80 - 200 mm x3	17.25	m2	229.68	3,961.98
	03.20.13,02	Concrete - 100 mm	0.58	m3	1,721.07	989.62
	03.20.21,01	PE foil	5.75	m2	16.71	96.08
	04.19.65,07	Bathroom floor ceramic tiles - 20 mm	5.75	m2	1,839.95	10,579.71
4		EXTERNAL WALL				
		Removal/Demolition				
	Estimate	Removal of Insulation - 70 mm	104.85	m²	13.20	1,384.02
	page 56 table 13	Demolition of brick façade - 108 mm	104.85	m²	74.42	7,802.94
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	22.65	m3	53.50	1,211.65
		Construction				
	(21)36.60,07	Rockwool - 2 x 190 - 380 mm	167.00	m²	169.92	28,376.64
	(41)36.50,01	Brick tiles - 20 mm	104.85	m²	931.58	97,676.16
5		KITCHEN RENOVATION				
		Removal and installation of new kitchen furniture	16.00	m2	2,798.75	44,780.00
6		ROOF				
		Removal				
	(47)10.12,01	Removal of Roof cladding (Fibercement sheet)	150.00	m²	196.92	29,538.00
	(47)10.30,01	Removal of battens	450.00	l.m	8.91	4,009.50
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	3.42	m3	53.50	182.97
		Construction				
	04.20.45,04	OSB board (plywood in Sigma) - 18 mm	150.00	m2	72.00	10,800.00
	03.20.21,01	Vapour barrier	150.00	m2	16.71	2,506.50
	(27)15.15,04	Adding extra rafters, 2x 50x180 - 360	539.00	lbm	188.37	101,531.43
	(27)16.90,21	Rockwool insulation (245 mm)	139.80	m2	296.47	41,446.51
	(27)16.90,17	Rockwool insulation (120 mm)	139.80	m2	150.15	20,990.97
	04.20.45,04	OSB board (plywood in Sigma) - 18 mm	150.00	m2	72.00	10,800.00

Figure .25: Budget for Ambitious renovation

7		WINDOWS AND DOORS				
		Removal				
	(31) 45.20	Labor cost - Removing window	14.00	hour	401.00	5,614.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.50	m3	53.50	133.75
		Only material price from Velfac				
	Velfac	kitchen	1.00	unit	6,132.00	6,132.00
	Velfac	kitchen	1.00	unit	3,882.00	3,882.00
	Velfac	Door - Entrance	1.00	unit	4,131.00	4,131.00
	Velfac	Toilet	1.00	unit	2,043.00	2,043.00
	Velfac	Bath	1.00	unit	2,043.00	2,043.00
	Velfac	Door - Service room	1.00	unit	4,131.00	4,131.00
	Velfac	Living window	1.00	unit	5,009.00	5,009.00
	Velfac	Living door	1.00	unit	4,131.00	4,131.00
	Velfac	Living window	2.00	unit	5,718.00	11,436.00
	Velfac	Bedroom 3	2.00	unit	3,763.00	7,526.00
	Velfac	Bedroom 2	1.00	unit	4,823.00	4,823.00
	Velfac	Bedroom 1.2	1.00	unit	3,382.00	3,382.00
	(31) 45.20	Labor cost - windows instalation	33.60	unit	401.00	13,473.60
8		DHW & HEATING SYSTEM - FLOOR HEATING				
		Removal				
	(56)10.10,01	Removal of the boiler	1.00	unit	421.13	421.13
	(56)30.07,02	Removal of the old radiators	8.00	unit	223.65	1,789.20
	(56)20.05,01	Removal of the old pipes	35.00	m	41.93	1,467.55
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	3.00	m3	53.50	160.50
		Construction				
	elogvvslageret.dk	Substation - District heating substation for indirect heating with primary connected tank for domestic hot water preparation and with thermostatic or electronic control. - Termix BVX T/E 1-1 with cover and ECL Comfort 110*	1.00	unit	33,874.36	33,874.36
	(56) 12.15,01	Labor cost - instalation of substation	4	hour	455.00	1,820.00
	(56)32.10,05	Piping, AluPex, 16 mm c/c 300mm	124.60	m2	189.59	23,622.91
	(56)32.10,02	Distribution unit with Manifold 2 ways - 2 loops - with shunt, pump, thermometer, regulation valve, distribution pipe with by-pass, wireless electrical regulation with room thermostat	1.00	unit	11,101.00	11,101.00
	(56)32.10,05	Distribution unit with Manifold 2 ways - 5 loops - with shunt, pump, thermometer, regulation valve, distribution pipe with by-pass, wireless electrical regulation with room thermostat	1.00	unit	17,415.00	17,415.00
8.2		District heating connection				
		Connection fee	1.00	unit	14,900.00	14,900.00
		Conduction in the footing	1.00	unit	-	-
		Connection pipe (10m)	1.00	unit	10,370.00	10,370.00
		Meter assembly and test	1.00	unit	-	-
	(56)13.20,01	Main consumption meter 1.5 m3/h	1.00	unit	2,729.66	2,729.66
9		VENTILATION SYSTEM				
	Dansk Klima-energ	AHU - Nilan Comfort 300 EC	1.00	unit	35,700.00	35,700.00
	(57)11.15,01	Installation for ventilation unit	1.50	hour	455.00	682.50
	05.35.01,02	Ducts - Flexible silencing - ciscular flexiable tubes, 125 mm.	50.00	m	316.14	15,807.00
	05.35.30,01	Air supply difuser	4.00	unit	1,524.96	6,099.84
	05.35.30,01	Air extraction diffuser	4.00	unit	1,524.96	6,099.84
	05.35.60,03	External in/out take diffuser	2.00	Unit	3,856.21	7,712.42
					TOTAL W/O INDIRECT COSTS	DKK 891,272.65
					% OF INDERECT COSTS	25.00
					TOTAL WITH INDIRECT COSTS	DKK 1,114,090.81

Figure .26: Budget for Ambitious renovation

.3.3 Budget for "Anyway maintenance" renovation

Item	Data base code	Description	Quant.	Unit	Unit cost (DKK)	Total cost (DKK)
1		**FOUNDATION**				
		Removal				
	(10)21.25,02	Excavation - machine, 0.5m wide - 480 mm deep	6.00	m3	606.37	3,638.22
	(10) 22.05,01	Grounding and compressing	6.00	m3	574.35	3,446.10
		Construction				
	(41) 16.10,01	Bitumen waterproof membrane 30 cm below the ground level	22.50	m2	120.17	2,703.83
2		**PARTITION FLOOR**				
		Removal/Demolition				
	(43)10.30,02	Removal of existing floor covering	124.60	m2	85.00	10,591.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	4.49	m3	53.50	239.98
		Construction				
	page 64, Table 17	New floor covering - Wooden planks	124.60	m2	396.04	49,346.58
3		**GROUND FLOOR - BATHROOM / TOILET**				
		Removal/Demolition				
		Linoleum removal	5.75	m2	59.00	339.25
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	0.07	m3	53.50	3.69
		Construction				
		Linoleum 2.5 mm including surface treatment	5.75	m2	553.00	3,179.75
4		**EXTERNAL WALL**				
		Maintenance				
	2.1-4.2,01	Changing mortar between bricks	83.50	m2	773.10	64,553.85
		Removal				
		Wood panel removal	21.35	m2	2,798.75	59,753.31
		Construction				
		Instalation of wood panel	21.35	m2	286.18	6,109.94
		Wood panel with weather proof paint.	21.35	m2	286.18	
5		**KITCHEN RENOVATION**				
		Removal and installation of new kitchen furniture	16.00	m2	2,798.75	44,780.00
6		**ROOF**				
		Removal				
	(47)10.12,01	Removal of Roof cladding (Fibercement sheet)	150.00	m2	196.92	29,538.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	1.80	m3	53.50	96.30
		Construction				
	(47)15.05,01	Wooden battens - 38 x 56 mm	450.00	l.m.	54.26	
	(47)13.06,01	Fibercement sheet - 0,5 cm thichness	150.00	m2	285.69	42,853.50
	04.22.50,03	Water proof sheet - PE- foil	150.00	m2	27.22	4,083.00
7		**WINDOWS AND DOORS**				
		Removal				
	(31) 45.20	Labor cost - Removing window	14.00	hour	401.00	5,614.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.50	m3	53.50	133.75
		Only material price from Velfac				
	Velfac	kitchen	1.00	unit	5,664.00	5,664.00
	Velfac	kitchen	1.00	unit	3,540.00	3,540.00
	Velfac	Door - Entrance	1.00	unit	3,840.00	3,840.00
	Velfac	Toilet	1.00	unit	1,543.00	1,543.00
	Velfac	Bath	1.00	unit	1,543.00	1,543.00
	Velfac	Door - Service room	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	1.00	unit	3,540.00	3,540.00
	Velfac	Living door	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	2.00	unit	5,373.00	10,746.00
	Velfac	Bedroom 3	2.00	unit	3,459.72	6,919.44
	Velfac	Bedroom 2	1.00	unit	3,540.00	3,540.00
	Velfac	Bedroom 1.2	1.00	unit	3,122.00	3,122.00
	(31) 45.20	Labor cost - windows instalation	33.60	unit	401.00	13,473.60

Figure .27: Budget for maintenance only renovation

Item	Data base code	Description	Quant.	Unit	Unit cost (DKK)	Total cost (DKK)
1		FOUNDATION				
		Removal				
	(10)21.25,02	Excavation - machine, 0.5m wide - 480 mm deep	6.00	m3	606.37	3,638.22
	(10) 22.05,01	Grounding and compressing	6.00	m3	574.35	3,446.10
		Construction				
	(41) 16.10,01	Bitumen waterproof membrane 30 cm below the ground level	22.50	m2	120.17	2,703.83
2		PARTITION FLOOR				
		Removal/Demolition				
	(43)10.30,02	Removal of existing floor covering	124.60	m2	85.00	10,591.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	4.49	m3	53.50	239.98
		Construction				
	page 64, Table 17	New floor covering - Wooden planks	124.60	m2	396.04	49,346.58
3		GROUND FLOOR - BATHROOM / TOILET				
		Removal/Demolition				
		Linoleum removal	5.75	m2	59.00	339.25
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	0.07	m3	53.50	3.69
		Construction				
		Linoleum 2.5 mm including surface treatment	5.75	m2	553.00	3,179.75
4		EXTERNAL WALL				
		Maintenance				
	2.1-4.2,01	Changing mortar between bricks	83.50	m2	773.10	64,553.85
		Removal				
		Wood panel removal	21.35	m2	2,798.75	59,753.31
		Construction				
		Instalation of wood panel	21.35	m2	286.18	6,109.94
		Wood panel with weather proof paint.	21.35	m2	286.18	
5		KITCHEN RENOVATION				
		Removal and installation of new kitchen furniture	16.00	m2	2,798.75	44,780.00
6		ROOF				
		Removal				
	(47)10.12,01	Removal of Roof cladding (Fibercement sheet)	150.00	m2	196.92	29,538.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	1.80	m3	53.50	96.30
		Construction				
	(47)15.05,01	Wooden battens - 38 x 56 mm	450.00	l.m.	54.26	
	(47)13.06,01	Fibercement sheet - 0,5 cm thichness	150.00	m2	285.69	42,853.50
	04.22.50,03	Water proof sheet - PE- foil	150.00	m2	27.22	4,083.00
7		WINDOWS AND DOORS				
		Removal				
	(31) 45.20	Labor cost - Removing window	14.00	hour	401.00	5,614.00
	02.40.10,02	Demolished material removal - transportation to final destination (10 km average distance)	2.50	m3	53.50	133.75
		Only material price from Velfac				
	Velfac	kitchen	1.00	unit	5,664.00	5,664.00
	Velfac	kitchen	1.00	unit	3,540.00	3,540.00
	Velfac	Door - Entrance	1.00	unit	3,840.00	3,840.00
	Velfac	Toilet	1.00	unit	1,543.00	1,543.00
	Velfac	Bath	1.00	unit	1,543.00	1,543.00
	Velfac	Door - Service room	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	1.00	unit	3,540.00	3,540.00
	Velfac	Living door	1.00	unit	3,840.00	3,840.00
	Velfac	Living window	2.00	unit	5,373.00	10,746.00
	Velfac	Bedroom 3	2.00	unit	3,459.72	6,919.44
	Velfac	Bedroom 2	1.00	unit	3,540.00	3,540.00
	Velfac	Bedroom 1.2	1.00	unit	3,122.00	3,122.00
	(31) 45.20	Labor cost - windows instalation	33.60	unit	401.00	13,473.60

Figure .28: Budget for maintenance only renovation

.4 Appendix 4 - Life cycle cost

.4.1 Considerations to calculate sale price increase of a house

Below is presented the considerations used in this project from the study from SBi about increase in house sells price due to better EPC label:

After the implementation of the EPC scheme, the SBi has shown an study that energy-efficient housing can have an increase in price, in the sense that the higher the EPC label, the higher the selling price. The study calculated the average square meter prices for each stage of the energy labeling scale for all sales in 2011 and 2012. The increase in sales price as the energy label improves was also calculated, with energy label G as a reference. It turns out that the energy label's position on the energy label scale has a positive influence on the sales price. However, the report has been critical since it would be desirable to provide reliable results to ensure that the price increment is only due to EPC escalation. For example a house with energy label C, is generally in a better condition than a house with label D or differ in other ways, thus achieving a better selling price. As mentioned in the report, a control variable is an essential parameter in order to obtain a picture of how much the regional difference affects the energy label for a selling price. The table below shows the price increase on house prices isolated from other parameters that influence house prices, using a regression analysis carried out based on multiple regression models:

	Forskel	Forbedring
1	923,9 kr./m2	Fra G til F
2	805,3 kr./m2	Fra E til D
3	797,2 kr./m2	Fra F til E
4	788,0 kr./m2	Fra D til C
5	46,0 kr./m2	Fra C til AB

Based on the results of the SBi study a prediction of the property value increase is applied to the study case to assess the potential of property value gain after selling a house after energy improving it. Below is presented the property value increase and loan debt for 10, 15, and 20 years:

Staged renovation					
Year	0	10	15	20	30
EPC label	E	D	B	A	A
House price increase from original price (DKK)	0	101,709	201,234	207,044	207,044
One-off renovation in the 1st year by a loan					
Year	0	10	15	20	30
EPC label	E	D	B	A	A
House price increase from original price (DKK)	0	207,044	207,044	207,044	207,044
Dept to pay off (DKK)	- 879,571	- 649,988	- 514,070	- 361,786	0
Difference property value and pay off (DKK)	- 879,571	- 442,944	- 307,027	- 154,743	207,044

Table .1: Price of house increase in years 0, 10, 15, 20, and 30 due to EPC label escalation, and dept pay offs for the same years

Threshold of energy consumption of the house for each EPC label

Threshold of energy consumption of the house for each EPC label				
		Official thresholds	Threshold for a 100 m² house	Threshold for Study case house
A	≤	≤ 52.5 + 1650/sq. m.	≤ 69	**65.56**
B	≤	≤ 70.0 + 2200/sq. m.	≤ 92	**87.42**
C	≤	≤ 110 + 3200/sq. m.	≤ 142	**135.34**
D	≤	≤ 150 + 4200/sq. m.	≤ 192	**183.25**
E	≤	≤ 190 + 5200/sq. m.	≤ 242	**231.17**
F	≤	≤ 240 + 6500/sq. m.	≤ 305	**291.46**
G	>	> 240 + 6500/sq. m.	> 305	**291.46**

House Sale Price increase for each EPC label escalation

	House area (m2):	126.3
EPC	Price increase for EPC label change (DKK/m²)	Price increase for EPC label change (DKK)
C - AB	46	5,809.80
D - C	788	99,524.40
E - D	805.3	101,709.39
F - E	797.2	
G - F	923.9	
Total:		207,043.59

Life cycle cost calculation of the staged renovation considering house sale price

Stage	Year	Heat source	Stage cost	House price gain	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (stage cost)	Accumulated (cost of stages)	Annual savings	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
			DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK
0	0	Gas oil	-			-	-	-	-	-	-			0	0
	1	Gas oil			254.7	32,693.29	29,975.38	30,724.76	30,724.76	29,975	29,975	48000	78,724.76	76,805	76,805
1	2	Gas oil	86,137.01		254.7	32,693.29	29,975.38	31,492.88	117,629.90	111,962	141,937	48000	79,492.88	75,662	152,467
	3	District heating			215.4	27,648.74	16,719.09	17,742.43	17,742.43	16,476	158,413	48000	65,742.43	61,048	213,516
	4	District heating			215.4	27,648.74	16,719.09	18,097.28	18,097.28	16,395	174,808	48000	66,097.28	59,881	273,396
2	5	District heating	135,507.87		182.97	23,486.03	14,361.95	15,856.76	151,364.63	133,784	308,592	48000	63,856.76	56,440	329,836
	6	District heating			182.97	23,486.03	14,361.95	16,173.89	16,173.89	13,947	322,539	48000	64,173.89	55,337	385,173
	7	District heating			182.97	23,486.03	14,361.95	16,497.37	16,497.37	13,879	336,418	48000	64,497.37	54,259	439,433
3	8	District heating	152,806.75		146.40	18,791.90	11,703.91	13,712.99	166,519.74	136,671	473,088	48000	61,712.99	50,651	490,084
	9	District heating			146.40	18,791.90	11,703.91	13,987.25	13,987.25	11,200	484,288	48000	61,987	49,635	539,718
	10	District heating		- 101,709.39	146.40	18,791.90	11,703.91	14,267.00	14,267.00	11,145	495,434	48000	- 39,442	- 30,812	508,906
	11	District heating			146.40	18,791.90	11,703.91	14,552.34	14,552.34	11,091	506,525	48000	62,552	47,674	556,580
4	12	District heating	175,327.34		111.30	14,286.47	9,152.70	11,607.84	186,935.18	138,997	645,521	48000	59,608	44,322	600,902
	13	District heating			111.30	14,286.47	9,152.70	11,840.00	11,840.00	8,589	654,110	48000	59,840	43,409	644,311
5	14	District heating	95,713.50		111.30	14,286.47	9,152.70	12,076.80	107,790.30	76,286	730,396	48000	60,077	42,518	686,829
	15	District heating			111.30	14,286.47	9,152.70	12,318.33	12,318.33	8,505	738,902	48000	60,318	41,648	728,477
	16	District heating			111.30	14,286.47	9,152.70	12,564.70	12,564.70	8,464	747,366	48000	60,565	40,798	769,275
6	17	District heating	125,564.43		86.20	11,064.63	7,328.34	10,261.44	135,825.87	89,264	836,630	48000	58,261	38,289	807,564
	18	District heating			86.20	11,064.63	7,328.34	10,466.67	10,466.67	6,711	843,341	48000	58,467	37,487	845,051
7	19	District heating	108,513.70		60.50	7,765.78	5,460.36	7,954.72	116,468.41	72,854	916,195	15571	23,525	14,716	859,766
	20	District heating			60.50	7,765.78	4,580.89	6,806.96	6,806.96	4,154	920,349		6,807	4,154	863,920
	21	District heating			60.50	7,765.78	4,580.89	6,943.10	6,943.10	4,134	924,483		6,943	4,134	868,054
	22	District heating			60.50	7,765.78	4,580.89	7,081.96	7,081.96	4,114	928,596		7,082	4,114	872,168
	23	District heating			60.50	7,765.78	4,580.89	7,223.60	7,223.60	4,094	932,690		7,224	4,094	876,261
	24	District heating			60.50	7,765.78	4,580.89	7,368.07	7,368.07	4,074	936,764		7,368	4,074	880,335
	25	District heating			60.50	7,765.78	4,580.89	7,515.43	7,515.43	4,054	940,817		7,515	4,054	884,389
	26	District heating			60.50	7,765.78	4,580.89	7,665.74	7,665.74	4,034	944,851		7,666	4,034	888,423
	27	District heating			60.50	7,765.78	4,580.89	7,819.06	7,819.06	4,014	948,866		7,819	4,014	892,437
	28	District heating			60.50	7,765.78	4,580.89	7,975.44	7,975.44	3,995	952,860		7,975	3,995	896,432
	29	District heating			60.50	7,765.78	4,580.89	8,134.95	8,134.95	3,975	956,836		8,135	3,975	900,407
	30	District heating			60.50	7,765.78	4,580.89	8,297.65	8,297.65	3,956	960,791		8,298	3,956	904,363
			879,570.60						879,570.60	960,791.48				904,363	

Table .2: House sold in 10 years

Stage	Year	Heat source	**Stage cost**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (stage cost)	Accumulated (cost of stages)	Annual savings	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
			DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK
0	0	Gas oil	-			-	-	-	-	-	-			0	0
	1	Gas oil			254.7	32,693.29	29,975.38	30,724.76	30,724.76	29,975	29,975	48000	78,724.76	76,805	76,805
1	2	Gas oil	86,137.01		254.7	32,693.29	29,975.38	31,492.88	117,629.90	111,962	141,937	48000	79,492.88	75,662	152,467
	3	District heating			215.4	27,648.74	16,719.09	17,742.43	17,742.43	16,476	158,413	48000	65,742.43	61,048	213,516
	4	District heating			215.4	27,648.74	16,719.09	18,097.28	18,097.28	16,395	174,808	48000	66,097.28	59,881	273,396
2	5	District heating	135,507.87		182.97	23,486.03	14,361.95	15,856.76	151,364.63	133,784	308,592	48000	63,856.76	56,440	329,836
	6	District heating			182.97	23,486.03	14,361.95	16,173.89	16,173.89	13,947	322,539	48000	64,173.89	55,337	385,173
	7	District heating			182.97	23,486.03	14,361.95	16,497.37	16,497.37	13,879	336,418	48000	64,497.37	54,259	439,433
3	8	District heating	152,806.75		146.40	18,791.90	11,703.91	13,712.99	166,519.74	136,671	473,088	48000	61,712.99	50,651	490,084
	9	District heating			146.40	18,791.90	11,703.91	13,987.25	13,987.25	11,200	484,288	48000	61,987	49,635	539,718
	10	District heating			146.40	18,791.90	11,703.91	14,267.00	14,267.00	11,145	495,434	48000	62,267	48,643	588,361
	11	District heating			146.40	18,791.90	11,703.91	14,552.34	14,552.34	11,091	506,525	48000	62,552	47,674	636,035
4	12	District heating	175,327.34		111.30	14,286.47	9,152.70	11,607.84	186,935.18	138,997	645,521	48000	59,608	44,322	680,357
	13	District heating			111.30	14,286.47	9,152.70	11,840.00	11,840.00	8,589	654,110	48000	59,840	43,409	723,766
5	14	District heating	95,713.50		111.30	14,286.47	9,152.70	12,076.80	107,790.30	76,286	730,396	48000	60,077	42,518	766,284
	15	District heating		- 207,044	111.30	14,286.47	9,152.70	12,318.33	12,318.33	8,505	738,902	48000	- 146,725	- 101,309	664,975
	16	District heating			111.30	14,286.47	9,152.70	12,564.70	12,564.70	8,464	747,366	48000	60,565	40,798	705,773
6	17	District heating	125,564.43		86.20	11,064.63	7,328.34	10,261.44	135,825.87	89,264	836,630	48000	58,261	38,289	744,062
	18	District heating			86.20	11,064.63	7,328.34	10,466.67	10,466.67	6,711	843,341	48000	58,467	37,487	781,549
7	19	District heating	108,513.70		60.50	7,765.78	5,460.36	7,954.72	116,468.41	72,854	916,195	15571	23,525	14,716	796,265
	20	District heating			60.50	7,765.78	4,580.89	6,806.96	6,806.96	4,154	920,349		6,807	4,154	800,419
	21	District heating			60.50	7,765.78	4,580.89	6,943.10	6,943.10	4,134	924,483		6,943	4,134	804,553
	22	District heating			60.50	7,765.78	4,580.89	7,081.96	7,081.96	4,114	928,596		7,082	4,114	808,667
	23	District heating			60.50	7,765.78	4,580.89	7,223.60	7,223.60	4,094	932,690		7,224	4,094	812,760
	24	District heating			60.50	7,765.78	4,580.89	7,368.07	7,368.07	4,074	936,764		7,368	4,074	816,834
	25	District heating			60.50	7,765.78	4,580.89	7,515.43	7,515.43	4,054	940,817		7,515	4,054	820,888
	26	District heating			60.50	7,765.78	4,580.89	7,665.74	7,665.74	4,034	944,851		7,666	4,034	824,922
	27	District heating			60.50	7,765.78	4,580.89	7,819.06	7,819.06	4,014	948,866		7,819	4,014	828,936
	28	District heating			60.50	7,765.78	4,580.89	7,975.44	7,975.44	3,995	952,860		7,975	3,995	832,931
	29	District heating			60.50	7,765.78	4,580.89	8,134.95	8,134.95	3,975	956,836		8,135	3,975	836,906
	30	District heating			60.50	7,765.78	4,580.89	8,297.65	8,297.65	3,956	960,791		8,298	3,956	840,862
			879,570.60						879,570.60	960,791.48				840,862	

Table .3: House sold in 15 years

Stage	Year	Heat source	Stage cost	House price gain	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (stage cost)	Accumulated (cost of stages)	Annual savings	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
			DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK
0	0	Gas oil	-			-	-	-	-	-	-			0	0
	1	Gas oil			254.7	32,693.29	29,975.38	30,724.76	30,724.76	29,975	29,975	48000	78,724.76	76,805	76,805
1	2	Gas oil	86,137.01		254.7	32,693.29	29,975.38	31,492.88	117,629.90	111,962	141,937	48000	79,492.88	75,662	152,467
	3	District heating			215.4	27,648.74	16,719.09	17,742.43	17,742.43	16,476	158,413	48000	65,742.43	61,048	213,516
	4	District heating			215.4	27,648.74	16,719.09	18,097.28	18,097.28	16,395	174,808	48000	66,097.28	59,881	273,396
2	5	District heating	135,507.87		182.97	23,486.03	14,361.95	15,856.76	151,364.63	133,784	308,592	48000	63,856.76	56,440	329,836
	6	District heating			182.97	23,486.03	14,361.95	16,173.89	16,173.89	13,947	322,539	48000	64,173.89	55,337	385,173
	7	District heating			182.97	23,486.03	14,361.95	16,497.37	16,497.37	13,879	336,418	48000	64,497.37	54,259	439,433
3	8	District heating	152,806.75		146.40	18,791.90	11,703.91	13,712.99	166,519.74	136,671	473,088	48000	61,712.99	50,651	490,084
	9	District heating			146.40	18,791.90	11,703.91	13,987.25	13,987.25	11,200	484,288	48000	61,987	49,635	539,718
	10	District heating			146.40	18,791.90	11,703.91	14,267.00	14,267.00	11,145	495,434	48000	62,267	48,643	588,361
	11	District heating			146.40	18,791.90	11,703.91	14,552.34	14,552.34	11,091	506,525	48000	62,552	47,674	636,035
4	12	District heating	175,327.34		111.30	14,286.47	9,152.70	11,607.84	186,935.18	138,997	645,521	48000	59,608	44,322	680,357
	13	District heating			111.30	14,286.47	9,152.70	11,840.00	11,840.00	8,589	654,110	48000	59,840	43,409	723,766
5	14	District heating	95,713.50		111.30	14,286.47	9,152.70	12,076.80	107,790.30	76,286	730,396	48000	60,077	42,518	766,284
	15	District heating			111.30	14,286.47	9,152.70	12,318.33	12,318.33	8,505	738,902	48000	60,318	41,648	807,932
	16	District heating			111.30	14,286.47	9,152.70	12,564.70	12,564.70	8,464	747,366	48000	60,565	40,798	848,730
6	17	District heating	125,564.43		86.20	11,064.63	7,328.34	10,261.44	135,825.87	89,264	836,630	48000	58,261	38,289	887,019
	18	District heating			86.20	11,064.63	7,328.34	10,466.67	10,466.67	6,711	843,341	48000	58,467	37,487	924,506
7	19	District heating	108,513.70		60.50	7,765.78	5,460.36	7,954.72	116,468.41	72,854	916,195	15571	23,525	14,716	939,222
	20	District heating		- 207,043.59	60.50	7,765.78	4,580.89	6,806.96	6,806.96	4,154	920,349		- 200,237	- 122,199	817,023
	21	District heating			60.50	7,765.78	4,580.89	6,943.10	6,943.10	4,134	924,483		6,943	4,134	821,157
	22	District heating			60.50	7,765.78	4,580.89	7,081.96	7,081.96	4,114	928,596		7,082	4,114	825,270
	23	District heating			60.50	7,765.78	4,580.89	7,223.60	7,223.60	4,094	932,690		7,224	4,094	829,364
	24	District heating			60.50	7,765.78	4,580.89	7,368.07	7,368.07	4,074	936,764		7,368	4,074	833,438
	25	District heating			60.50	7,765.78	4,580.89	7,515.43	7,515.43	4,054	940,817		7,515	4,054	837,491
	26	District heating			60.50	7,765.78	4,580.89	7,665.74	7,665.74	4,034	944,851		7,666	4,034	841,525
	27	District heating			60.50	7,765.78	4,580.89	7,819.06	7,819.06	4,014	948,866		7,819	4,014	845,540
	28	District heating			60.50	7,765.78	4,580.89	7,975.44	7,975.44	3,995	952,860		7,975	3,995	849,534
	29	District heating			60.50	7,765.78	4,580.89	8,134.95	8,134.95	3,975	956,836		8,135	3,975	853,510
	30	District heating			60.50	7,765.78	4,580.89	8,297.65	8,297.65	3,956	960,791		8,298	3,956	857,465
			879,570.60						879,570.60	960,791.48				857,465	

Table .4: House sold in 20 years

Stage	Year	Heat source	**Stage cost**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (stage cost)	Accumulated (cost of stages)	Annual savings	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
			DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK	DKK
0	0	Gas oil	-			-	-	-	-	-	-			0	0
	1	Gas oil			254.7	32,693.29	31,423.47	32,209.05	32,209.05	31,423	31,423	48000	80,209.05	78,253	78,253
1	2	Gas oil	86,137.01		254.7	32,693.29	31,423.47	33,014.28	119,151.29	113,410	144,833	48000	81,014.28	77,111	155,363
	3	District heating			215.4	27,648.74	16,719.09	17,742.43	17,742.43	16,476	161,309	48000	65,742.43	61,048	216,412
	4	District heating			215.4	27,648.74	16,719.09	18,097.28	18,097.28	16,395	177,704	48000	66,097.28	59,881	276,293
2	5	District heating	135,507.87		182.97	23,486.03	14,361.95	15,856.76	151,364.63	133,784	311,489	48000	63,856.76	56,440	332,733
	6	District heating			182.97	23,486.03	14,361.95	16,173.89	16,173.89	13,947	325,435	48000	64,173.89	55,337	388,070
	7	District heating			182.97	23,486.03	14,361.95	16,497.37	16,497.37	13,879	339,314	48000	64,497.37	54,259	442,329
3	8	District heating	152,806.75		146.40	18,791.90	11,703.91	13,712.99	166,519.74	136,671	475,984	48000	61,712.99	50,651	492,980
	9	District heating			146.40	18,791.90	11,703.91	13,987.25	13,987.25	11,200	487,184	48000	61,987	49,635	542,615
	10	District heating			146.40	18,791.90	11,703.91	14,267.00	14,267.00	11,145	498,330	48000	62,267	48,643	591,258
	11	District heating			146.40	18,791.90	11,703.91	14,552.34	14,552.34	11,091	509,421	48000	62,552	47,674	638,931
4	12	District heating	175,327.34		111.30	14,286.47	9,152.70	11,607.84	186,935.18	138,997	648,417	48000	59,608	44,322	683,253
	13	District heating			111.30	14,286.47	9,152.70	11,840.00	11,840.00	8,589	657,006	48000	59,840	43,409	726,662
5	14	District heating	95,713.50		111.30	14,286.47	9,152.70	12,076.80	107,790.30	76,286	733,293	48000	60,077	42,518	769,180
	15	District heating			111.30	14,286.47	9,152.70	12,318.33	12,318.33	8,505	741,798	48000	60,318	41,648	810,828
	16	District heating			111.30	14,286.47	9,152.70	12,564.70	12,564.70	8,464	750,262	48000	60,565	40,798	851,626
6	17	District heating	125,564.43		86.20	11,064.63	7,328.34	10,261.44	135,825.87	89,264	839,526	48000	58,261	38,289	889,915
	18	District heating			86.20	11,064.63	7,328.34	10,466.67	10,466.67	6,711	846,237	48000	58,467	37,487	927,402
7	19	District heating	108,513.70		60.50	7,765.78	5,460.36	7,954.72	116,468.41	72,854	919,091	15571	23,525	14,716	942,118
	20	District heating			60.50	7,765.78	4,580.89	6,806.96	6,806.96	4,154	923,245		6,807	4,154	946,272
	21	District heating			60.50	7,765.78	4,580.89	6,943.10	6,943.10	4,134	927,379		6,943	4,134	950,406
	22	District heating			60.50	7,765.78	4,580.89	7,081.96	7,081.96	4,114	931,493		7,082	4,114	954,519
	23	District heating			60.50	7,765.78	4,580.89	7,223.60	7,223.60	4,094	935,586		7,224	4,094	958,613
	24	District heating			60.50	7,765.78	4,580.89	7,368.07	7,368.07	4,074	939,660		7,368	4,074	962,686
	25	District heating			60.50	7,765.78	4,580.89	7,515.43	7,515.43	4,054	943,714		7,515	4,054	966,740
	26	District heating			60.50	7,765.78	4,580.89	7,665.74	7,665.74	4,034	947,748		7,666	4,034	970,774
	27	District heating			60.50	7,765.78	4,580.89	7,819.06	7,819.06	4,014	951,762		7,819	4,014	974,789
	28	District heating			60.50	7,765.78	4,580.89	7,975.44	7,975.44	3,995	955,757		7,975	3,995	978,783
	29	District heating			60.50	7,765.78	4,580.89	8,134.95	8,134.95	3,975	959,732		8,135	3,975	982,758
	30	District heating		- 207,044	60.50	7,765.78	4,580.89	8,297.65	8,297.65	3,956	963,688		- 198,746	- 94,751	888,008
			879,570.60						879,570.60	**963,687.65**				888,008	

Table .5: House sold in 30 years

Life cycle cost calculation of one-off renovation considering house sale price

Year	Heat source	**Loan payments**	**Residual loan**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
		DKK	DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK
1	Gas oil	40,911.21 kr.			254.7	32,693.29	19,575.57	20,064.96	60,486.77	59,011.49	59,011.49
2	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,680.96	46,371.57	44,137.13	103,148.61
3	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,794.58	46,371.57	43,060.61	146,209.23
4	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,910.47	46,371.57	42,010.35	188,219.58
5	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,028.68	46,371.57	40,985.71	229,205.29
6	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,149.26	46,371.57	39,986.06	269,191.35
7	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,272.24	46,371.57	39,010.79	308,202.14
8	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,397.69	46,371.57	38,059.31	346,261.45
9	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,525.64	46,371.57	37,131.03	383,392.48
10	District heating	40,911.21 kr.	649,987.68	- 207,044	60.5	7,765.78	5,460.36	6,656.15	489,315.66	382,252.61	765,645.09
11	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,789.27	46,371.57	35,341.85	800,986.94
12	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,925.06	46,371.57	34,479.85	835,466.79
13	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,063.56	46,371.57	33,638.88	869,105.68
14	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,204.83	46,371.57	32,818.42	901,924.10
15	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,348.93	46,371.57	32,017.97	933,942.07
16	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,495.91	46,371.57	31,237.05	965,179.11
17	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,645.83	46,371.57	30,475.17	995,654.28
18	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,798.74	46,371.57	29,731.87	1,025,386.15
19	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,954.72	46,371.57	29,006.70	1,054,392.85
20	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,113.81	46,371.57	28,299.22	1,082,692.07
21	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,276.09	46,371.57	27,609.00	1,110,301.07
22	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,441.61	46,371.57	26,935.61	1,137,236.68
23	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,610.44	46,371.57	26,278.64	1,163,515.32
24	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,782.65	46,371.57	25,637.70	1,189,153.02
25	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,958.30	46,371.57	25,012.39	1,214,165.40
26	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,137.47	46,371.57	24,402.33	1,238,567.73
27	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,320.22	46,371.57	23,807.15	1,262,374.89
28	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,506.62	46,371.57	23,226.49	1,285,601.38
29	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,696.76	46,371.57	22,659.99	1,308,261.36
30	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,890.69	46,371.57	22,107.31	1,330,368.67
		1,227,336.21							**1,848,206.39**	**1,330,368.67**	

Table .6: House sold in 10 years

House sold in 15 years

Year	Heat source	**Loan payments**	**Residual loan**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
		DKK	DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK
1	Gas oil	40,911.21 kr.			254.7	32,693.29	19,575.57	20,064.96	60,486.77	59,011.49	59,011.49
2	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,680.96	46,371.57	44,137.13	103,148.61
3	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,794.58	46,371.57	43,060.61	146,209.23
4	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,910.47	46,371.57	42,010.35	188,219.58
5	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,028.68	46,371.57	40,985.71	229,205.29
6	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,149.26	46,371.57	39,986.06	269,191.35
7	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,272.24	46,371.57	39,010.79	308,202.14
8	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,397.69	46,371.57	38,059.31	346,261.45
9	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,525.64	46,371.57	37,131.03	383,392.48
10	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,656.15	46,371.57	36,225.40	419,617.87
11	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,789.27	46,371.57	35,341.85	454,959.72
12	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,925.06	46,371.57	34,479.85	489,439.58
13	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,063.56	46,371.57	33,638.88	523,078.46
14	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,204.83	46,371.57	32,818.42	555,896.88
15	District heating	40,911.21 kr.	514,070.17	-207043.6	60.5	7,765.78	5,460.36	7,348.93	353,398.15	244,009.25	799,906.13
16	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,495.91	46,371.57	31,237.05	831,143.17
17	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,645.83	46,371.57	30,475.17	861,618.34
18	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,798.74	46,371.57	29,731.87	891,350.21
19	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,954.72	46,371.57	29,006.70	920,356.91
20	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,113.81	46,371.57	28,299.22	948,656.13
21	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,276.09	46,371.57	27,609.00	976,265.13
22	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,441.61	46,371.57	26,935.61	1,003,200.74
23	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,610.44	46,371.57	26,278.64	1,029,479.38
24	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,782.65	46,371.57	25,637.70	1,055,117.07
25	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,958.30	46,371.57	25,012.39	1,080,129.46
26	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,137.47	46,371.57	24,402.33	1,104,531.79
27	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,320.22	46,371.57	23,807.15	1,128,338.94
28	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,506.62	46,371.57	23,226.49	1,151,565.43
29	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,696.76	46,371.57	22,659.99	1,174,225.42
30	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,890.69	46,371.57	22,107.31	1,196,332.73
		1,227,336.21						-	1,712,288.87	1,196,332.73	

Table .7: House sold in 15 years

Year	Heat source	**Loan payments**	**Residual loan**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
		DKK	DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK
1	Gas oil	40,911.21 kr.			254.7	32,693.29	19,575.57	20,064.96	60,486.77	59,011.49	59,011.49
2	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,680.96	46,371.57	44,137.13	103,148.61
3	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,794.58	46,371.57	43,060.61	146,209.23
4	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,910.47	46,371.57	42,010.35	188,219.58
5	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,028.68	46,371.57	40,985.71	229,205.29
6	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,149.26	46,371.57	39,986.06	269,191.35
7	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,272.24	46,371.57	39,010.79	308,202.14
8	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,397.69	46,371.57	38,059.31	346,261.45
9	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,525.64	46,371.57	37,131.03	383,392.48
10	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,656.15	46,371.57	36,225.40	419,617.87
11	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,789.27	46,371.57	35,341.85	454,959.72
12	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,925.06	46,371.57	34,479.85	489,439.58
13	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,063.56	46,371.57	33,638.88	523,078.46
14	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,204.83	46,371.57	32,818.42	555,896.88
15	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,348.93	46,371.57	32,017.97	587,914.85
16	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,495.91	46,371.57	31,237.05	619,151.90
17	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,645.83	46,371.57	30,475.17	649,627.06
18	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,798.74	46,371.57	29,731.87	679,358.93
19	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,954.72	46,371.57	29,006.70	708,365.64
20	District heating	40,911.21 kr.	361,786.40	-207043.6	60.5	7,765.78	5,460.36	8,113.81	408,157.97	249,086.95	957,452.59
21	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,276.09	46,371.57	27,609.00	985,061.58
22	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,441.61	46,371.57	26,935.61	1,011,997.19
23	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,610.44	46,371.57	26,278.64	1,038,275.83
24	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,782.65	46,371.57	25,637.70	1,063,913.53
25	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,958.30	46,371.57	25,012.39	1,088,925.92
26	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,137.47	46,371.57	24,402.33	1,113,328.25
27	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,320.22	46,371.57	23,807.15	1,137,135.40
28	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,506.62	46,371.57	23,226.49	1,160,361.89
29	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,696.76	46,371.57	22,659.99	1,183,021.88
30	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,890.69	46,371.57	22,107.31	1,205,129.18
		1,227,336.21						-	1,767,048.70	1,205,129.18	

Table .8: House sold in 20 years

Year	Heat source	**Loan payments**	**Residual loan**	**House price gain**	Energy consumption	Energy consumption	Energy cost	Future E. Cost	Total annual cost	PV (savings cost)	Accumulated (cost of savings)
		DKK	DKK	DKK	kWh/m2	kWh	DKK	DKK	DKK	DKK	DKK
1	Gas oil	40,911.21 kr.			254.7	32,693.29	19,575.57	20,064.96	60,486.77	59,011.49	59,011.49
2	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,680.96	46,371.57	44,137.13	103,148.61
3	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,794.58	46,371.57	43,060.61	146,209.23
4	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	5,910.47	46,371.57	42,010.35	188,219.58
5	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,028.68	46,371.57	40,985.71	229,205.29
6	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,149.26	46,371.57	39,986.06	269,191.35
7	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,272.24	46,371.57	39,010.79	308,202.14
8	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,397.69	46,371.57	38,059.31	346,261.45
9	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,525.64	46,371.57	37,131.03	383,392.48
10	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,656.15	46,371.57	36,225.40	419,617.87
11	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,789.27	46,371.57	35,341.85	454,959.72
12	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	6,925.06	46,371.57	34,479.85	489,439.58
13	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,063.56	46,371.57	33,638.88	523,078.46
14	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,204.83	46,371.57	32,818.42	555,896.88
15	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,348.93	46,371.57	32,017.97	587,914.85
16	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,495.91	46,371.57	31,237.05	619,151.90
17	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,645.83	46,371.57	30,475.17	649,627.06
18	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,798.74	46,371.57	29,731.87	679,358.93
19	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	7,954.72	46,371.57	29,006.70	708,365.64
20	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,113.81	46,371.57	28,299.22	736,664.86
21	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,276.09	46,371.57	27,609.00	764,273.85
22	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,441.61	46,371.57	26,935.61	791,209.46
23	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,610.44	46,371.57	26,278.64	817,488.10
24	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,782.65	46,371.57	25,637.70	843,125.80
25	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	8,958.30	46,371.57	25,012.39	868,138.19
26	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,137.47	46,371.57	24,402.33	892,540.52
27	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,320.22	46,371.57	23,807.15	916,347.67
28	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,506.62	46,371.57	23,226.49	939,574.16
29	District heating	40,911.21 kr.			60.5	7,765.78	5,460.36	9,696.76	46,371.57	22,659.99	962,234.15
30	District heating	40,911.21 kr.		-207043.6	60.5	7,765.78	5,460.36	9,890.69	- 160,672.02	- 76,599.21	885,634.94
		1,227,336.21						-	1,198,218.71	885,634.94	

Table .9: House sold in 30 years

.5 Appendix 5 - Input for BE18 calculation - existing conditions

Langøvænget 1, loft + 100 mm file:///C:/Users/AndrewPC/Google Drive/BED 4 Masters/Simulat...

Be18 model: L101 Existing - FINAL Date 10.01.2019 08.12

Langøvænget 1, loft + 100 mm	
BBR-no	751-572042-001
Owner	Realea
Address	Langøvænget 1, 8381 Tilst

Comment	
The building	
Building type	Detached house
Rotation	0.0 deg
Area of heated floor	126.3 m²
Area heated basement	0.0 m²
Area existing / other usage	0.0 m²
Heated gross area incl. basement	126.3 m²
Heat capacity	100.0 Wh/K m²
Normal usage time	168 hours/week
Usage time, start at - end at, time	0 - 24
Calculation rules	
Calculation rules	BR: Actual conditions
Suplement to energy frame	0.0 kWh/m² år
Heat supply and cooling	
Basic heat supply	Boiler
Electric panels	No
Wood stoves, gas radiators etc.	No
Solar heating plant	No
Heat pumps	No
Solar cells	No
Wind mills	No
Mechanical cooling	No

Room temperatures, set points	
Heating	20.0 °C
Wanted	23.0 °C
Natural ventilation	24.0 °C
Mechanical cooling	25.0 °C
Heating store	15.0 °C
Dimensioning temperatures	
Room temp.	20.0 °C
Outdoor temp.	-12.0 °C

1 of 6 10/01/2019, 08:13

Figure .29: Be18 input data

Langøvænget 1, loft + 100 mm file:///C:/Users/AndrewPC/Google Drive/BED 4 Masters/Simulat...

Dimensioning temperatures	
Room temp. store	15.0 °C

External walls, roofs and floors					
Building component	Area (m²)	U (W/m²K)	b	Dim.Inside (C)	Dim.Outside (C)
Crawl space floor	117.8	0.68	0.700		
External wall	101.0	0.49	1.000		
External wall lightweight	7.6	0.80	1.000		
Ceiling towards attic	126.3	0.44	1.000		
Hatch towards attic	0.5	1.80	1.000		
Ground supported floor at bathrooms	8.5	1.20	0.700		
Ialt	361.7	-	-	-	-

Foundations etc.					
Building component	l (m)	Loss (W/mK)	b	Dim.Inside (C)	Dim.Outside (C)
Fundamenter	50.8	0.70	1.000		
Windows linear loss	65.2	0.11	1.000		
Ialt	116.0	-	-	-	-

Windows and outer doors													
Building component	Number	Orient	Inclination	Area (m²)	U (W/m²K)	b	Ff (-)	g (-)	Shading	Fc (-)	Dim.Inside (C)	Dim.Outside (C)	Ext
Bedroom 1	1	270	90.0	1.7	2.80	1.000	0.80	0.63	Generel	1.00			0
Bedroom 2	1	270	90.0	2.2	2.80	1.000	0.82	0.63	Generel	1.00			0
Bedroom 3 E	1	90	90.0	1.9	2.80	1.000	0.81	0.63	Generel	1.00			0
Bedroom 3 W	1	270	90.0	1.9	2.80	1.000	0.81	0.63	Generel	1.00			0
Corridor (door)	1	90	90.0	1.8	2.80	1.000	0.75	0.63	Generel	1.00			0
Bathroom & WC	2	90	90.0	0.4	2.80	1.000	0.59	0.63	Generel	1.00			0
Entrance (door)	1	90	90.0	1.8	2.80	1.000	0.75	0.63	Generel	1.00			0
Kitchen E	1	90	90.0	2.6	2.80	1.000	0.83	0.63	Generel	1.00			0
Kitchen S	1	180	90.0	2.4	2.80	1.000	0.83	0.63	Generel	1.00			0
Living room big	1	270	90.0	8.9	2.00	1.000	0.87	0.63	Generel	1.00			0
Living room small	1	270	90.0	2.3	2.80	1.000	0.82	0.63	Generel	1.00			0
Ialt	12	-	-	28.3	-	-	-	-	-	-	-	-	

Shading					
Description	Horizon (°)	Eaves (°)	Left (°)	Right (°)	Window opening (%)
Generel	15	40	0	0	5

2 of 6 10/01/2019, 08:13

Figure .30: Be18 input data

Langøvænget 1, loft + 100 mm file:///C:/Users/AndrewPC/Google Drive/BED 4 Masters/Simulat...

Ventilation													
Zone	Area (m²)	Fo, -	qm (l/s m²), Winter	n vgv (-)	ti (°C)	El-HC	qn (l/s m²), Winter	qi,n (l/s m²), Winter	SEL (kJ/m³)	qm,s (l/s m²), Summer	qn,s (l/s m²), Summer	qm,n (l/s m²), Night	qn,n (l/s m²), Night
Natural ventilation	126.3	1.00	0.00	0.00	0.0	No	0.30	0.00	0.0	0.00	1.20	0.00	0.00

Internal heat supply				
Zone	Area (m²)	Persons (W/m²)	App. (W/m²)	App,night (W/m²)
Internal gains	126	1.5	3.5	0.0

Lighting											
Zone	Area (m²)	General (W/m²)	General (W/m²)	Lighting (lux)	DF (%)	Control (U, M, A, K)	Fo (-)	Work (W/m²)	Other (W/m²)	Stand-by (W/m²)	Night (W/m²)

Other el. consumption	
Outdoor lighting	0.0 W
Spec. apparatus, during service	0.0 W
Spec. apparatus, always	0.0 W

Basement car parkings etc.											
Zone	Area (m²)	General (W/m²)	General (W/m²)	Lighting (lux)	DF (%)	Control (U, M, A, K)	Fo (-)	Work (W/m²)	Other (W/m²)	Stand-by (W/m²)	Night (W/m²)

Mechanical cooling	
Description	Mekanisk køling
Share of floor area	0
El-demand	0.00 kWh-el/kWh-cool
Heat-demand	0.00 kWh-heat/kWh-cool
Load factor	0
Heat capacity phase shift (cooling)	0 Wh/m²
Increase factor	1.00
Documentation	

Heat distribution plant		
Composition and temperature		
Supply pipe temperature	70.0 °C	Fremløbstemperatur
Return pipe temperature	40.0 °C	Returtemperatur
Type of plant	2-string	Anlægstype

Pumps				
Pump type	Description	Number	Pnom	Fp
Constant service all year	UPS 15-40, trin 3 ved vesigtigelse	1	60.0 W	1.00

3 of 6 10/01/2019, 08:13

Figure .31: Be18 input data

Heating pipes					
Pipe lengths in supply and return	l (m)	Loss (W/mK)	b	Outdoor comp (J/N)	Unused summer (J/N)
Pipe in the crawl space	30.0	0.14	0.700	N	N
Pipes cast in terrain deck	5.0	0.14	0.700	N	N

Domestic hot water	
Description	Varmt brugsvand
Hot-water consumption, average for the building	250.0 litre/year per m² of floor area
Domestic hot water temp.	55.0 °C
Hot-water tank	
Description	VBV Beholder
Number of hot-water containers	1.0
Tank volume	100.0 liter
Supply temperature from central heating	60.0 °C
El. heating of DHW	No
Solar heat tank with heating coil	No
Heat loss from hot-water tank	1.1 W/K
Temp. factor for setup room	0.0
Charging pump	
Effect	0.0 W
Controled	No
Charge effect	5.0 kW

Heat loss from connector pipe to DHW tank			
Length	Loss	b	Description
1.0 m	1.0 W/K	0.00	Rør i unit er uisolerede
0.0 m	0.0 W/K	0.00	

Cirkulating pump for DHW	
Description	PumpCirc
Number	0.0
Effect	0.0 W
Number	0.0
Effect	0.0 W
Reduction factor	1.00 [-]
El. tracing of discharge water pipe	No

Domestic hot water discharge pipes			
Pipe lengths in supply	l (m)	Loss (W/mK)	b

Figure .32: Be18 input data

Langøvænget 1, loft + 100 mm file:///C:/Users/AndrewPC/Google Drive/BED 4 Masters/Simulat...

Domestic hot water discharge pipes			
and return			

Water heaters	
Electric water heater	
Description	Elvandvarmer
Share of DHW in separate el. water heaters	0.0
Heat loss from hot-water tank	0.0 W/K
Temp. factor for setup room	1.00
Gas water heater	
Description	Gasvandvarmer
Share of DHW in separate gas water heaters	0.0
Heat loss from hot-water tank	0.0 W/K
Efficiency	0.5
Pilot flame	50.0 W
Temp. factor for setup room	1.00

Boiler				
Description	Boiler			
Fuel	Oil			
Number of boilers	1			
Nominal effect	20.0 kW			
Share of nominal effect for DHW production, -	1.0			
Nominal efficiencies				
Type	Load	Efficiency	Boiler temp.	Correction
Full load	1.0	0.93	70.0 °C	0.000 -/°C
Partial load	0.3	0.96	50.0 °C	0.000 -/°C
Idle loss				
Type	Load	Loss factor	Share for room	Temp. dif.
Idle	0.0	0.013	0.50	30.0 °C
Operating				
Boiler temp., min	60.0 °C			
Temp. factor for setup room	0.00			
Fan	100.0 W			
El for automatics	5.0 W			

District heat exchanger

5 of 6 10/01/2019, 08:13

Figure .33: Be18 input data

District heat exchanger	
Description	Ny fjernvarmeveksler
Nominal effect	0.0 kW
Heat loss	0.0 W/K
DHW heating through exchanger	No
Exchanger temperature, min	60.0 °C
Temp. factor for setup room	1.00
Automatics, stand-by	5.0 W

Other room heating	
Direct el for room heating	
Description	Supplerende direkte rumopvarmning
Share of floor area	0.0
Wood stoves, gas radiators etc.	
Description	
Share of floor area	0.0
Efficiency	0.4
Air flow requirement	0.1 m³/s

Solar heating plant		
Description	Nyt solvarmeanlæg	
Type	Domestic hot water	
Solar collector		
Area 0.0 m²	Start 0.8	-
Coefficient of heat loss a1 3.5 W/m²K	Coefficient of heat loss a2 0.0 W/m²K	Anglefactor 0.0
Orientation	Slope 0.0 °	-
Horizon 10.0 °	Left 0.0 °	Right 0.0 °
Solar collector pipe		
Length 0.0 m	Heat loss 0.00 W/mK	Circuit 0.8
Electricity		
Pump in solar collector circuit 50.0 W	Automatics, stand-by 5.0 W	

Figure .34: Be18 input data

.6 Appendix 6 - Data from dynamic simulation - Design Builder

.6.1 Input parameters for Occupancy

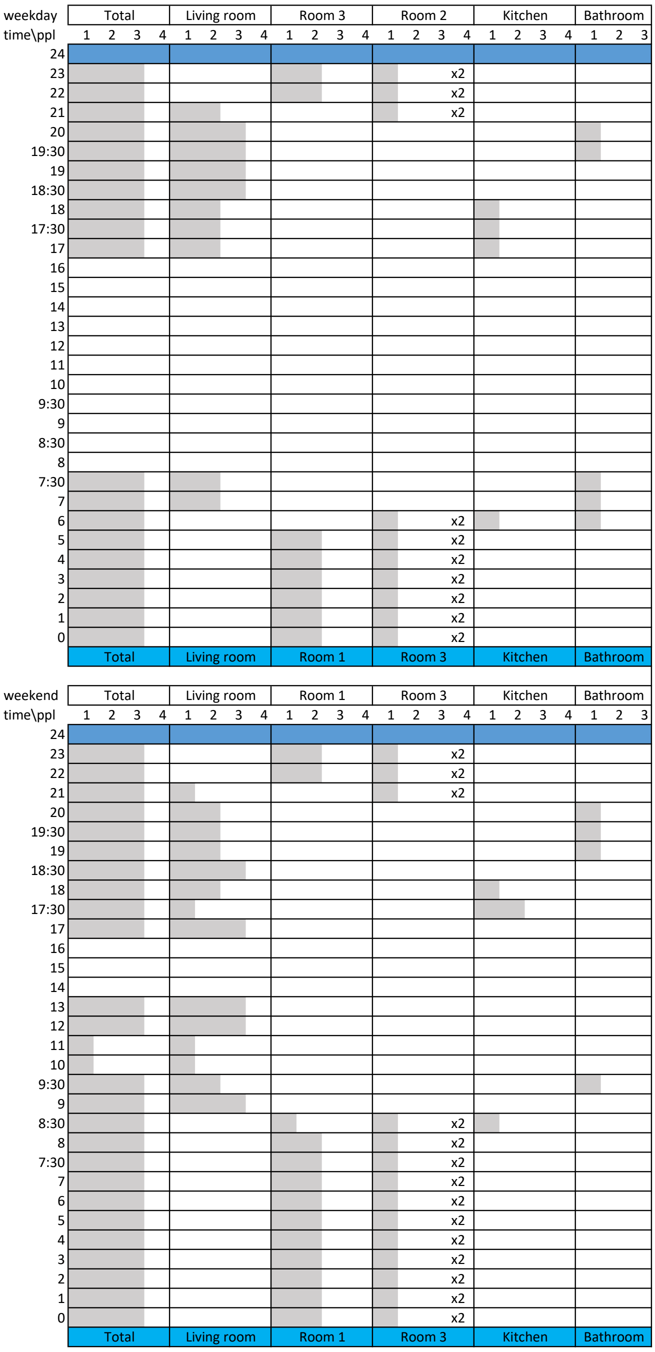


Figure .35: Occupancy for the whole house for weekdays and weekends

.6.2 Input parameters for Design Builder

Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	153.76	22.94	53.94	22.94	53.94
Above Ground Wall Area [m2]	153.76	22.94	53.94	22.94	53.94
Window Opening Area [m2]	29.14	0	9.03	2.08	18.03
Gross Window-Wall Ratio [%]	18.95	0	16.73	9.07	33.43
Above Ground Window-Wall Ratio [%]	18.95	0	16.73	9.07	33.43

Conditioned Window-Wall Ratio

	Total	North (315 to 45 deg)	East (45 to 135 deg)	South (135 to 225 deg)	West (225 to 315 deg)
Gross Wall Area [m2]	153.76	22.94	53.94	22.94	53.94
Above Ground Wall Area [m2]	153.76	22.94	53.94	22.94	53.94
Window Opening Area [m2]	29.14	0	9.03	2.08	18.03
Gross Window-Wall Ratio [%]	18.95	0	16.73	9.07	33.43
Above Ground Window-Wall Ratio [%]	18.95	0	16.73	9.07	33.43

Skylight-Roof Ratio

	Total
Gross Roof Area [m2]	128.76
Skylight Area [m2]	0
Skylight-Roof Ratio [%]	0

Zone Summary

	Area [m2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [m3]	People [m2 per person]
GROUNDFLOOR:SLEEPINGROOM2	11.2	Yes	Yes	34.73	3.73
GROUNDFLOOR:CORRIDOR	11.88	Yes	Yes	36.84	3.96
GROUNDFLOOR:SLEEPINGROOM1	7.47	Yes	Yes	23.15	2.49
GROUNDFLOOR:ENTRANCE	4.69	Yes	Yes	14.54	1.56
GROUNDFLOOR:TOILET	1.79	Yes	Yes	5.54	0.6
GROUNDFLOOR:LIVINGROOM	35.21	Yes	Yes	109.15	11.74
GROUNDFLOOR:KITCHEN	15.76	Yes	Yes	48.87	5.25
GROUNDFLOOR:BATHROOM	4.49	Yes	Yes	13.93	1.5
GROUNDFLOOR:SLEEPINGROOM3	15.57	Yes	Yes	48.26	5.19
Total	108.07			335.01	4
Conditioned Total	108.07			335.01	4
Unconditioned Total	0			0	
Not Part of Total	0			0	

GROUNDFLOOR:SLEEPINGROOM2	Above Ground Gross Wall Area [m2]	Underground Gross Wall Area [m2]	Window Glass Area [m2]	Opening Area [m2]	Plug and Process [W/m2]
GROUNDFLOOR:CORRIDOR	11.22	0	1.98	2.21	3.29
GROUNDFLOOR:SLEEPINGROOM1	6.39	0	1.65	1.88	2.94
GROUNDFLOOR:ENTRANCE	7.59	0	1.49	1.69	3.29
GROUNDFLOOR:TOILET	5.95	0	1.65	1.88	2.94
GROUNDFLOOR:LIVINGROOM	3.35	0	0.27	0.36	2.94
GROUNDFLOOR:KITCHEN	41.2	0	11.4	12.18	3.61
GROUNDFLOOR:BATHROOM	30.47	0	4.2	4.68	3.29
GROUNDFLOOR:SLEEPINGROOM3	7.9	0	0.27	0.36	3.29
Total	39.68	0	3.46	3.9	3.29
Conditioned Total	153.76	0	26.36	29.14	3.3348
Unconditioned Total	153.76	0	26.36	29.14	3.3348
Not Part of Total	0	0	0	0	
	0	0	0	0	

Figure .36: Design builder input data

	Construction	Reflectance	U-Factor with Film [W/m2-K]	U-Factor no Film [W/m2-K]	Gross Area [m2]	Net Area [m2]	Azimuth [deg]	Tilt [deg]	Cardinal Direction
GROUNDFLOOR:SLEEPINGROOM2_WALL_4_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	11.22	9.01	270	90	W
GROUNDFLOOR:SLEEPINGROOM2_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	12.96	12.96	0	180	
GROUNDFLOOR:SLEEPINGROOM2_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	12.96	12.96	180	0	
GROUNDFLOOR:CORRIDOR_WALL_2_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	6.39	4.51	90	90	E
GROUNDFLOOR:CORRIDOR_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	4.59	4.59	0	180	
GROUNDFLOOR:CORRIDOR_GROUNDFLOOR_0_0_1	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	2.35	2.35	0	180	
GROUNDFLOOR:CORRIDOR_GROUNDFLOOR_0_0_2	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	6.56	6.56	0	180	
GROUNDFLOOR:CORRIDOR_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	1.58	1.58	180	0	
GROUNDFLOOR:CORRIDOR_ROOF_1_0_1	LANGELINIE CEILING	0.4	0.332	0.347	4.05	4.05	180	0	
GROUNDFLOOR:CORRIDOR_ROOF_1_0_2	LANGELINIE CEILING	0.4	0.332	0.347	7.87	7.87	180	0	
GROUNDFLOOR:SLEEPINGROOM1_WALL_4_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	7.59	5.9	270	90	W
GROUNDFLOOR:SLEEPINGROOM1_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	8.77	8.77	0	180	
GROUNDFLOOR:SLEEPINGROOM1_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	8.77	8.77	180	0	
GROUNDFLOOR:ENTRANCE_WALL_7_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	5.95	4.07	90	90	E
GROUNDFLOOR:ENTRANCE_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	0.55	0.55	0	180	
GROUNDFLOOR:ENTRANCE_GROUNDFLOOR_0_0_1	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	5.26	5.26	0	180	

Figure .37: Design builder input data

GROUNDFLOOR:ENTRANCE_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	4.28	4.28	180	0	
GROUNDFLOOR:ENTRANCE_ROOF_1_0_1	LANGELINIE CEILING	0.4	0.332	0.347	1.53	1.53	180	0	
GROUNDFLOOR:TOILET_WALL_2_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	3.35	2.99	90	90	E
GROUNDFLOOR:TOILET_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 BATHROOM GROUND FLOOR	0.71	0.125	0.128	2.41	2.41	0	180	
GROUNDFLOOR:TOILET_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	2.41	2.41	180	0	
GROUNDFLOOR:LIVINGROOM_WALL_5_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	26.75	14.57	270	90	W
GROUNDFLOOR:LIVINGROOM_WALL_6_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	14.45	14.45	180	90	S
GROUNDFLOOR:LIVINGROOM_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	40.22	40.22	0	180	
GROUNDFLOOR:LIVINGROOM_ROOF_1_0_	LANGELINIE CEILING	0.4	0.332	0.347	40.22	40.22	180	0	
GROUNDFLOOR:KITCHEN_WALL_2_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	21.98	19.38	90	90	E
GROUNDFLOOR:KITCHEN_WALL_5_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	8.49	6.41	180	90	S
GROUNDFLOOR:KITCHEN_GROUNDFLOOR	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	19.43	19.43	0	180	
GROUNDFLOOR:KITCHEN_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	19.43	19.43	180	0	
GROUNDFLOOR:BATHROOM_WALL_2_0_0	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	7.9	7.54	90	90	E
GROUNDFLOOR:BATHROOM_GROUNDFLOO	MASTER PROJECT BE18 BATHROOM GROUND FLOOR	0.71	0.125	0.128	5.69	5.69	0	180	
GROUNDFLOOR:BATHROOM_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	5.69	5.69	180	0	
GROUNDFLOOR:SLEEPINGRO	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	8.37	6.42	90	90	E
GROUNDFLOOR:SLEEPINGRO	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	22.94	22.94	0	90	N
GROUNDFLOOR:SLEEPINGROOM3_WALL_4	MASTER PROJECT BE18 EXTERNAL WALL	0.3	0.175	0.18	8.37	6.42	270	90	W
GROUNDFLOOR:SLEEPINGROOM3_GROUNDFLOOR_0_0_0	MASTER PROJECT BE18 CRAWLSPACE GROUND FLOOR	0.4	0.234	0.243	19.98	19.98	0	180	
GROUNDFLOOR:SLEEPINGROOM3_ROOF_1_0_0	LANGELINIE CEILING	0.4	0.332	0.347	19.98	19.98	180	0	

Figure .38: Design builder input data

.6.3 Simulated living room air, radiant and operative temperatures

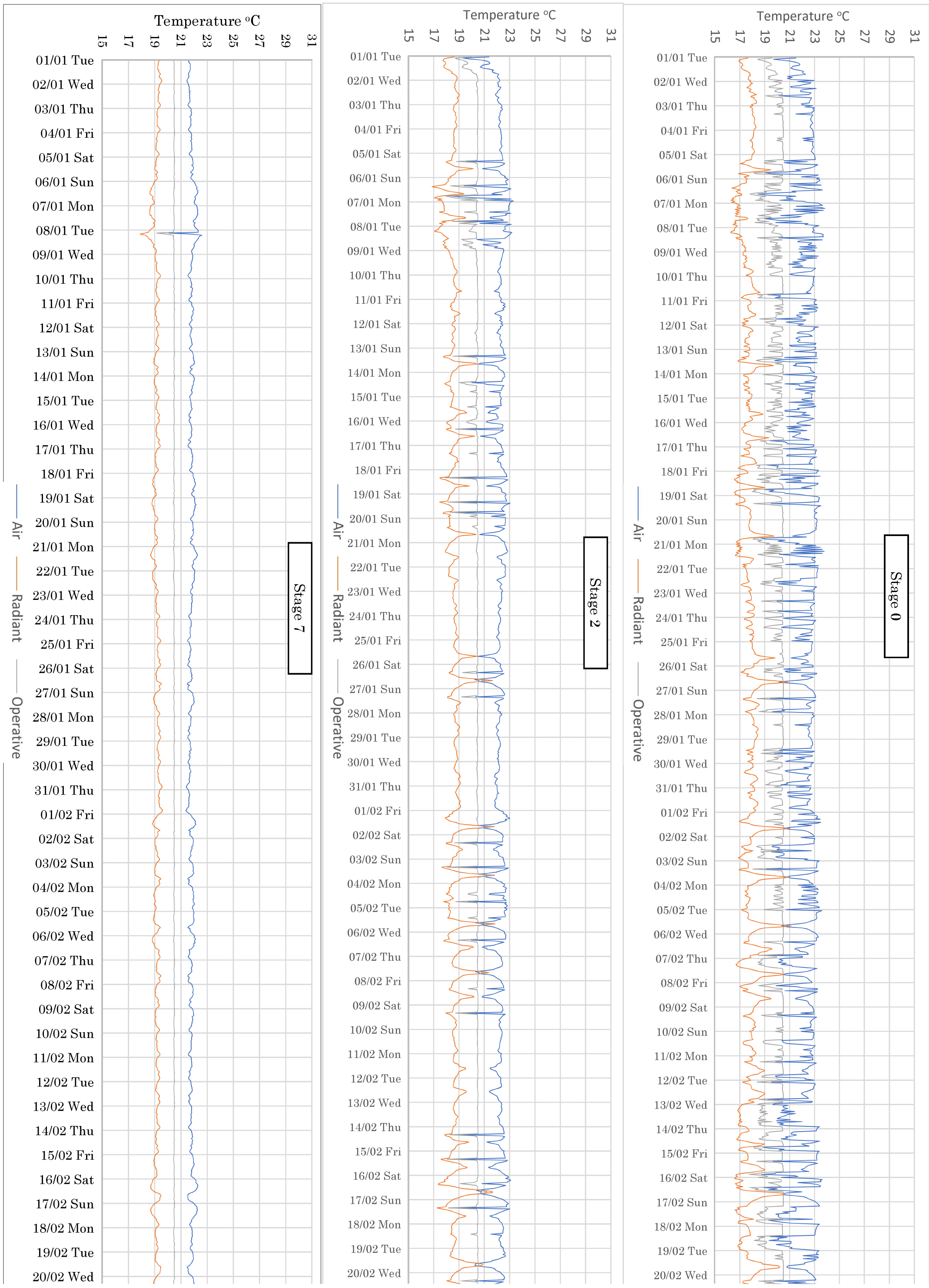


Figure .39: Design builder Living room temperatures

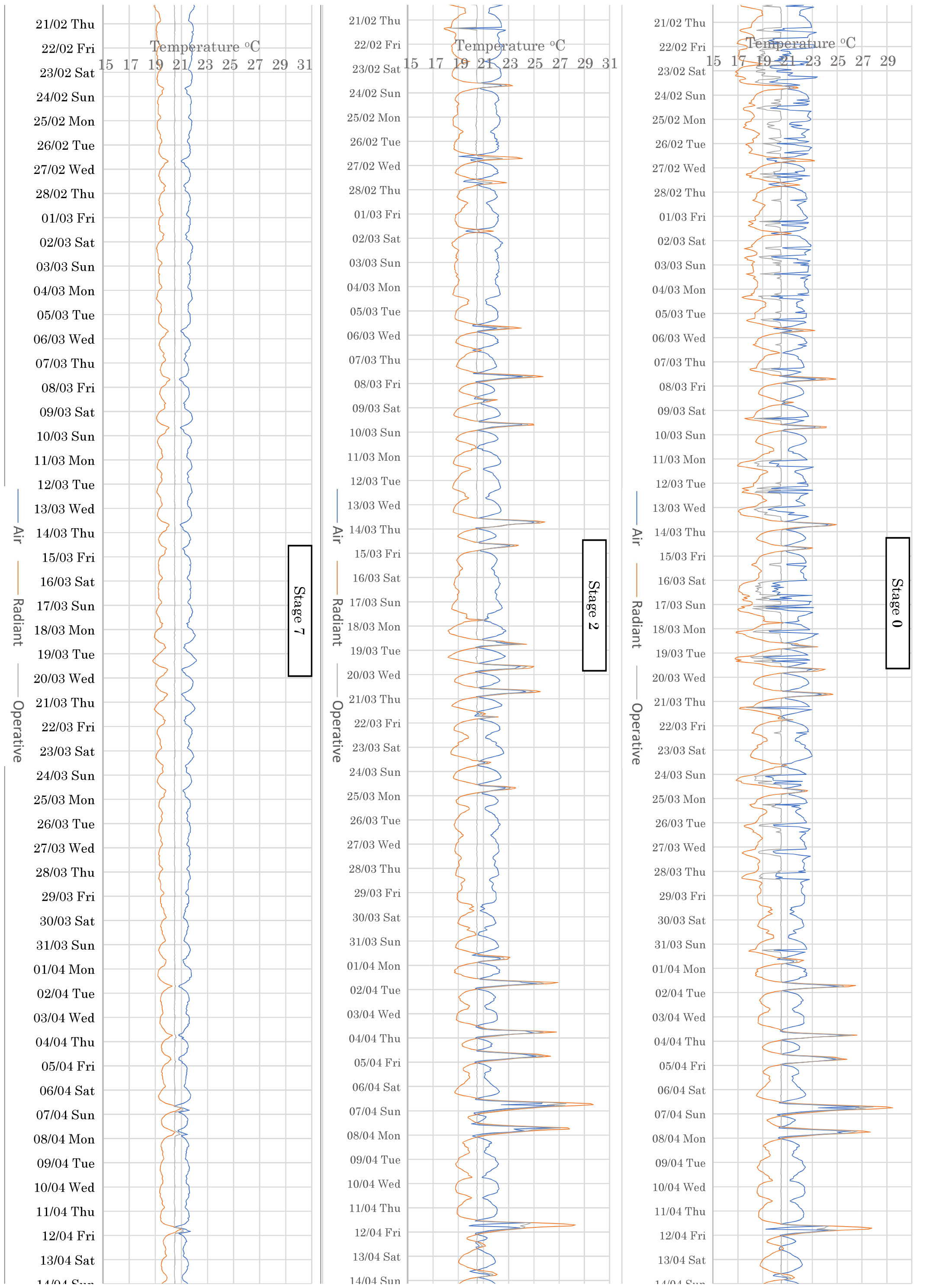


Figure .40: Design builder Living room temperatures

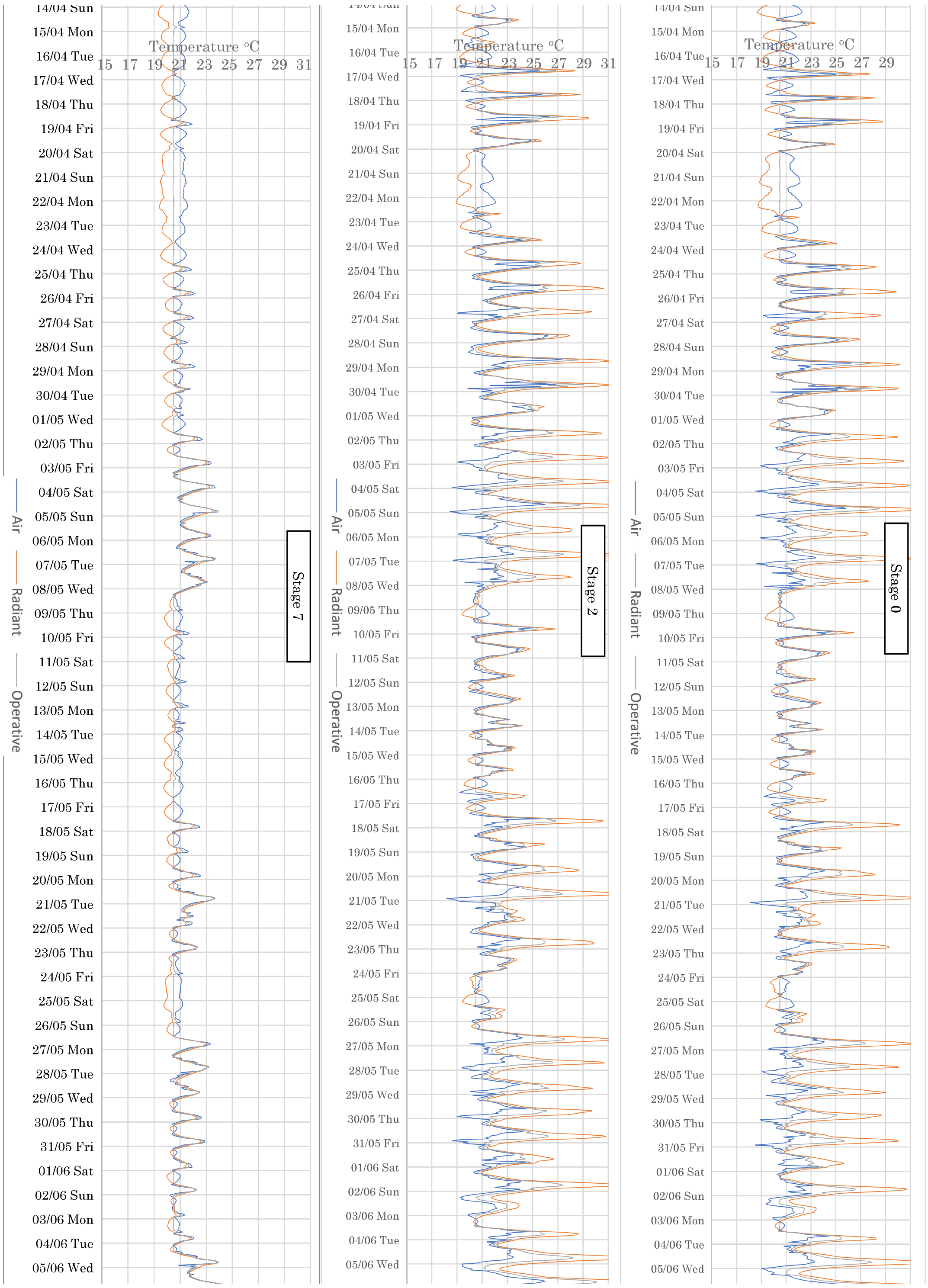


Figure .41: Design builder Living room temperatures

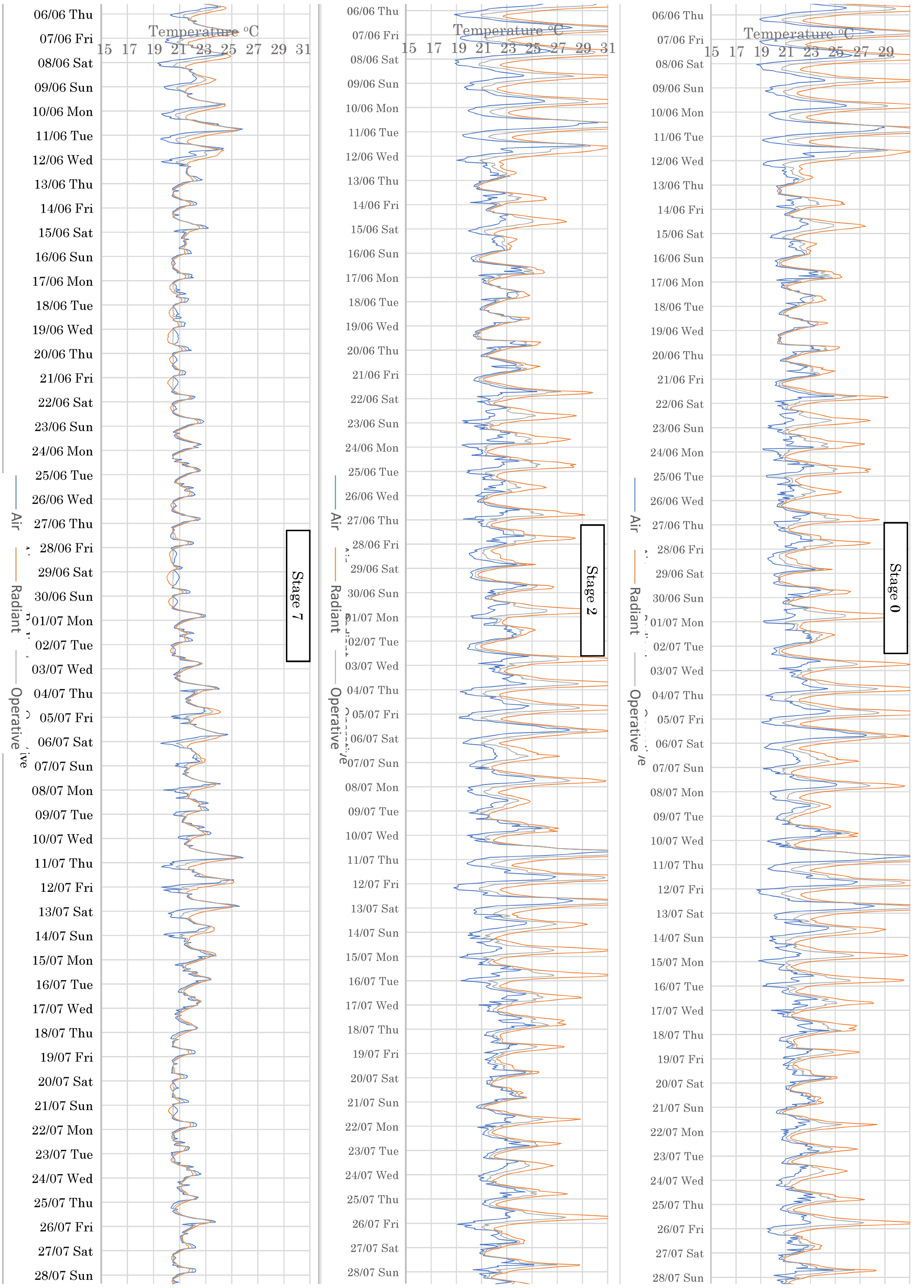


Figure .42: Design builder Living room temperatures

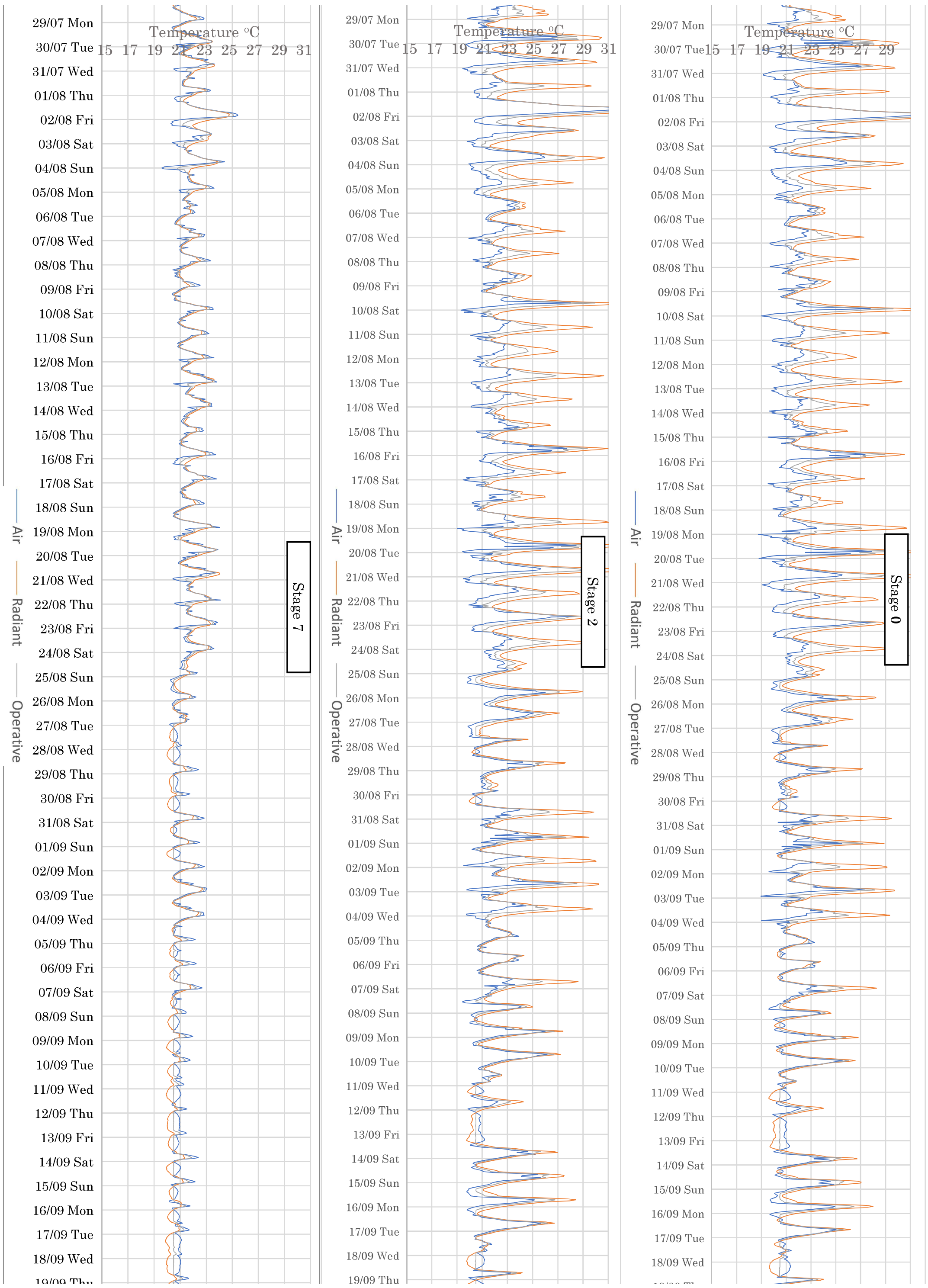


Figure .43: Design builder Living room temperatures

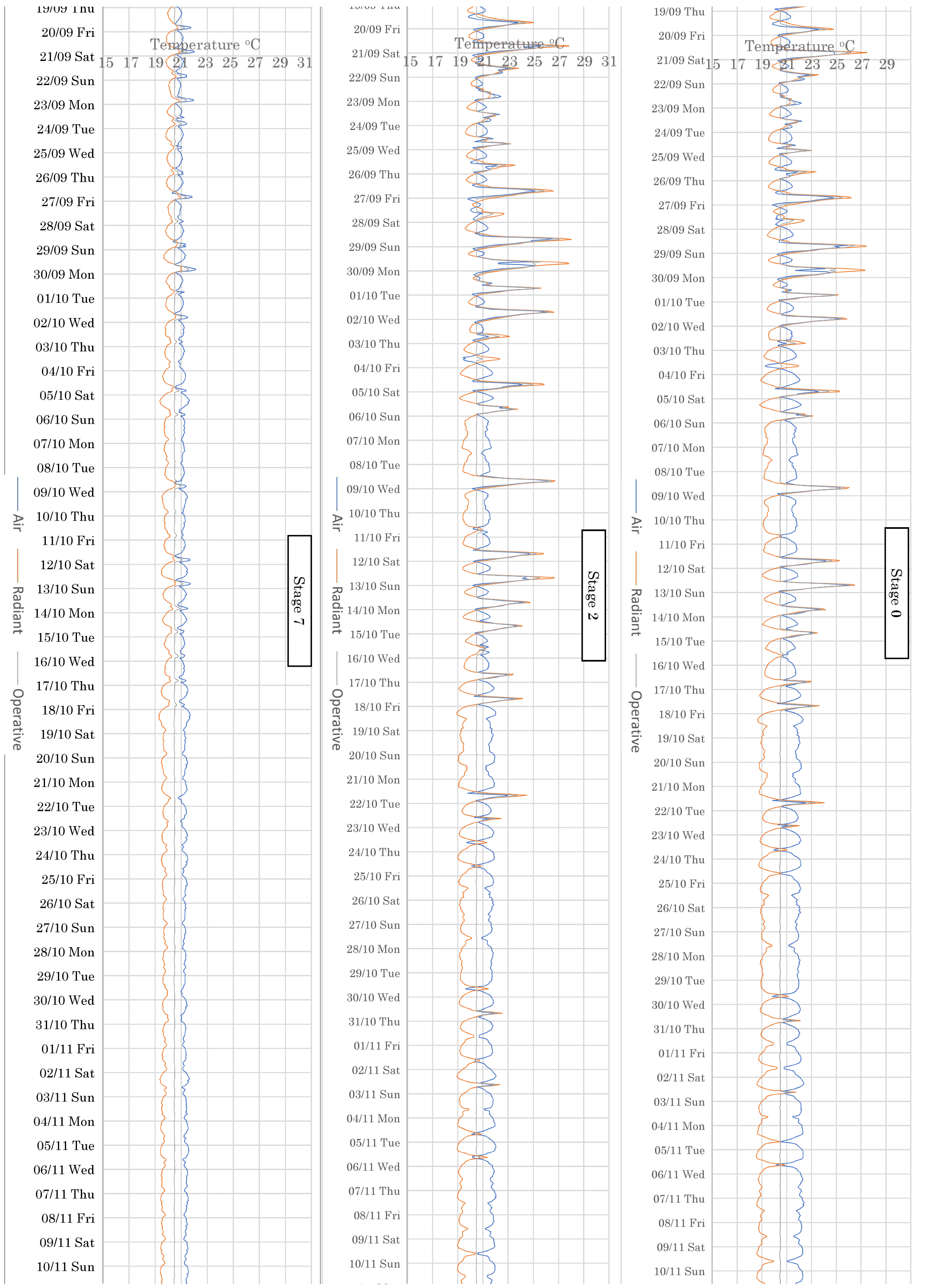


Figure .44: Design builder Living room temperatures

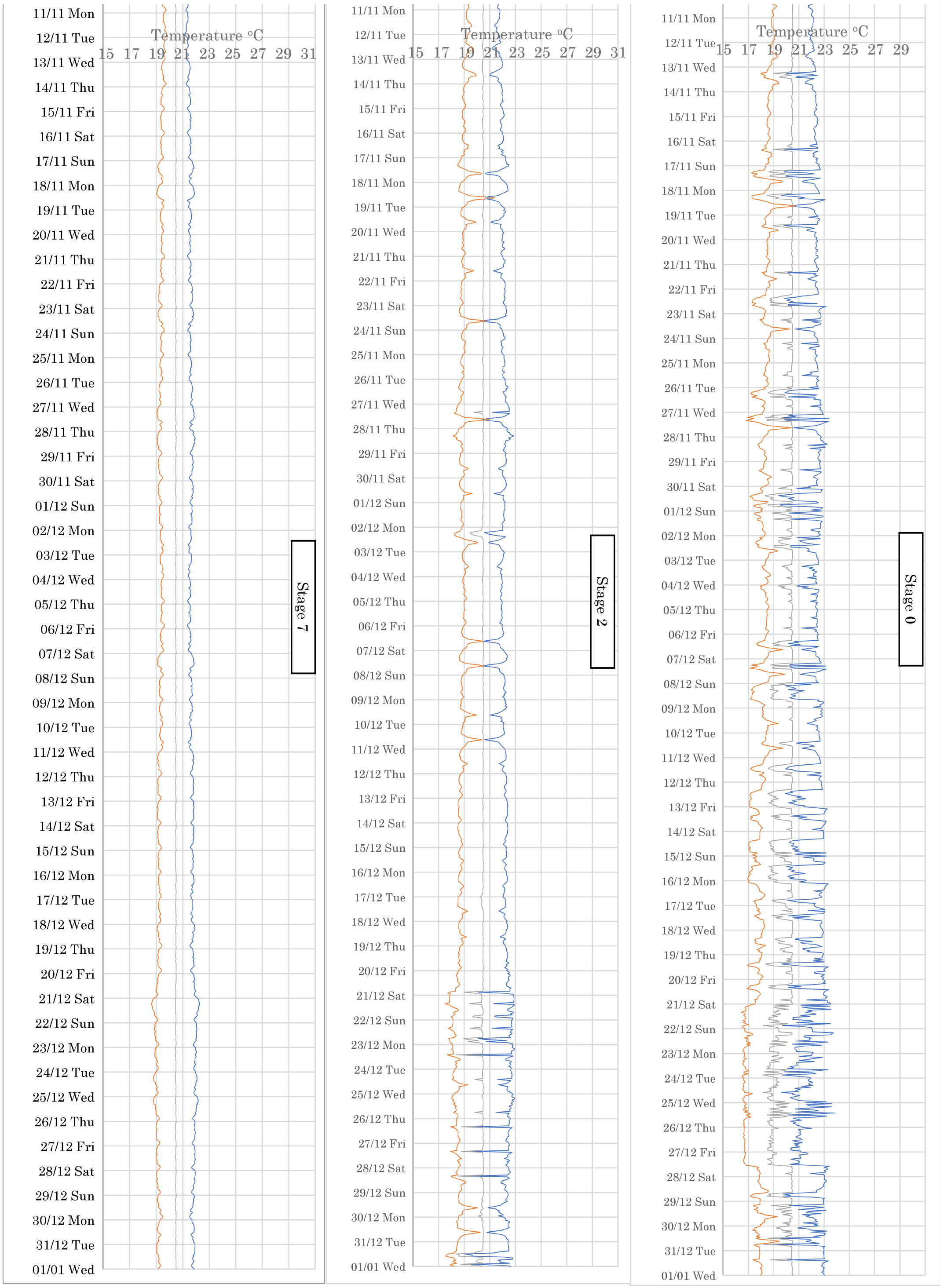


Figure .45: Design builder Living room temperatures

.6.4 Simulated iving room surface temperatures

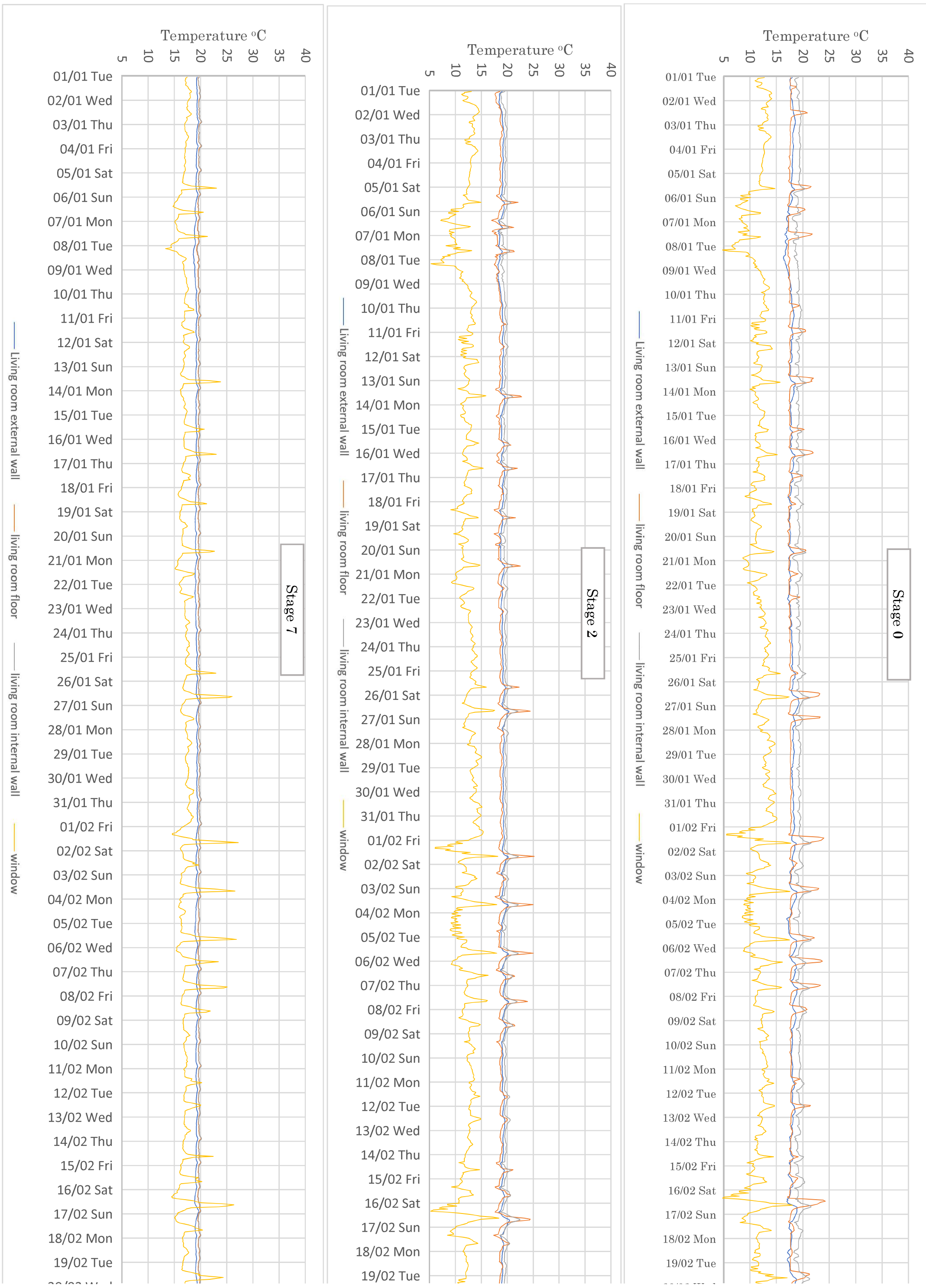


Figure .46: Design builder Living room surface temperatures

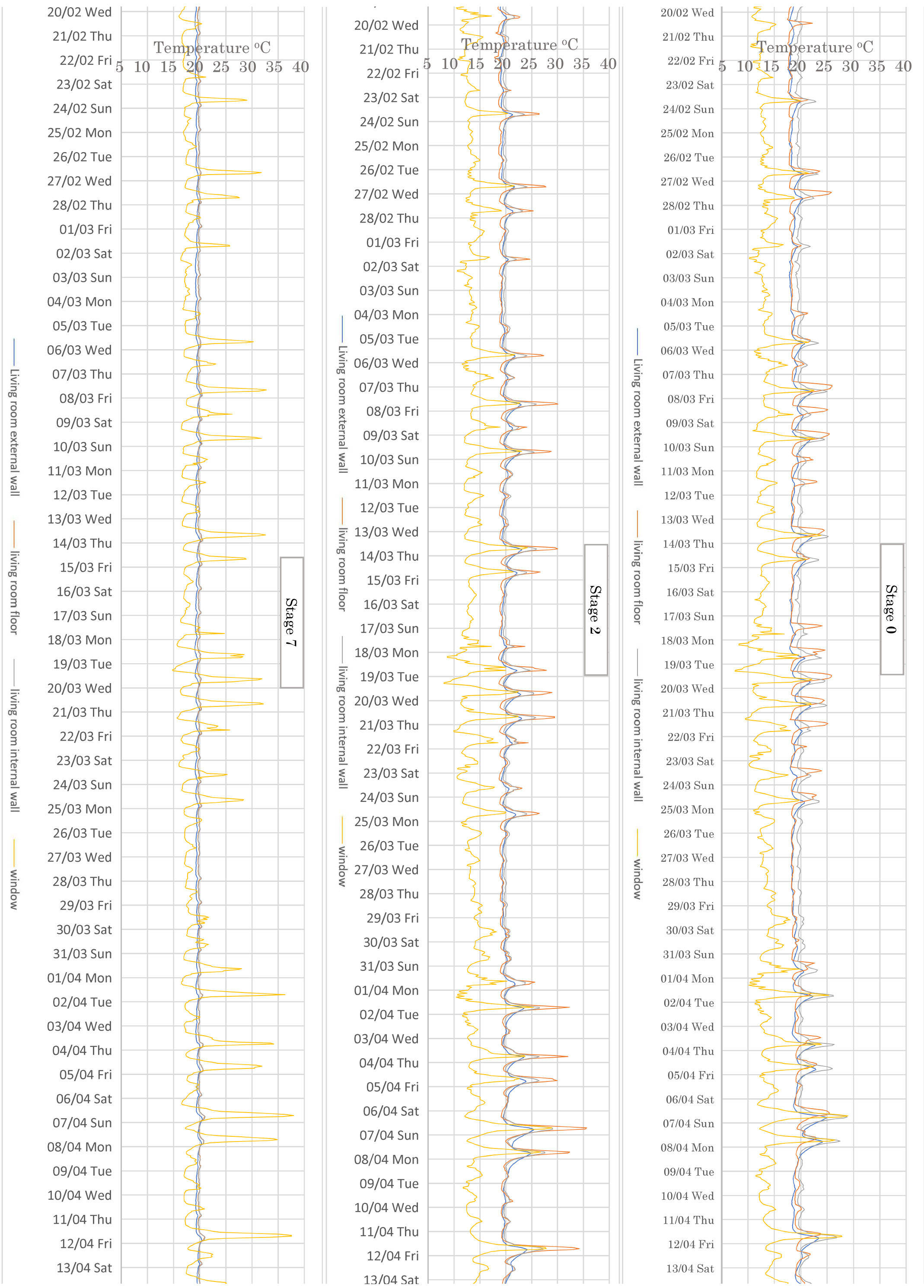


Figure .47: Design builder Living room surface temperatures

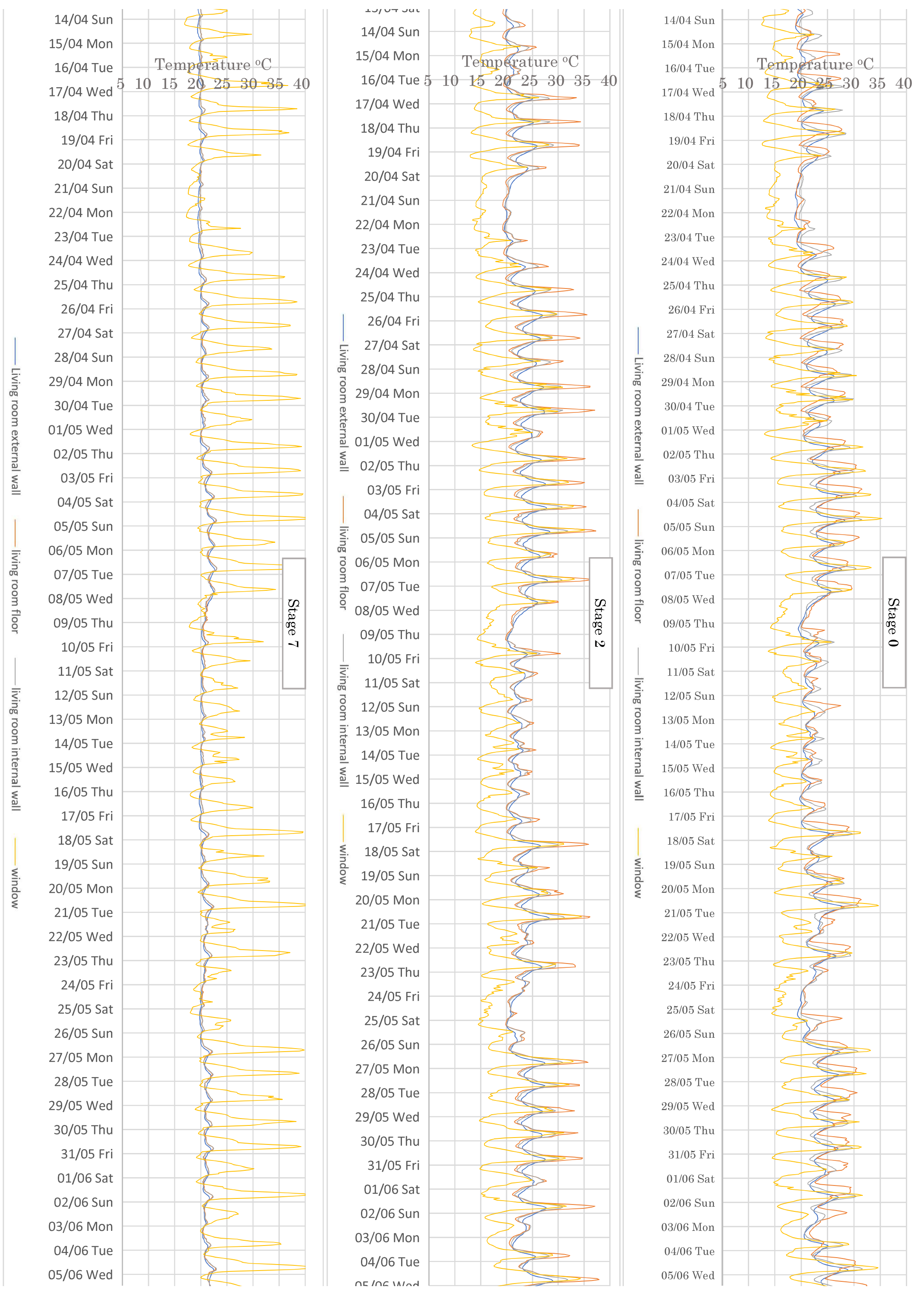


Figure .48: Design builder Living room surface temperatures

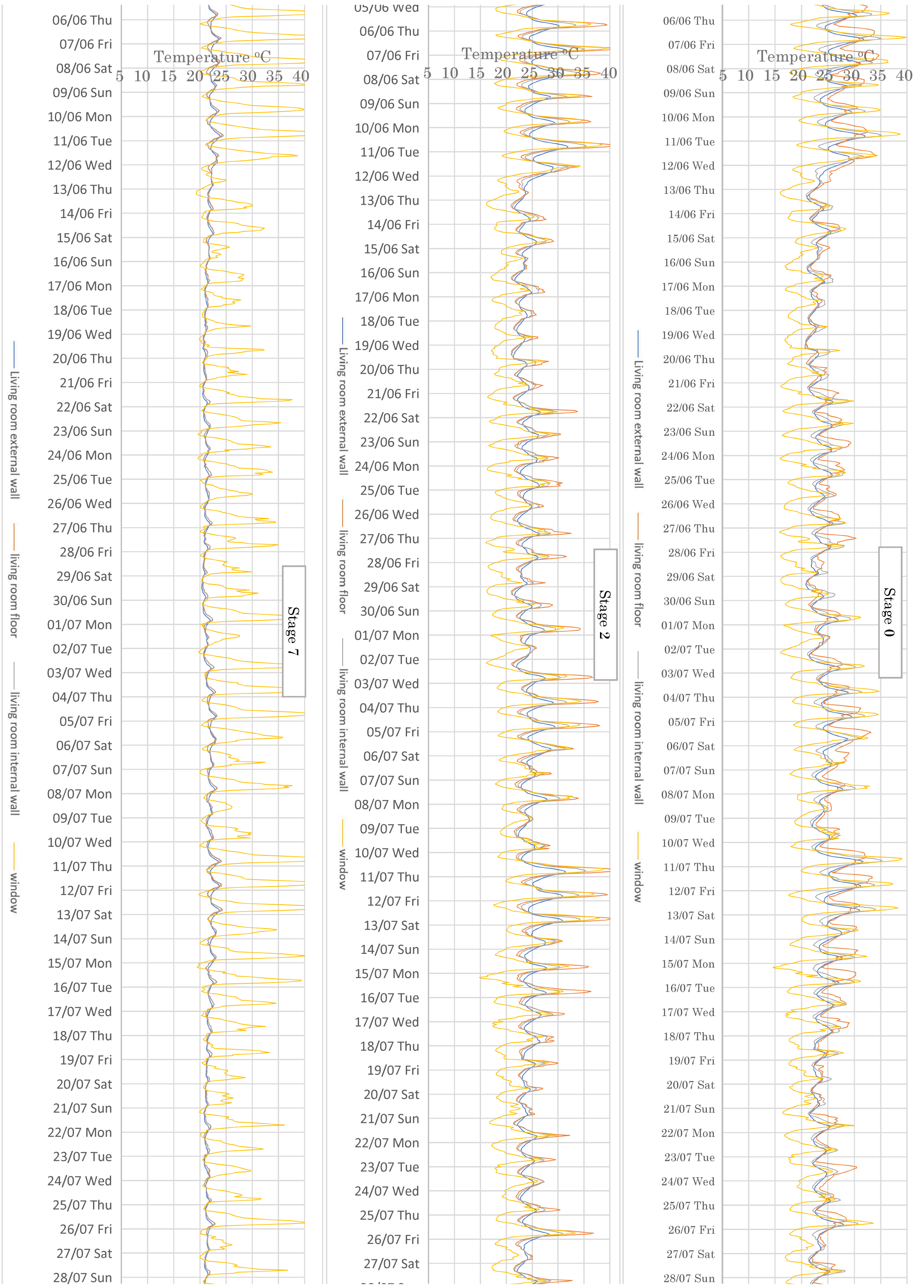


Figure .49: Design builder Living room surface temperatures

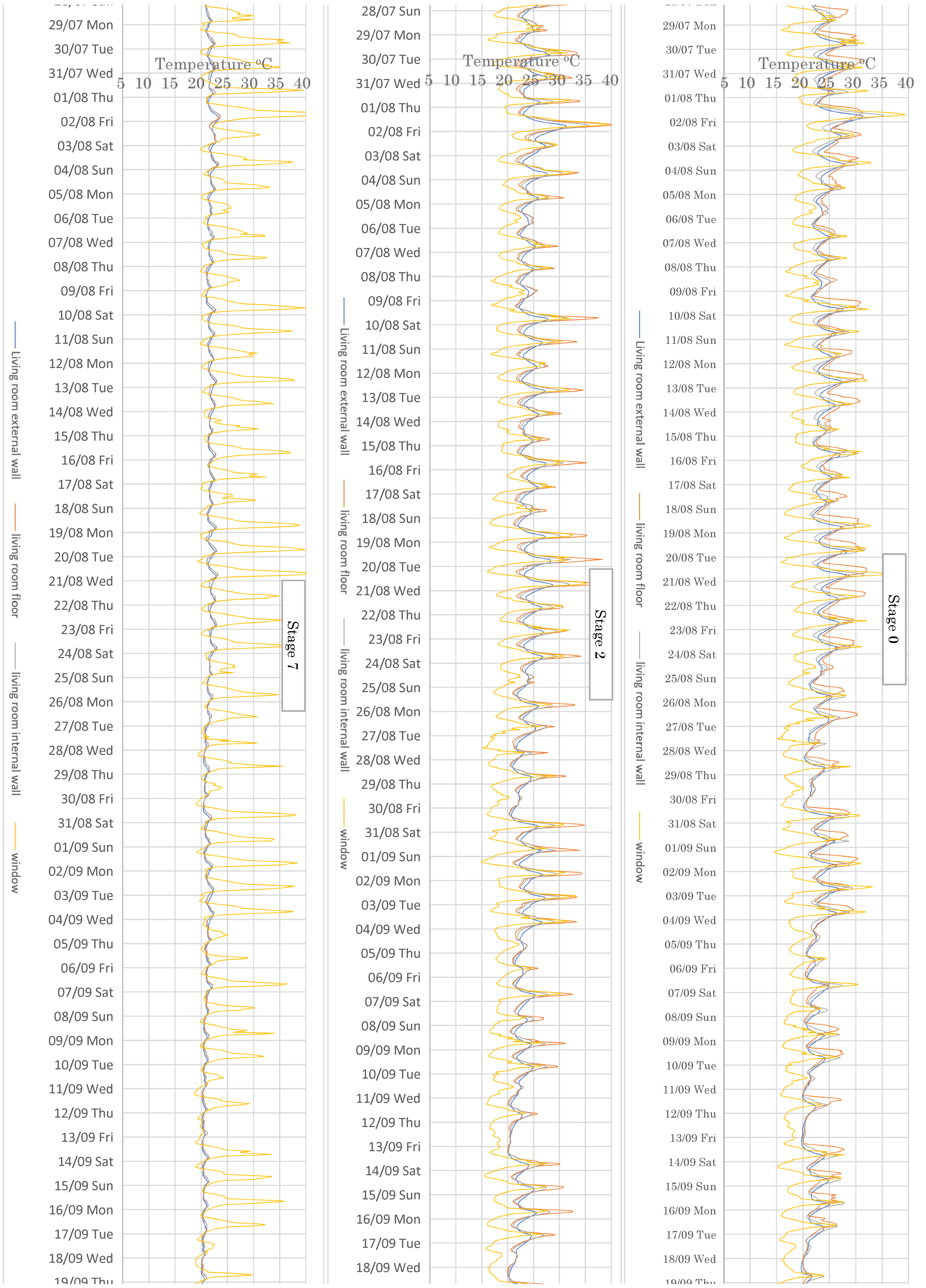


Figure .50: Design builder Living room surface temperatures

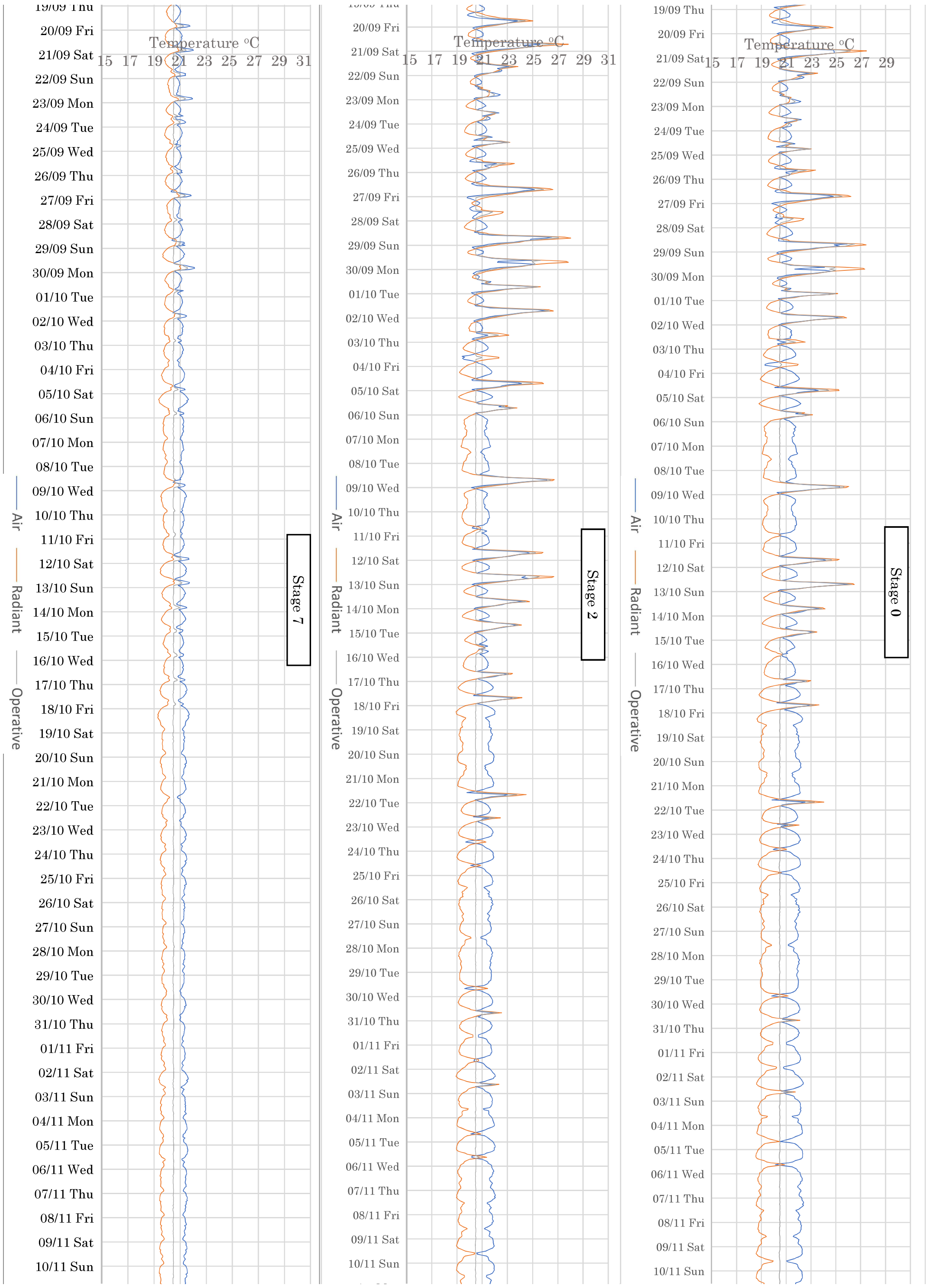


Figure .51: Design builder Living room surface temperatures

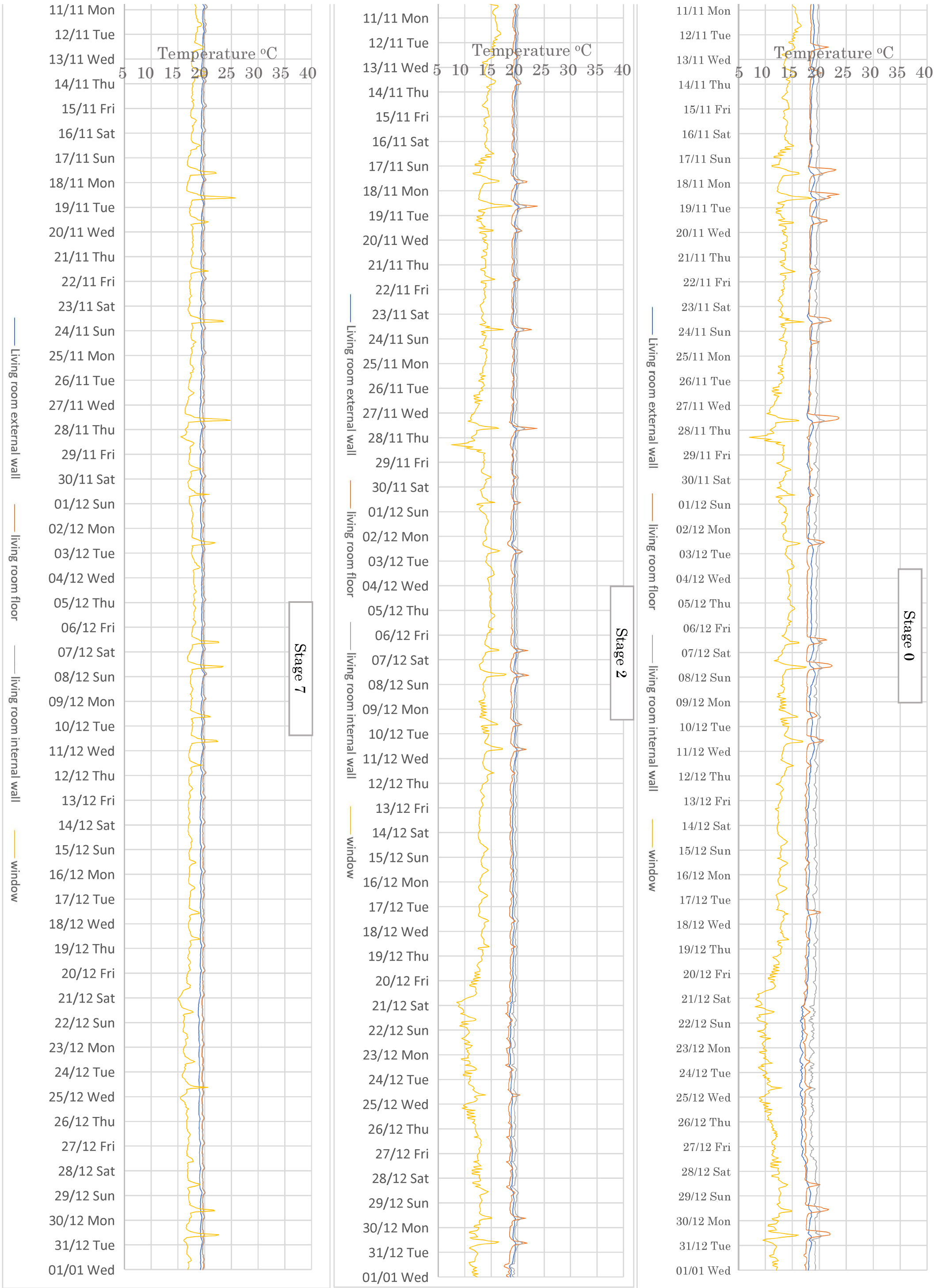


Figure .52: Design builder Living room surface temperatures

.6.5 Simulated living room and bedroom3 CO_2

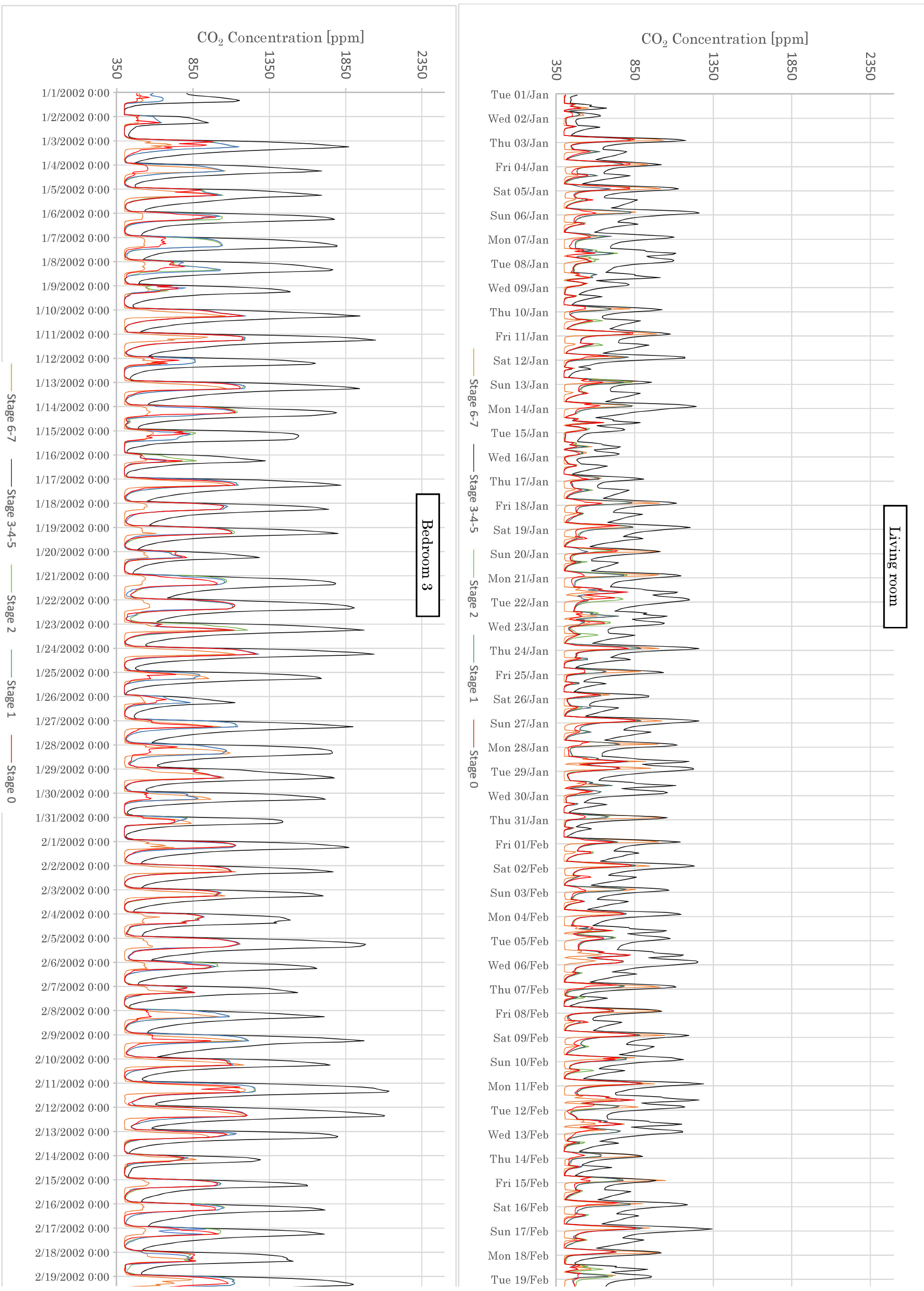


Figure .53: Design builder living room and bedroom 3 CO_2 simulations

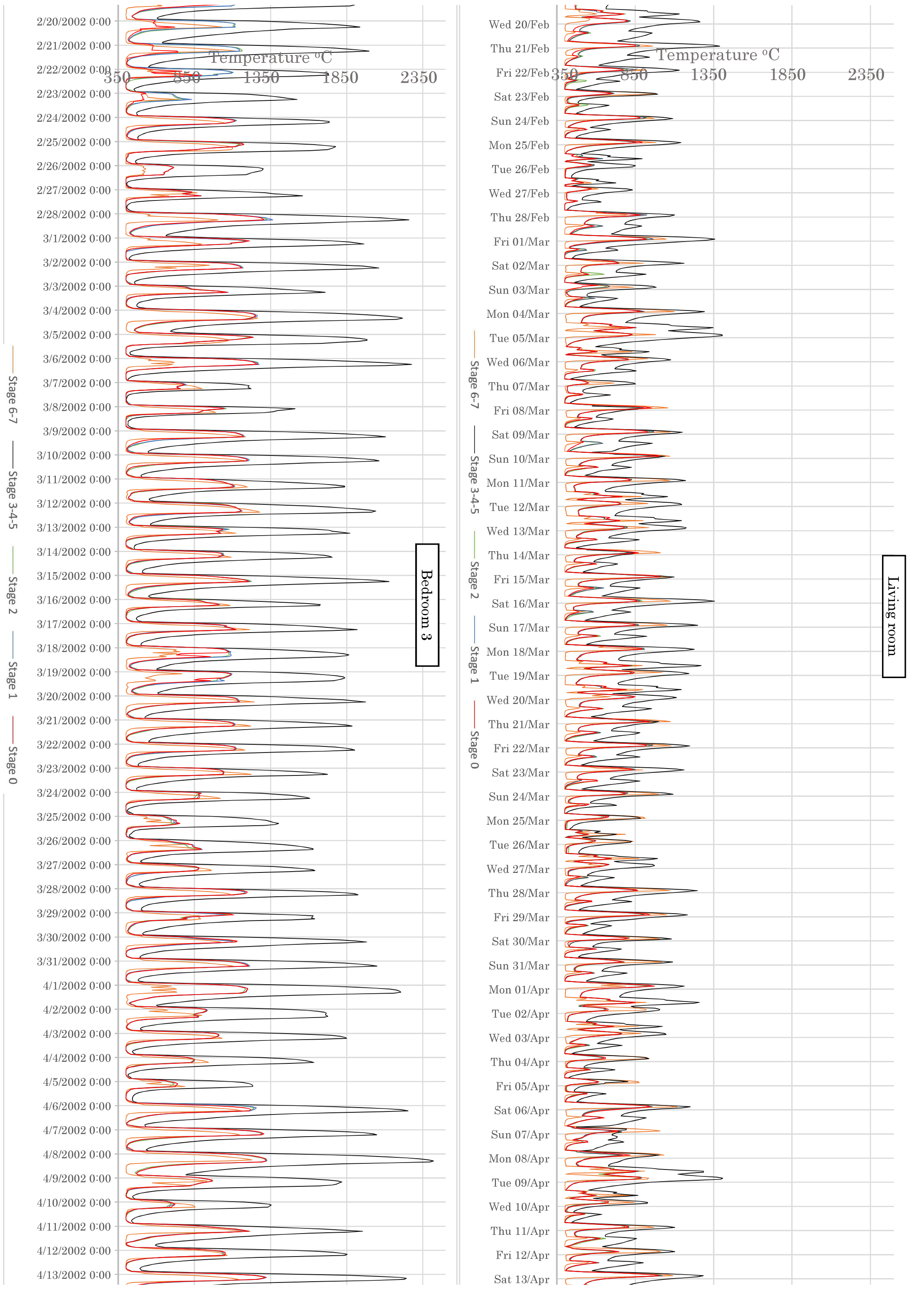


Figure .54: Design builder living room and bedroom 3 CO_2 simulations

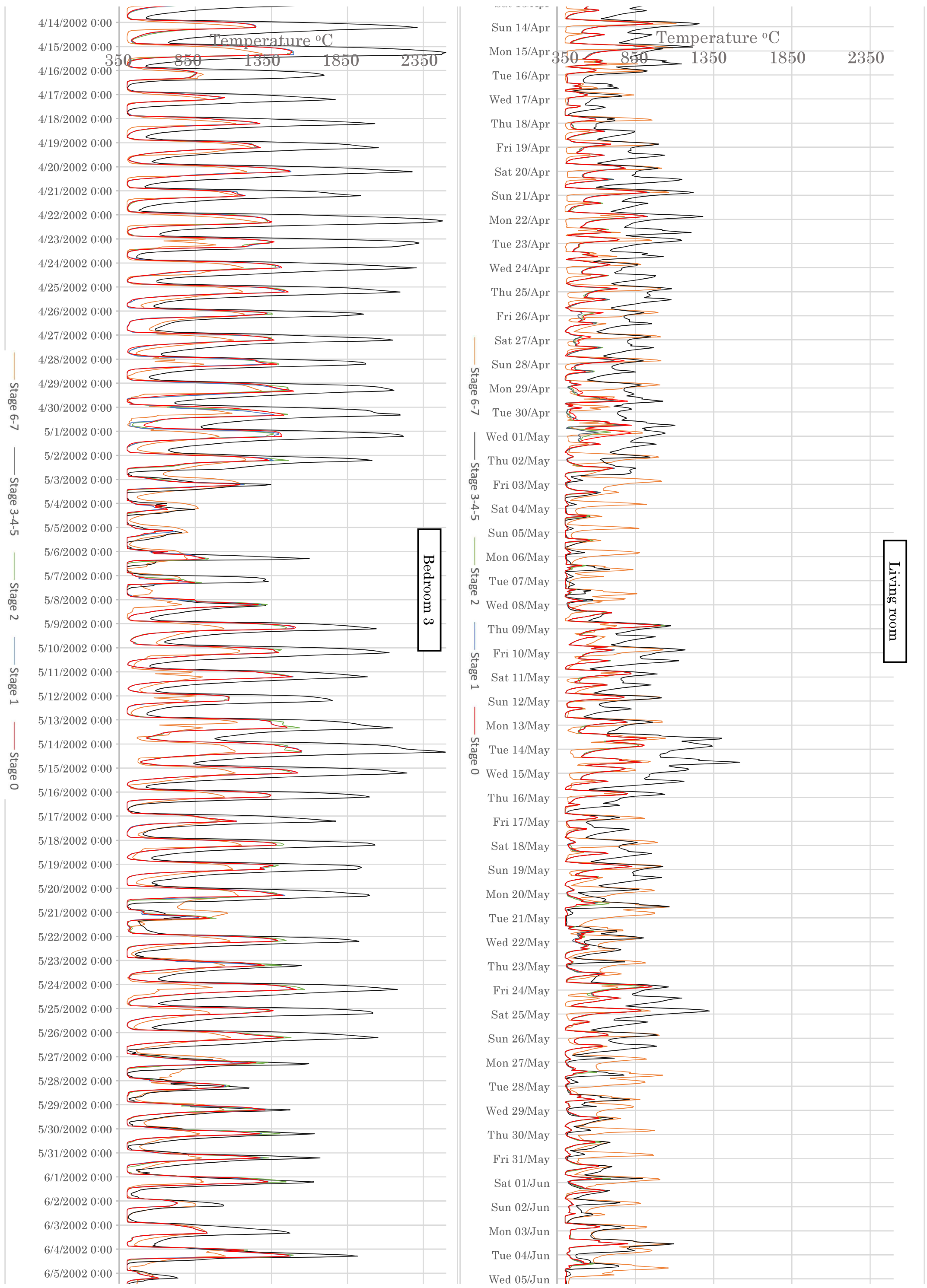


Figure .55: Design builder living room and bedroom 3 CO_2 simulations

Figure .56: Design builder living room and bedroom 3 CO_2 simulations

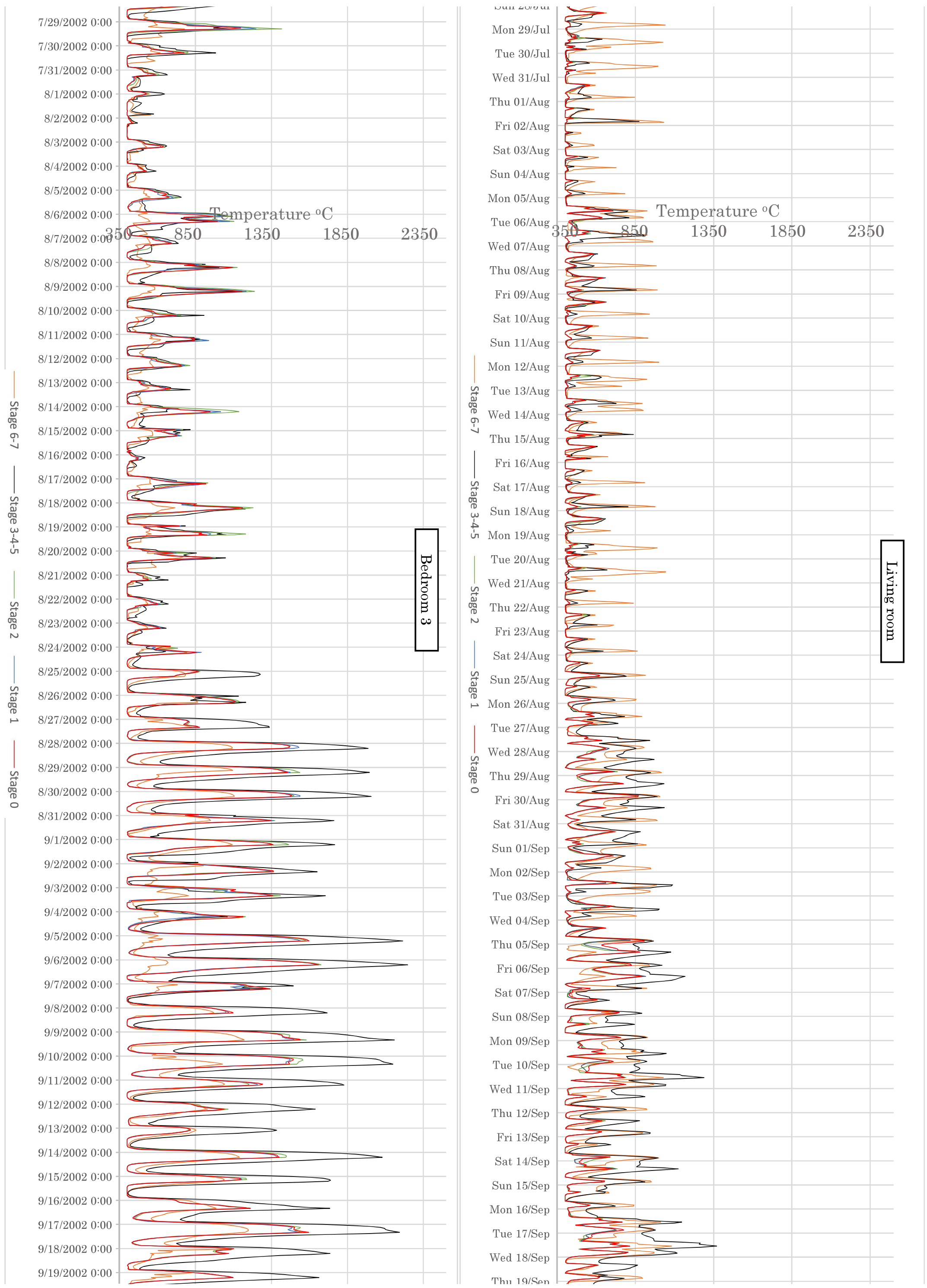


Figure .57: Design builder living room and bedroom 3 CO_2 simulations

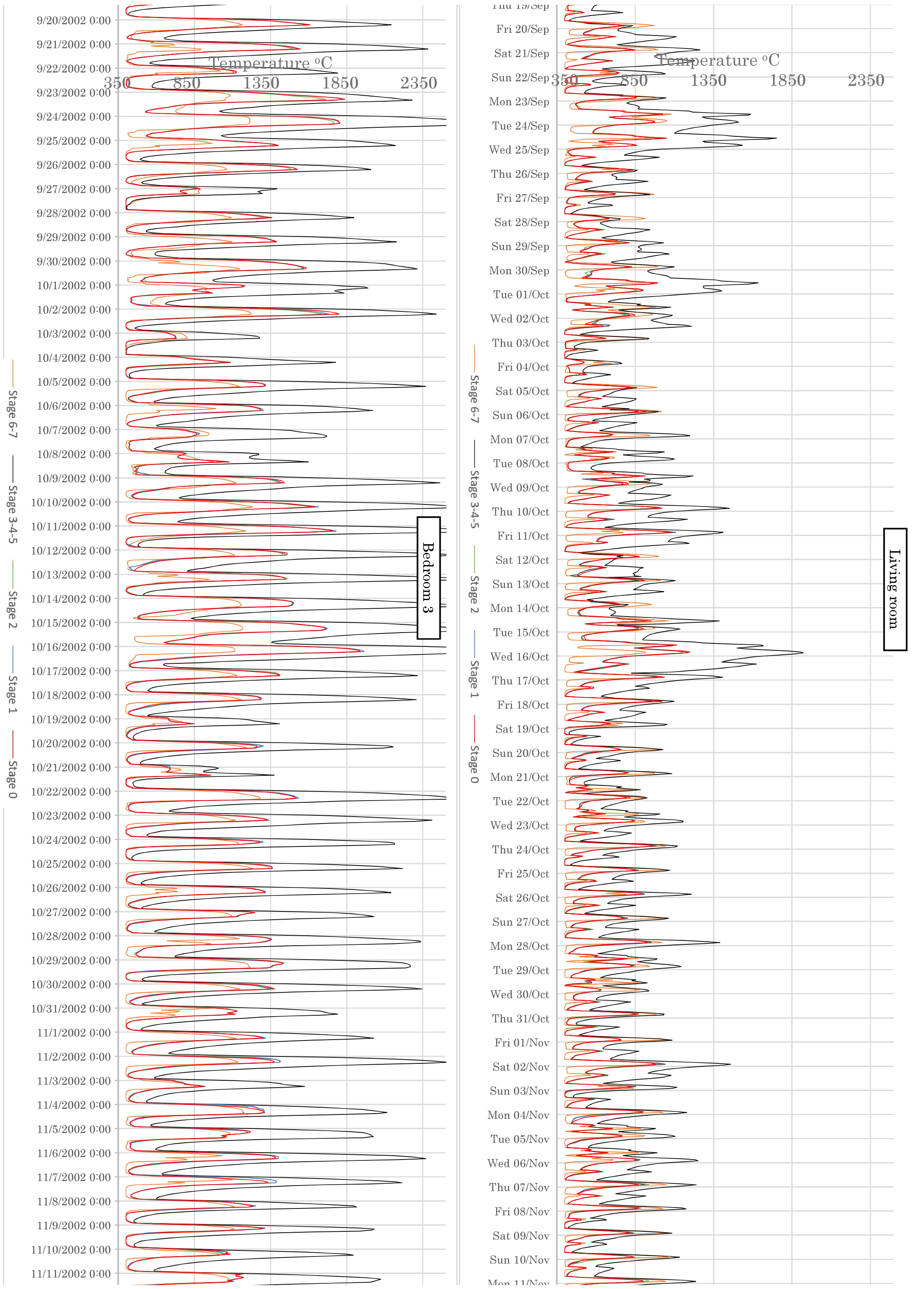


Figure .58: Design builder living room and bedroom 3 CO_2 simulations

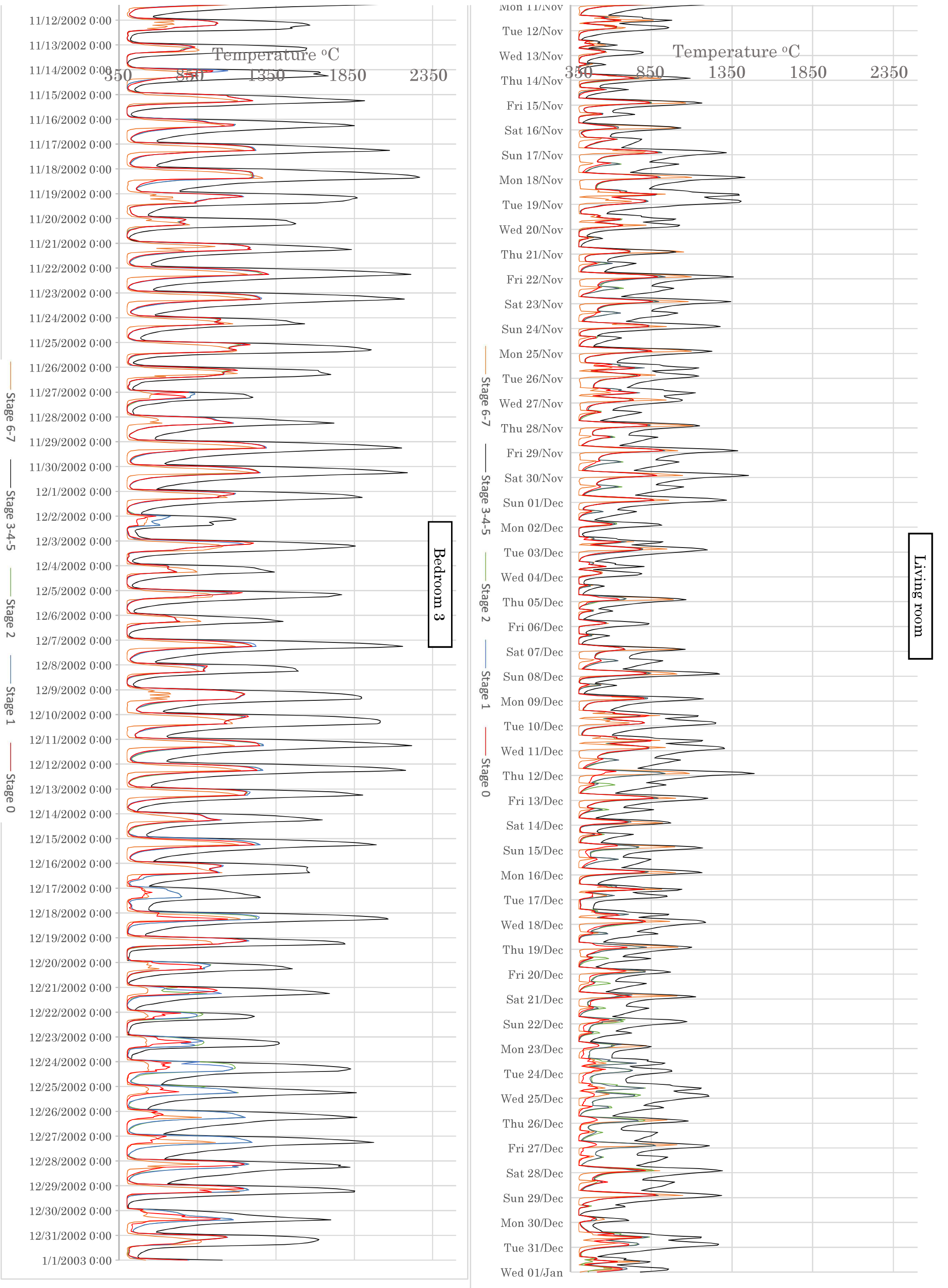


Figure .59: Design builder living room and bedroom 3 CO_2 simulations