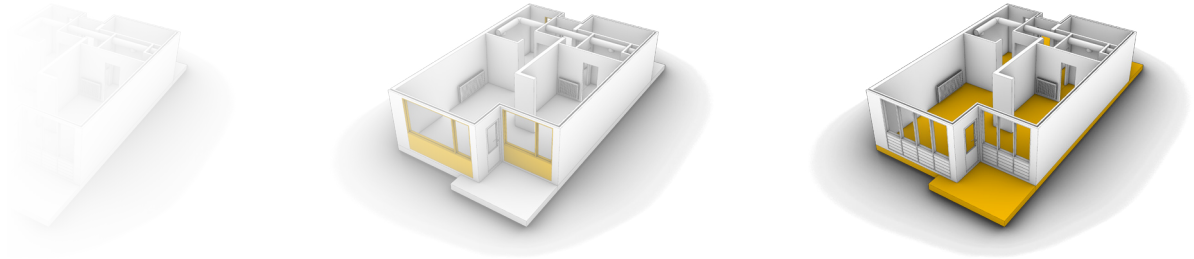
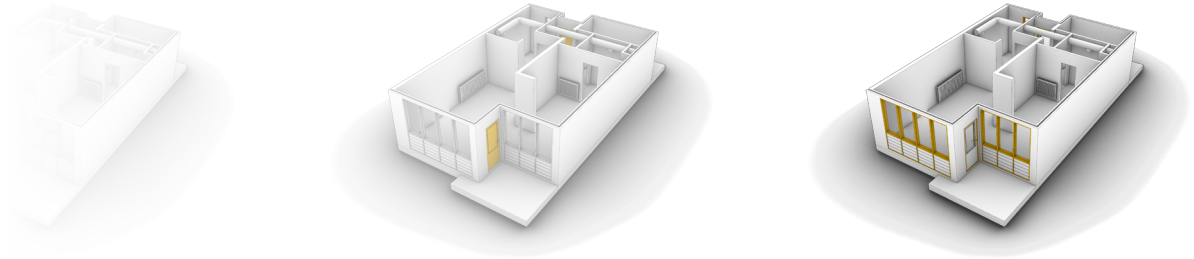
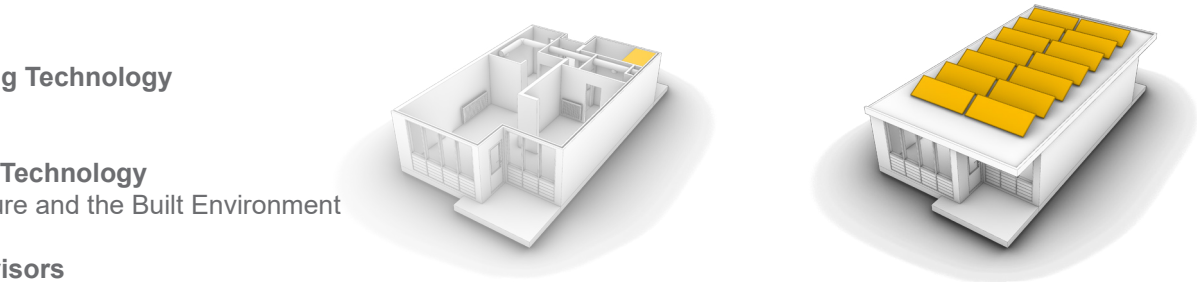


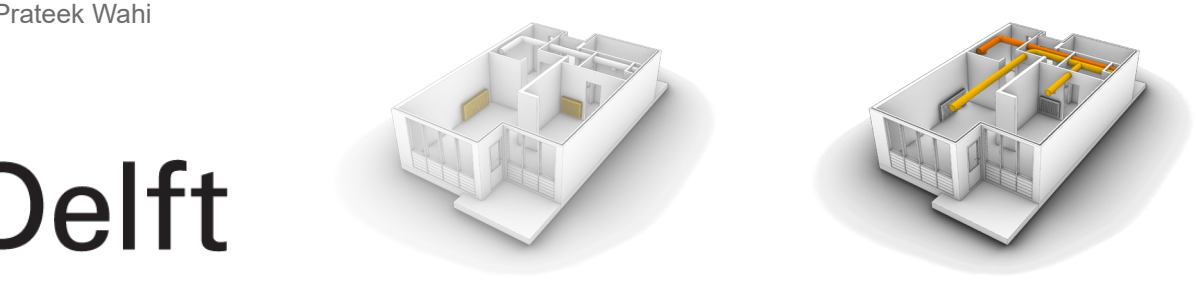
DECISION-SUPPORT FOR LT-RENOVATIONS

Development of a decision-support framework & tool to enable low-temperature heating in multi-family buildings









Vera Koster
4368789

MSc thesis Building Technology
23 June 2024

Delft University of Technology
Faculty of Architecture and the Built Environment

Graduation supervisors
1st mentor | Thaleia Konstantinou
2nd mentor | Eric van den Ham
PhD consultant | Prateek Wahi

TU Delft

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Graduation in itself is quite the challenge. Trying to graduate while dealing with impaired cognitive functions adds a whole new dimension to this challenge. My patience, along with the patience of my supervisors, friends and family, has been fully tested. A valuable lesson learned during this process is that perseverance and willpower are not only useful to slowly but steadily progress the graduation, but can also be employed to find trust in the process and acceptance in the things that are out of my control.

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This thesis is quite lengthy, just like my graduation process, so I recommend you pour yourself a cup of your favourite drink and take enough breaks while reading it. Enjoy!

Vera Koster
23 June 2024

ABSTRACT

The current Dutch building sector is heavily dependent on natural gas for its energy consumption, of which a very significant part is used to meet the space heating demand. To mitigate the climate crisis, a transition from fossil fuels to renewable energies has to be made. However, renewable energy sources are usually low-temperature heating sources, prompting the need for renovation. There are often multiple renovation solutions per project, with each their unique effect. Determining the optimal solution out of those renovation concepts that enable low-temperature heating (LTH) is challenging due to the varying performance of the renovation scenarios, multi-stakeholder involvement with each their own preferences and the lack of a clear decision-making process.

This research aims to provide holistic decision-support and aid in the identification of the most suitable renovation alternative. The research question central to this study is: 'How can the decision-making process of selecting an energy renovation concept be supported that aims to make existing residential buildings compatible with low-temperature heating?'. This research focuses on multi-family buildings in the Netherlands and considers a temperature range of 30-55 °C to be LT.

To answer the research question, an extensive literature research is conducted on the topics of LTH and decision-support in energy renovations. Based on the results from the literature study, a LTH decision-support framework and tool is developed. The MCDM TOPSIS method is used to evaluate the performance of the renovation alternatives and is combined with the pairwise comparison method to capture the stakeholders preferences. The framework and tool is validated on its function and usability through a case study application on a 1979 apartment building and a workshop with 4 expert stakeholders. In addition to the evaluation of the 4 renovation scenarios from the case study, 9 additional renovation scenarios are developed and compared. A LTH-Rhino/grasshopper tool is used to simulate the heating demand and thermal comfort for all 13 scenarios to evaluate the LT-readiness of the alternatives.

One of the key findings of this research is that the developed framework and tool can support the decision-making process on LT-renovation scenarios. This support is provided by structuring the decision-making process through aiding in the identification of decision parameters, making the stakeholders' preferences explicit through pairwise comparison and ranking the renovation alternatives based on quantified performance values and criteria weights representing the stakeholders' preferences through TOPSIS. The framework evaluates LT-readiness to identify if there is a need for renovation, and filters non-suitable scenarios based on the LTH-grasshopper simulation results.

The framework ensures that all relevant decision-making aspects are considered systematically, and the tool facilitates a transparent and data-driven selection process. Together, they provide holistic decision-support, leading to better-informed decisions. This research motivates to enable LTH, thereby mitigating climate change and ensuring a sustainable future.

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NOMENCLATURE

AHP	Analytical Hierarchy Process
ASHP	Air Source Heat Pump
CBA	Cost Benefit Analysis
CHP	Collective Heat Pump
CI	Consistency Index
COP	Coefficient Of Performance
CR	Consistency Ratio
CV	Consistency Vector
DH	District Heating
DHW	Domestic Hot Water
DS	Decision Support
DSS	Decision Support System
EI	Energy Index
ELECTRE	ÉLimination Et Choix Traduisant la REalité
GHG	Greenhouse Gas Emissions
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HP	Heat pump
HT	High Temperature
HTH	High Temperature Heating
KPI	Key Performance Indicator
LCA	Life Cycle Analysis
LCC	Life Cycle Cost
LT	Low-Temperature
LTDH	Low-Temperature District Heating
LTH	Low-Temperature Heating
LTH-DS	Low-Temperature Heating Decision-Support
MADM	Multi - Attribute Decision Making
MCDA	Multi - Criteria Decision Analysis
MCDM	Multi - Criteria Decision Making
MODA	Multi - Objective Decision Analysis
MODM	Multi - Objective Decision Making
MRT	Mean Radiant Temperature
MT	Medium Temperature
NIS	Negative Ideal Solution
NPV	Net Present Value
O&M	Operational & Maintenance
OAT	One At a Time
PIS	Positive Ideal Solution
PMV	Predicted Mean Vote
PP	Payback Period
PPD	Predicted Percentage of Dissatisfied
PROMETHEE	Preference Ranking Organization METHod for Enrichment of Evaluations
PV	Photo Voltaic
PVT	Photo Voltaic Thermal
RI	Random Index
SAHP	Solar Assisted Heat Pump
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
ULT	Ultra Low Temperature
WSHP	Water Source Heat Pump

RESEARCH FRAMEWORK

1. RESEARCH FRAMEWORK

1.1 Background

1.1.1 The necessity of the Energy Transition

The current global energy sector is dependent on fossil fuels as their primary source of energy. Up to 73% of the total human-induced greenhouse gas emissions (GHG) originates in the global energy sector of today (United Nations, 2021). Absence of interventions to reduce GHG will lead to a high risk of irreparable climate damage in the form of unprecedented natural disasters caused by extreme weather conditions (de Boer, 2022). To prevent the world from becoming unfit to inhabit, both international and national climate agreements have been drafted.

In 2015 a total of 195 parties signed the Paris Agreement, agreeing to the goal of limiting global warming to a maximum of 2 °C, with a preferred limitation of 1.5 °C compared to the pre-industrial era (European Commission, 2015). In order to reach that goal, GHG emissions should be reduced by half in 2030, and climate neutral by 2050. In 2019 the Dutch cabinet presented the National Climate Agreement, het Klimaatakkoord, agreeing to the goal to reduce the production of GHG in the Netherlands by 49% in 2030, and by 95% in 2050, which has also been laid down by the Climate Law (Klimaatwet article 2.1-2.2, 2019; Ministerie van Economische Zaken en Klimaat, 2019). By 2030, at least 1.500.000 Dutch dwellings have to switch from an energy system based on natural gas to a renewable energy-efficient alternative to reach the set goals (Ministerie van Binnenlandse Zaken, 2022). At the same time, the Dutch cabinet is currently working on tightening the targets and amending the law to 55% by 2030 and to be completely climate neutral in 2050 (de Boer, 2022). This is a consequence of the European Climate Law that was accepted in June 2021, stating those same targets (Regulation (EU) 2021/1119, article 2.1, 4.1, 2021).

Some sectors have a higher energy consumption compared to other sectors, therefore contributing to GHG emissions in varying degrees. In the Netherlands, dwellings are with 19% the second largest contributor to the total final energy consumption (figure 1.1.1), which is approximately 445 PJ on an annual basis (de Boer, 2022). Residential buildings in the Netherlands are highly dependent on natural gas as their primary energy source: up to 90% of the building stock uses natural gas for space heating, hot tap water and cooking. The households that are natural gas dependent use up to 76% of their gas consumption for space heating (figure 1.1.2) (de Boer, 2022). Space heating thus plays a significant role in the current energy consumption of dwellings. Transitioning space heating from natural gas to more sustainable sources therefore offers a high reduction potential for the total amount of GHG emissions in the energy sector, and would contribute to achieving both national and international climate agreements. Nevertheless, transitioning from a finite energy system to a renewable energy system is not the only part that should be addressed. In order for the renewable energy system to become energy efficient, reducing the total energy demand should be a focal point (NPLW, 2022b). One of the approaches to do this is introducing low-temperature heating (LTH) accompanied by fitting renovation measures for the existing residential building stock.

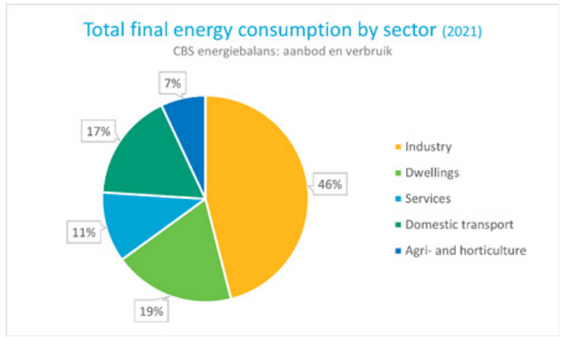


Figure 1.1.1 Total final energy consumption by sector in 2021
Image adapted from De energietransitie uitgelegd (p.87) by de Boer, 2022

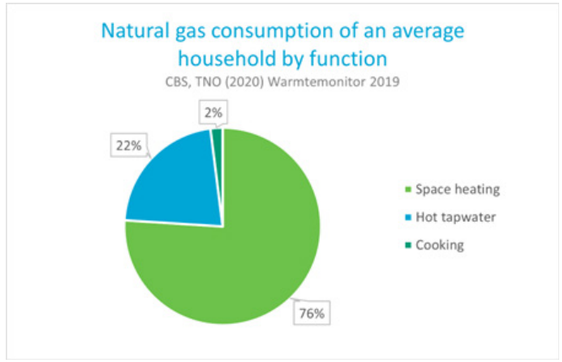


Figure 1.1.2 Natural gas consumption of average household by function
Image adapted from De energietransitie uitgelegd (p.88) by de Boer, 2022

1.1.2 Introducing Low-Temperature Heating

The definition of LTH varies per researcher and institute. In this research the definition as given by the Dutch government funded institute TKI Urban Energy (2022) is used, which considers a supply temperature of 30-55 °C to be low-temperature (LT). In line with LT, there's medium-temperature (MT) with a supply range from 55-75 °C and high-temperature (HT) with a supply range from >75 °C.
As mentioned in the previous section, the most common energy source used for heating in the Netherlands is natural gas. Traditionally this provides a HT supply temperature with high levels of thermal comfort. With moderate to well insulated houses the setpoint temperature is sometimes already lowered to the MT range to save energy. Lowering the temperature from HT to MT in those houses will still provide enough thermal comfort, since there is often an overcapacity of the system present, and therefore the heating demands remain met (Cauberg-Huygen Raadgevende Ingenieurs bv & Boerstra, 2001; Østergaard, & Svendsen, 2017; Pothof, Vreeken & van Meerkerk, 2023).
However, this is a short term solution: although using less energy of fossil origin definitely contributes to the goal of reducing GHG, it is still a finite source that produces harmful emissions (Brand & Svendsen, 2013). Transitioning to LTH would be a long term solution, since it has the potential to become a fully renewable energy system. Nevertheless, several steps need to be taken for that potential to come through, like reducing the overall energy demand (Cauberg-Huygen Raadgevende Ingenieurs bv & Boerstra, 2001; TKI Urban Energy, 2022). In addition, the transition from high temperature heating (HTH) to LTH requires a different approach to sources, distribution and heating systems, which leads to several challenges. Some of the challenges that arise however, are potential benefits in disguise, which will be elaborated on in chapter 2.

LTH is relatively easy to apply in new-build dwellings, because the space heating demand of those dwellings is designed to be low since current building standards require high insulation values (Bouwbesluit 2012, 2023). LTH is more difficult to apply in the existing building stock, because of the existing high space heating demand due to former building standards with low(er) required insulation values. The existing construction can also be a limiting factor, since LTH requires space for installations and adds weight (Cauberg-Huygen Raadgevende Ingenieurs bv & Boerstra, 2001). However, the increase of the total housing stock due to new-build homes in the Netherlands is only 1-2% every year (Netherlands Statistics, 2023a), therefore the focus should be on the transformation of the existing building stock to reach the climate goals. The main challenge that arises with lowering the supply temperature in the existing building stock, is that the heating power is lowered when the heat emission system remains unchanged and heat losses are not addressed. This causes a potential disbalance between the existing heating demand and the new (lower) heating capacity combined with the existing internal and solar heat gains, creating (high) levels of thermal discomfort (Wahi et al., 2023a). Figure 1.1.3 illustrates this concept. There are two

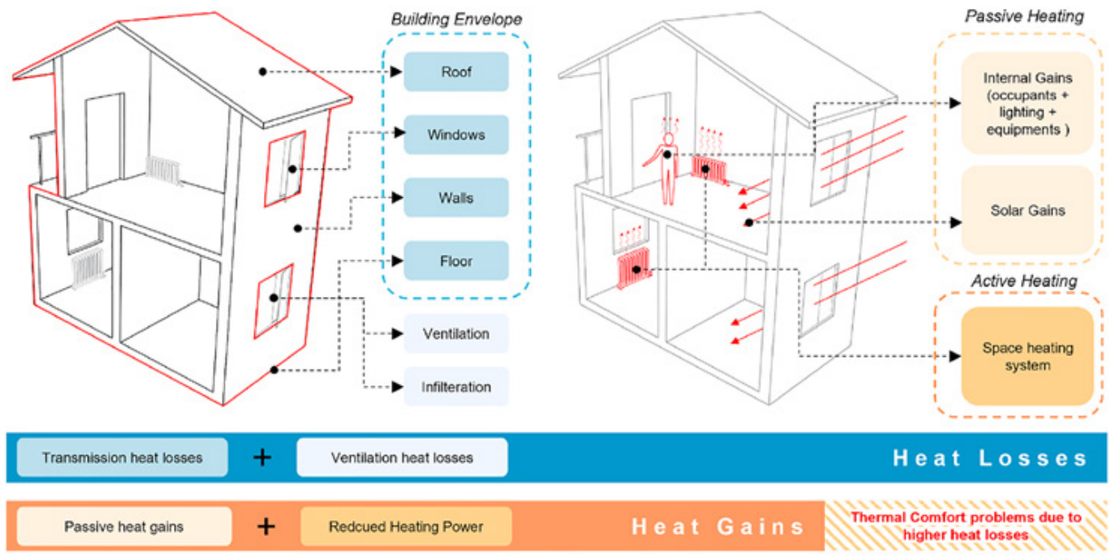


Figure 1.1.3 Thermal comfort problems due to higher heat losses and inability to compensate them by heat gains due to reduced heating power of the space heating system under lower supply temperatures.
Taken from Lower temperature heating integration in the residential building stock: A review of decision-making parameters for lower-temperature-ready energy renovations (p.8) by Wahi et al., 2023a

main solutions to this challenge: to lower the heating demand, and/or to increase the capacity. Both solutions have been widely researched, leading to many options for renovation measures to enable LTH (see chapter 2.2 for elaboration). Those measures involve adaptions on different levels like the building envelope, building systems and/or controls, where combinations of measures lead to numerous working renovation concepts (Wahi et al., 2023b). Having multiple working LTH renovation concepts with each their own unique effect instead of one clear solution, contributes to the challenge of selecting a renovation concept.

1.1.3 Complex decision-making

Selecting a renovation concept involves complex decision-making, not only because of the multiple renovation options, but also because of the multiple stakeholders involved in the process. Energy renovation stakeholders make trade-offs between the concepts based on their interests (Nielsen et al, 2016). However, those interests might be conflicting in nature, due to the different type of stakeholders involved, like housing corporations, energy companies, advisors, municipalities and tenants (Amorocho & Hartmann, 2022). Kamari et al. (2017) emphasizes the importance of comprehending the interaction and interconnection between relevant factors of the renovation process.
There are methods developed to help solve complex problems. Multi-criteria decision-making (MCDM) is one of the known approaches to support complex decision-making in the engineering field. MCDM is an analytical way of evaluating potentially conflicting criteria for multiple alternatives (Pohekar & Ramachandran, 2004). In the case of LTH-renovation the numerous renovation concepts can be considered as the multiple alternatives, with the trade-off factors based on the stakeholders interests as the potentially conflicting criteria. For example, the renovation scenario of retrofitting the whole building has a significant impact on the reduction of the energy demand, but requires high investment costs, high amount of working hours and restrictions for its occupants. Another, less extensive renovation scenario could lead to lower investments costs and less working hours, but could reduce the energy saving potential of the renovation.
The current body of knowledge on LTH renovations provides extensive research on the quantitative performance of the renovation scenarios, like Rutten (2021) did with designing renovation concepts that provide thermal comfort with LTH in existing dwellings based on limited investment budgets. The research of Jafari & Valentin (2018) also shows that it is common in energy renovation concepts to focus on minimizing costs while maximizing the energy performance. However, there is still a lack of research on the aspects of the decision-making process when selecting a concept, leading to unclear decision-making processes (Amorocho & Hartmann, 2022).

The combination of multiple renovation options, conflicting interests of stakeholders and the absence of a clear decision-making process makes selecting a renovation concept a complex challenge that requires further research.

1.2 PROBLEM STATEMENT

1.2.1 Research gap

The complex nature of decision-making on renovation concepts causes it to be a time-consuming process. Björkqvist & Wene (1993) researched that on average 18 hours are spent on making the decision for energy efficiency renovations per household, in this case specifically for changing the heating system. Rutten (2021) made over 100 dynamic simulations of LT-renovation concepts for just one case study to find 40 concepts that are LT-ready and affordable. Although this is thorough and provides interesting information on the effect of renovation measures, the research lacks information on how to select one of those 40 suitable concepts. Also, in the perspective of accelerating the energy transition, simulating 100 concepts for one building is not an efficient approach. There is a lack of simple estimation tools to quickly inquire the potential effect of a renovation measure.

There are already tools developed that support the decision-making process of renovations. Nielsen et al. (2016) reviewed 43 decision support tools for renovation projects, but those tools are complex and often designed to only aid for one or two areas of the decision making process, for example performance estimation and criteria weighting. The identified criteria in the review are divided into three categories of environmental, economic and social, but only 40% of the reviewed tools included all three categories, showing a lack of holistic approach. Kamari et al. (2018) advocate for a holistic approach in building renovation to deal with the complex nature of energy renovations.

Although there are already tools and frameworks developed to support the decision-making process of energy renovations, none of them are focussed specifically on LTH renovations. Additional research is required to identify the unique decision parameters that entails LTH renovations to

support the decision-making process as well as the scenario selection process.

Hence, there is currently a research gap on the decision-making process for selecting a renovation concept from a holistic perspective that enables low-temperature heating in residential buildings.

1.2.2 Main & sub-problems

The identified research gap leads to the following main problem statement:

It is unclear how to select a renovation concept that enables low-temperature heating due to the varying effects of the renovation scenarios, multiple stakeholders with conflicting interests and the absence of a clear decision-making process.

The problem is thus threefold, where the following sub-problems are identified:

1. The presence of multiple renovation solutions with varying effects to enable LTH;
   a. The lack of a structured approach to estimate the qualitative and quantitative performance of the renovation scenarios
2. The involvement of multiple stakeholders with conflicting interests;
   a. The lack of consensus on the decision parameters involved when selecting a LT- renovation concept;
3. The absence of a clear decision-making process in LT-renovations;
   a. Lack of decision support for analytically evaluating the effects of multiple energy renovation scenarios

Each renovation option that enables low-temperature heating has its own unique effect. Multiple solutions to a complex problem can cause analysis paralysis and requires a structured approach to estimate the effect of both qualitative and quantitative aspects of each scenario. There is currently a lack of quick estimation tools, which would be beneficial for speeding up the decision-making process.

The multiple stakeholders involved in LTH-renovations lack consensus on which decision parameters should be considered when selecting a LT-renovation concept, due to their conflict of interests. Which renovation scenario is 'the best option' therefore differs per stakeholder, thus a compromise is required to balance the stakeholders interests. There is currently a lack of holistic approach in the decision-making process on what decision criteria should be considered and how to balance the preferences when evaluating the LT-renovation alternatives.
There is an absence of a clear decision-making process due to the complexity of renovation processes caused by the multiple renovation options and multiple stakeholders. There is currently a lack of structured decision support and tools that can analytically evaluate the effect of energy renovation alternatives for all relevant decision criteria at an early stage.

1.3 Objective

1.3.1 General Objective

The aim of this thesis is to develop a decision-support framework that incorporates a holistic approach to aid the decision-making process and scenario selection process for low-temperature renovation projects. The purpose of the framework is to simplify the decision-making process of LT-renovation by providing a structured approach with elements like problem definition, identification of decision parameters, generation of renovation scenarios with quick performance analysis, and decision analysis. This structured approach provides overview and creates room for targeted discussions on different aspects of the renovation selection process. The intended users of the framework are the stakeholders (decision-makers and informants) involved in energy renovation processes, especially those related to LT-renovations. This leads to the second objective of the framework, which is to help select a LT-renovation scenario based on the balanced interests of the involved stakeholders. Introducing decision support for the selection process of a renovation concept provides potential to shorten the decision-making process, and therefore contributing to the acceleration of the energy transition by expediting the rate of renovations and preparing existing dwellings for gas free heating.

1.3.2 Sub-Objectives

It is essential to identify the key building characteristics of dwellings that influence the energy performance, with the aim to determine the minimal renovation requirements to enable LTH. Identifying decision parameters like objectives and criteria is crucial to be able to evaluate the performance of each renovation scenario on both quantitative and qualitative aspects. This has the aim of enabling a holistic approach to the evaluation of the scenarios and ensures renovation goals are met. Another sub-objective is to balance the stakeholders interests by weighting the criteria based on the relative importance. The development of a simple Rhino model with a list of energy renovation values as input for the LTH-grasshopper simulation model from P. Wahi will provide a way to estimate the effect of the renovation measures on the energy performance. The aim for this model is to get a quick overview on the heating demand and thermal discomfort performance of multiple renovation scenarios, limiting the need for time-consuming dynamic simulations. Performance quantification for renovation scenarios is necessary to rank the alternatives based on the selected decision parameters and the balanced interests of the stakeholders. The aim for ranking the renovation scenarios is to provide direction for a certain scenario, to help make a balanced and informed decision to initiate the renovation process. The framework aims for acceptable evaluation of performance accuracy, but the focus lies on supporting the selection process by evaluating quick estimations of the performance. The aim of the framework is to provide early stage decision-support by identifying more and less suitable LT-renovation options based on the specific building characteristics and stakeholders interests.

1.3.3 Final Products

This thesis will deliver the following products:

1. Descriptive analysis on low-temperature renovations
2. Descriptive analysis on decision-making processes in energy renovations
3. Decision-support framework for selecting LTH renovation concepts (figure 6.1.3)
4. Info tables and figures as backbone of the framework steps
   a. Stakeholder identification (table 5.1.1)
   b. Data collection for building analysis (appendix B)
   c. Renovation measures (table 2.2.1 & 2.2.2)
   d. Objectives & criteria decision-tree (figure 4.1.1)
5. Tool to assist the decision analysis of the framework
   a. Decision Support Tool (based on pairwise comparison & TOPSIS)

The LTH-performance Rhino/Grasshopper tool from P. Wahi will be utilized to quickly simulate the heating demand and thermal discomfort of the renovation scenario's, which will be used as input for the decision matrix tool. The framework will be visualized in a flowchart, accompanied by a textual elaboration on each step of the framework. The info tables, figures and decision support tool are developed to assist the users of the framework to complete all the steps. An overview of the stages in which these products are delivered can be found in 1.5. Approach & Methodology, 1.5.2 Research Stages, figure 1.5.1: Thesis Methodology.

1.3.4 Hypothesis

The hypothesis of this thesis is that the selection process of LT-renovation concepts as well as the decision-making process itself can be supported and potentially shortened by the developed framework and accompanying tool. The presented theory is that the framework will be able to balance the conflicting interests of multiple stakeholders and present a satisfying ranking based on the scenarios' qualitative and quantitative performance, simplifying the decision-making process of selecting a renovation concept. The assumption is made that the users of the framework have reasonable knowledge on the subject of energy renovations, enough to comprehend the frameworks' steps, tools and info tables, and are familiar with stakeholder collaboration.

1.3.5 Boundary conditions

A couple of starting points and boundaries are set for this research, since the research area needs to be restricted in order to complete the master thesis in a reasonable timeframe. The following boundary conditions apply:

- This thesis is focused on LT-renovations in the Netherlands. Therefore the renovation measures, analyses, calculations and other input for the framework will be related to Dutch building standards and Dutch rules and regulations, like the ISSO-51, the NTA8800 and the Dutch National Climate Agreement.
- This research is concentrated on stacked, multi-family residential buildings in the Netherlands that require (extensive) energy renovations, e.g. apartment buildings like Gallerijwoningen, Portiekwoningen and Flats built before 1992. The decision-support framework is designed to assist complex renovation issues, and these cases are most likely to be complex due to multiple stakeholder involvement. Multi-family homes occur mostly in dense urban areas, which makes it feasible to consider LTDH as a viable option.
- Within literature, the definition of low-temperature supply varies widely from 30 °C till 75 °C. This thesis will use the definition of 30-55 °C as a range for LT-supply temperature, which is the TKI Urban Energy LT-definition, a Dutch energy institution that strives for sustainable, reliable and affordable energy systems.
- The framework, tools and info sheets in this research are developed with specifically low-temperature renovations in mind. It should be further

researched to check if the framework and tools could also support decisions on MT renovation scenarios, which might be the case if the criteria and renovation measures are re-evaluated and/or different benchmarks are set. For now, the framework is only relevant for LT-renovation options.

- The framework and tool promote holistic decision-making by equally incorporating decision parameters from the three pillars of sustainability: environmental, economic, and social. The current economic system, predominantly based on late-stage capitalism, often prioritizes endless growth while disregarding planetary limitations and basic social needs. However, there is a growing recognition that sustainable development requires a balanced approach that transcends these limitations. Extending the evaluation of renovation alternatives beyond mere cost-benefits through a holistic decision-making approach acknowledges the complex interdependencies between economic viability, environmental protection, and social well-being. Decision-makers in energy renovations are currently limited to operating within this economic system, influencing how decisions are made and necessitating trade-offs based on existing priorities. As long as decision-makers have not adopted the paradigm shift to evaluate renovation scenarios in alignment with the principles of the donut economy, the current economic system remains a limitation in the decision-making process.
- The tools provide (rough) estimations on the performance of renovation scenarios. The framework is designed to support decision-making at an the early stage when multiple renovations scenarios are still considered, and therefore does not provide nor require a high performance accuracy. It is recommended to do an in-depth analysis on the performance after a renovation scenario is selected, to ensure performance accuracy.
- The actual selection of a scenario is not a part of this thesis, since the decision-making is up to the stakeholders. This thesis merely provides a literary research and a framework with complementary elements to ease the decision-making process.

1.4 Research Questions

1.4.1 Main Research Question

The formulated problem statement and objective leads to the following research question:

"How can the decision-making process of selecting an energy renovation concept be supported that aims to make existing residential apartment buildings compatible with low-temperature heating?"

1.4.2 Sub-questions

In order to answer the main research question, the following sub-questions need to be answered:

Low-Temperature Heating Renovations

1. How can an existing residential building be made compatible for low-temperature heating?
   - a) Which factors indicate LT-readiness?
   - b) What are the current state-of-the-art renovation measures which can enable LT-heating?

Decision-Support in Energy Renovations

2. Which decision-making phases can be identified in energy renovation processes?
   - a) Which MCDM methods are suitable to support decision-making in energy renovation projects?
3. What are the key decision parameters in energy renovations?
   - a) In what way can the decision criteria be analytically assessed?
4. Who are the stakeholders involved in LTH renovation projects and what is their role?
   - a) How can conflicting stakeholders' preferences be captured and balanced?

Decision-Support for Low-Temperature Heating Renovations

5. How can the acquired knowledge on LTH and Decision-Support be combined in a way that supports the assessment and selection of LT-renovation scenario's?

1.5 Approach & Methodology

1.5.1 Thesis Structure

This thesis employs a design by research approach, where a research question is formulated for an in-depth literary research to gather relevant information. This information serves as a guideline for the framework design process. This type of methodology is in line with the objective of the research, which is to develop a holistic framework that simplifies the decision-making process by providing structure and overview through knowledge and tools. The intended outcome is a decision-support framework. During the thesis it became clear that the design science research methodology is an approach that could also be applicable, as the thesis aims to design, validate and evaluate a framework to solve a real-world problem. Consequently, this thesis adopts a mixed-methodology approach.

The introduction section (Chapter 1) contains the research framework, including the background, problem statement, objectives, research question, and methodology. Additionally, the relevance of the research is also discussed. The method of the introduction phase is based on literary research.

Following that, the exploration phase features a state-of-the-art literary review on LT-renovations (Chapter 2) and decision-making processes in energy renovations (Chapter 3-5). The first topic will provide relevant information to gather a deeper understanding of the available LT-renovation measures and how to assess their effect on the energy performance of a residential building. The second topic will provide relevant information to gather a deeper understanding of the involved decision-makers during energy renovations (Chapter 5), common decision parameters like objectives and criteria (Chapter 4), and the methods on how to rank the renovation scenarios for a systematic decision-analysis (Chapter 3.5 & 5.2). Those themes together cover the basis for a decision-support framework.

With this deeper understanding of those topics, they will be combined in the next phase: the framework development phase (Chapter 6). This phase integrates knowledge on LT-renovations and multi-criteria decision-making (MCDM) to design a decision-support framework that aids in selecting LT-renovation scenarios. The framework, specifically tailored to LT-renovations, ranks scenarios based on their performance and combined interests of decision-makers. It includes a flowchart and a detailed textual explanation of the framework steps, establishing boundaries and conditions based on the gathered information. A tool is also developed to support the framework steps, balancing stakeholders' preferences and ranking renovation alternatives based on performance and preferences. This tool employs both qualitative and quantitative methods, forming a robust foundation to validate and evaluate the frameworks' usability, functionality and completeness.

Validation of the decision-support function of the framework and tools is conducted through expert feedback and case study application in Chapter 7. This involves a workshop with expert stakeholders in the field of residential energy renovations, featuring the framework presentation and application to a case study, a semi-structured group interview and questionnaires. The LTH-grasshopper model, based on the NTA8800, ISSO-51 and other relevant literature related to energy performance calculations, supports the case study analysis. If case study data is insufficient, assumptions from the Voorbeeldwoningen (Netherlands Enterprise Agency, 2022) are used as placeholders. The decision support tool, an Excel-based tool, combines the pairwise comparison method with the TOPSIS method to determine criteria weights representing the stakeholders' preferences and rank renovation alternatives based on performances and preferences.

Following the framework validation phase, the thesis discusses research limitations and provides recommendations for further research in Chapter 8. Finally, in Chapter 9, the conclusion addresses the research question as presented in the introduction.

The research tools utilized in this thesis include literary databases like Google Scholar, ResearchGate, ScienceDirect, TUD Repository and the TUD and BK libraries for gathering sources for the literature review. The type of literature includes scientific papers, reports, books, PhD-theses and MSc-theses related to complex decision making and/or energy renovations. Data is gathered from websites such as Netherlands Statistics (CBS) and energy research institutes like ECW, NPLW and TKI Urban Energy. Atlas.ti is partially used to organise collected literature. Software like Adobe Indesign, AutoCAD, draw.io, and Excel are used for framework and tool development, while Rhino-Grasshopper is used for case study application. All presentations, including the workshop presentation, is created in PowerPoint.

1.5.2 Research Stages

The thesis will go through six stages that will deliver several products. A quick methodological overview of the thesis is provided in figure 1.5.1.

Stage 1
The first stage is identifying the research problem, which is done in the introduction (research framework) and based on research gaps identified in literature.

Stage 2
The second stage is the exploration phase, which is a literature review on low-temperature renovations and the decision-making process in energy renovations. The products delivered in this stage are the descriptive analysis on low-temperature renovations, and a descriptive analysis on decision-making processes in energy renovations.

Stage 3
The third stage is the framework development phase, starting with the design of a concept framework based on the knowledge of the descriptive analyses combined. After conceptualizing the decision support tool and some additional literature review, a structured and step by step framework is defined. The product delivered in this stage is the decision-support framework for selecting LTH renovation concepts, done through flowchart visualization accompanied by textual elaboration.

Stage 4
The fourth stage is the tool development phase as an expansion on the framework development, where a decision support tool is designed to assist the actions of the framework steps.

Stage 5
The fifth stage is the validation phase, where the framework and tool will be validated on its supportive function by testing its usability, functionality and completeness through a workshop with expert stakeholders and case study application. The results of the workshop lead to framework and tool improvement suggestions.

Stage 6
The sixth stage is the documentation phase, where the research is written down and supported through visuals, concluding with a discussion on the research, recommendations for future development and the answer to the research question. The final product will be the MSc thesis and presentation.
The author of this thesis would like to emphasize that these stages are not linear, but iterative and entwined.

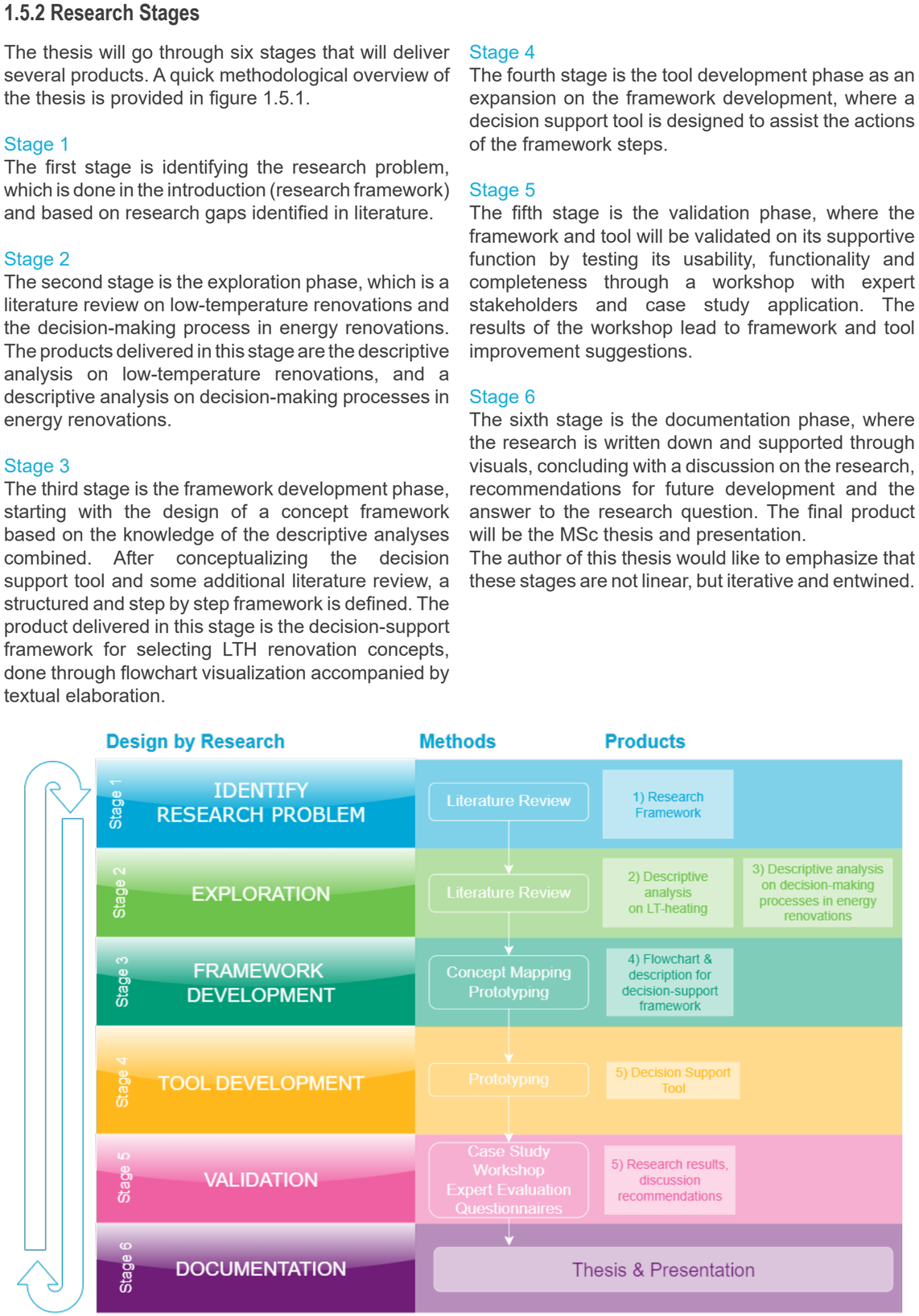


Figure 1.5.1 Thesis Methodology

1.6 Relevance

1.6.1 Societal Relevance

The discussion on climate change and sustainability has over the last decade quickly become a part of our daily life. Extensive media coverage on climate protests, greenwashing companies and the seriousness of the climate crisis as a political position is proof of a growing environmental consciousness, where some more than others are convinced of the urgency to address the climate crisis. One of the solutions to mitigate climate change are energy renovations to improve the energy efficiency of buildings, which is one of the topic of this research. Renovating dwellings to become LT-ready reduces the energy consumption, improves thermal comfort and reduces greenhouse gas emissions (Cauberg-Huygen Raadgevende Ingenieurs bv & Boerstra, 2001; Østergaard & Svendsen, 2017; Pothof, Vreeken & van Meerkerk, 2023; Wahi et al., 2023a). An additional advantage to energy renovations is the potential for energy cost reduction, contributing to the expulsion of energy poverty. Specifically LTH-systems, which rely on renewable energy sources, are less susceptible to energy price fluctuations (de Boer, 2022). The war between Russia and Ukraine caused the gas prices to skyrocket (Guan et al., 2023), something that would be less likely to happen if the energy source is locally available and not dependent on geopolitical situations. Although the changes to the infrastructure to switch to LT-heating are extensive and come with high investment costs, it will provide a long term sustainable solution instead of a temporary quick fix (Cauberg-Huygen Raadgevende Ingenieurs bv & Boerstra, 2001). LTH provides the potential to use renewable thermal energy sources like geothermal, solar- and aquathermal, contributing to the reduction of electricity grid congestion problems. Another societal objective that makes this thesis relevant is the aim to support the decision-making process. This way, the time pressure issue of the energy transition is addressed and the compliance with climate and building regulations is stimulated.

It is due to these societal objectives that this research on decision-support for selecting LT-renovation concepts is extremely relevant to our current society.

1.6.2 Scientific Relevance

Contributing to body of knowledge
The research gap identified in chapter 2. Problem Statement shows that this research will contribute to the body of knowledge by providing new research and products on decision-support for selecting LTH-renovation concepts. This research combines the knowledge on decision-support and LTH-renovation concepts to identify specific LT decision parameters, and provides a structured approach to the decision-making process where the interests of multiple stakeholders will be balanced through decision analysis. Allowing for multiple stakeholders and incorporating a holistic perspective is an innovative approach in decision support for energy renovations. The framework that will be developed can be seen as a starting point for LTH decision-support, leaving room for further research and applications. For example, the framework could potentially be scaled for other dwelling types, and the concept tools can be further developed.

Building Stock
Current studies on LT-renovations in the Netherlands are most likely to be focussed on terraced housing, since this is with 41% the most common building type (Netherlands Statistics, 2023b). Building characteristics, or generalized the building type, influences the parameters for energy performance massively. By focussing this thesis on a new building type (multi-family covers 33% of the Dutch building stock (Netherlands Statistics, 2023b)), it is an expansion of the research field on LT-renovations in the Netherlands.

Low-temperature heating
Renewable LTH-systems are cutting-edge technologies, providing a high potential to expand the energy transition (TKI Urban Energy, 2022). Identifying LTH-renovation measures and quickly estimating the influence on the energy performance delivers knowledge that makes LT-renovations more accessible. This will eventually lead to the diversification of our current energy system. This thesis also delivers a contribution to the Integrale Energietransitie in Bestaande Bouw (IEBB) 1.5 Collective Heat, which researches innovative solutions on how to connect neighbourhoods to collective heat networks that provides a low supply temperature.

Expanding beyond Building Technology field
This thesis is an interdisciplinary research, combining the field of building technology with environmental science and science communications. Combining research on different academic fields is promising for discovering new links leading to innovation.

EXPLORATION LTH

2. LT-RENOVATION

The first step to answering sub-question 1a, *´What are the current state-of-the-art renovation measures that can enable LT-heating?´*, is researching what LT-heating encompasses. This provides boundary conditions for the intended decision-support framework and identifies LT-requirements. It also makes the research into renovation measures more focused, since the state-of-the-art measures can now be explored to enable LTH.

2.1 Low-temperature heating

2.1.1 Definition of Low-Temperature

First a clear definition of what LT encompasses needs to be given, since the temperature range that is considered LT varies in literature. The definition used in this research is based on LT-definition used by TKI Urban Energy (2022) and the NPLW (2022c), which are both Dutch government funded knowledge institutes that focus on sustainable energy innovations and strategies in the built environment. Table 2.1.1 provides an overview of the temperature ranges, use of heat and common energy sources in HT, MT, LT and ULT heating.

LT and ULT heat cannot directly be used for the production of domestic hot water (DHW). This is due to the increased risk of legionella when water temperature reaches below 55 °C for an extended period of time. Therefore LT, ULT and potentially MT water supply requires a booster for DHW to prevent this risk (Criel et al., 2022; TKI Urban Energy, 2022).

The majority of current Dutch energy sources are fossil based, namely natural gas and coal. These non-renewable chemical energy sources are of high quality, meaning it can easily be converted from chemical to thermal or kinetic energy, and can relatively easy produce a high supply temperature for heating. Renewable energy sources are often of low quality, since their applicability is limited. Those sources are often thermal (geo-, aqua-, solarthermal) or electric (PV, HP) and are harder to transform into other energy types. Biomass is the exemption, but is more scarce compared to the widely available ULT/

Temperature Definition	Supply Temperature Range	Use of Heat		Energy Source	
		Space Heating	Domestic Hot Water	Non-renewable	Renewable
High temperature (HT)	75-90 °C	Direct use	Direct use	• Combined heat and power (CHP) using natural gas, coal, or waste • Heat plants using natural gas • Waste heat from power plants, industry or waste incineration	• Combined heat and power (CHP) using biomass • Heat plants using biomass • Deep geothermal energy
Medium temperature (MT)	55-75 °C	Direct use	Direct use if DHW is ≥65 °C, otherwise upgrade temperature with booster	• Combined heat and power (CHP) using natural gas, coal, or waste • Heat plants using natural gas • Waste heat from power plants, industry or waste incineration	• Deep geothermal energy • Biomass boilers • Solar thermal energy • Heat pumps
Low temperature (LT)	30-55 °C	Direct use if LT-distribution systems are in place (e.g. LT-raditators, underfloor heating)	No direct use, upgrade DHW temperature to ≥65 °C with booster	• LT-waste heat from data centres or cold storage	• Shallow geothermal energy • Solar thermal energy • Heat pumps
Ultra-low temperature (ULT)	<30 °C	No direct use, upgrade to temperature required for space heating, use LT-distribution systems	No direct use, upgrade DHW temperature to ≥65 °C with booster	• ULT-waste heat from data centres or supermarkts	• Aquathermal energy • Solar thermal energy

Table 2.1.1 Temperature definition, use of heat and common energy sources. Based on ref. TKI Urban Energy (2022); NPLW (2022c).

LT/MT renewable thermal and electric sources (de Boer, 2022). Although non-renewable, waste heat from power plants and waste incinerators are also commonly used as a LTH source, still contributing to a more sustainable environment by giving residual heat a new purpose (TKI Urban Energy, 2022).

It is important to note the difference between source temperature and supply temperature. By boosting an ULT or LT source through a (collective) heat pump, the supply temperature could become MT. The use of an ULT or LT source therefore doesn't necessary lead to a ULT or LT supply range. A recent study by Pothof, Vreeken & van Meerkerk (2023) shows that the supply temperature for 60% of existing Dutch dwellings can be lowered to MT supply of 55 °C without causing a need for renovation. It is thus the supply temperature combined with the capacity of the heating system that is an important indicator for the requirement of renovations. Since this thesis researches decision support for renovation, it is evident that the renovation aspect should be a part of the research. Therefore, this thesis will focus mainly on dwellings with a designed LT-supply temperature, where renovation action is most likely a necessity.

Transitioning from a HT supply temperature to a LT supply temperature requires change on multiple levels, covering energy sources, heating systems (chapter 2.1.2), and building properties (chapter 2.2). In order to identify the requirements that this change will cause, the current heating situation in the Netherlands will be briefly addressed.

2.1.2 Heating Systems

Common heating systems in NL

The most common heating system in the Netherlands is a central heating system that uses a MT or HT water radiator system (de Boer, 2022). The heat is usually generated in a natural gas boiler, and the hot water is continuously circulated by a water circulation pump through the pipes. If the valves of the radiators are opened, heat is released into the space mainly through convection, and partly through radiation. The radiators are typically placed near or under cold surfaces like windows to make use of natural convection (Sârbu & Sebarchievici, 2014).

Over 82% of the total Dutch residential building stock uses individual gas boilers for space heating. Up to 92% of the residential buildings uses natural gas as their primary source of energy (Netherlands Statistics, 2021). As visible in figure 2.1.1, in the Netherlands only 6,7% of the building stock is connected to a district heating system, and only 2,4% is electrically heated by (hybrid) heat pumps (Netherlands Statistics, 2023c). However, it is expected that by 2050 approximately 50% of the Dutch building stock will be connect to a district heating system and the other 50% will be connected to a heat pump (of which 25% hybrid), where heating is provided by a sustainable source of energy (Beckman & van den Beukel, 2019).

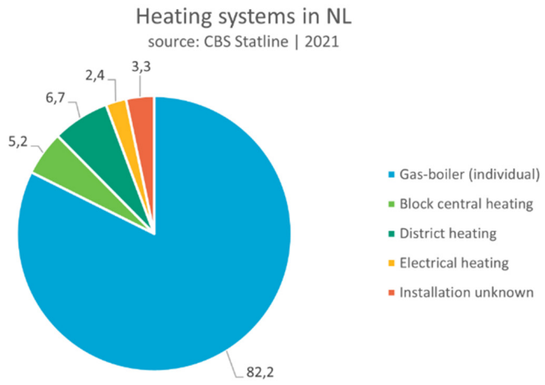


Figure 2.1.1 Residential heating systems in NL 2021*. Based on CBS data (2023c). *preliminary data

Collective, individual & hybrid low-temperature heating systems

LTH can be implemented on different scales. For instance, it can be applied to a neighbourhood with multiple building typologies, a single-family terraced building or a multi-family apartment block. Those scales can be categorized as collective, individual and hybrid heating systems, utilizing respectively low-temperature district heating (LTDH), heat pumps (HP) and collective heat pump (CHP) (NPLW, 2022c). LTH requires alternative heating systems for LTDH, HP and CHP to become energy efficient.

District Heating

District heating is a heating system that distributes steam or hot water through an underground network of (insulated) pipes to provide thermal energy to buildings. LTDH is a fourth-generation district heating and currently state-of-the-art. Although district heating (DH) is still relatively uncommon in the Netherlands, the first generation DH developed around 1880. Previous generations of DH carried water of temperatures around 100 °C, delivering high temperatures of 90 °C (2nd generation) and 70 °C (3rd generation) for space heating (Lund et al., 2014). Both Hesaraki et al. (2015) and Lund et al. (2014) predicted the development of a fourth generation LTDH around 2020. The net temperature according to Hesaraki et al. (2015) would be between 50-60°C, while Lund et al. (2014) expected it to be between 30-70°C, delivering low temperate heat of 50 °C for space heating. Figure 2.1.2 illustrates the concept of multiple generations of district heating.

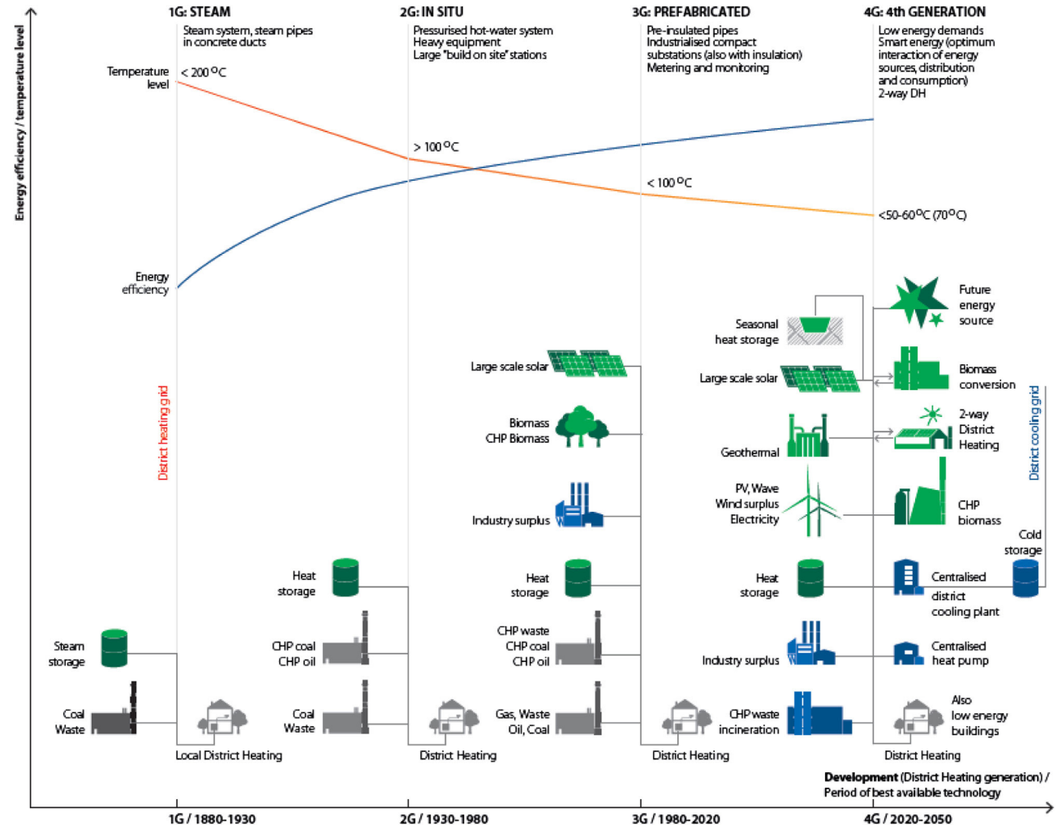


Figure 2.1.2 Illustration of the concept of 4th Generation District Heating in comparison to the previous three generations. Taken from *4th Generation District Heating (4GDH) Integrating smart thermal grids into future sustainable energy systems* (p.9) by Lund et al., 2014.

The energy efficiency of a DH network is dependent on its heat source and the heat loss occurring in the network (TKI Urban Energy, 2022). The higher the supply temperature of the network, and the longer the travel distance, the more transport losses will occur. Another factor that contributes to preventable heat losses is the constant net temperature of traditional DH networks, while on average the Netherlands only has 6-8 heating months. Lowering the net temperature in general (Hesaraki et al., 2015; Lund et al., 2014) and/or lowering the temperature of the net during warmer months (Østergaard & Svendsen, 2017) are both measures that would improve the energy efficiency of the network. Combining LTDH with (seasonal) storing of thermal energy could even further improve the energy efficiency (Lund et al., 2014).

LTDH is most suitable for dense urban areas (e.g. areas with apartment blocks), since this would limit the length of pipes and amount of connection points, leading to lower investment costs compared to single-family houses that would require individual connections to the net (NPLW, 2022c; TKI Urban Energy, 2022). LTH systems in general have high investment costs, but have low lifecycle costs compared to traditional heating systems (Cauberg-Huygen Raadgevende Ingenieurs bv, & Boerstra, A.C., 2001).

Ecofys et Greenvis (2016) expects that the use of LTDH will increase considerably over the coming decades, due to two main reasons. The first reason is the expectation that a reduction in conventional HT sources will happen due to CO2 reduction regulations, together with expected improvement of industrial processes itself. This will lead to a reduction in HT waste heat, which is currently an important source for high temperature district heating networks. The second reason is the expected reduction of heat demand in dwellings due to energy renovations, which will allow the use of LT sources. Several studies have researched the feasibility of introducing LTDH in existing neighbourhoods, showing promising results (Lund et al., 2014; Østergaard & Svendsen, 2017).

Heat Pumps

Besides LTDH, heat pumps are also promising LTH systems. A HP extracts ambient heat (e.g. from water, air, ground, solar) using electricity to upgrade the temperature to 45-55°C for space heating. Figure 2.1.3 illustrates the concept of a HP. To provide thermal comfort HPs require well insulated dwellings, a DHW storage tank, and benefit from

heat recovery systems. A HP requires space for both indoor and outdoor units within individual dwellings. HPs are most suitable for single-family buildings, but something to consider especially in urban areas is that the outside unit of heat pumps can produce up to 40 dB (NPLW, 2022a).

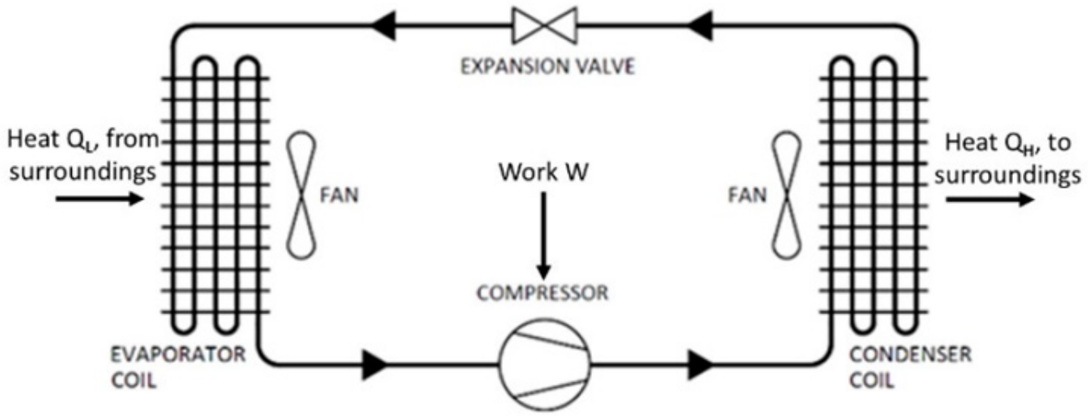


Figure 2.1.3 The schematic of a basic refrigeration cycle. Taken from *State of the Art on Heat Pumps for Residential Buildings* (p.3) by Wang et al., 2021.

According to the state-of-the-art review on heat pumps from Wang et al. (2021) there are currently 6 distinct types used in residential buildings: air source heat pump (ASHP), water source heat pump (WSHP), ground source heat pump (GSHP), solar assisted heat pump (SAHP), cascade heat pump and two stage heat pump. ASHP are less energy efficient when low ambient temperatures are reached, resulting in a low Coefficient Of Performance (COP) and lower heating capacity. Heat pumps with a low COP require a relatively high input of electrical energy, which can contribute to congestion of the electricity grid (NPLW, 2022a). A heat pump can reach a high COP when the source temperature and supply temperature are relatively close (Hesaraki et al., 2015; NPLW, 2022a). WSHP and GSHP are more resilient to cold weather conditions in terms of energy efficiency compared to ASHP. The cascade heat pump and two stage heat pump are designed to reduce the sensitivity to cold weather in ambient sources by having multiple refrigerants with separate cycles, so that the refrigerants can function at their optimum (Wang et al., 2021). The pros and cons of various HP types are summarized in table 2.1.2.

A HP can be combined with PV panels to produce the electricity needed to operate the HP in a completely renewable and self-sufficient way. However, the intermittent character of solar energy would lead to the requirement of either a thermal energy storage or electrical energy storage (NPLW, 2022a; Wang et al., 2021), requiring additional space inside the dwelling for technical installations.

Transitioning to a renewable energy system has the aim to reduce the environmental impact of the energy sector. It is therefore important to note that, although HPs can massively contribute to the reduction of GHG emissions, most refrigerants used in HPs have a negative environmental impact along with the antifreeze used in the heat transfer fluid to prevent freezing of the system. Using natural refrigerants like R290 or R744 can contribute to an overall environmental beneficial energy system (Wang et al., 2021).

Collective Heat Pumps

Collective heat pumps (CHP) are hybrid systems, meaning that a large scale HP extracts ambient heat from a collective source, and distributing the thermal energy for space heating to individual houses in the same neighbourhood or individual apartments in the same block. Figure 2.1.4 illustrates the concept of a CHP. Just like LTDH and HP, CHP requires a booster with a storage tank to provide for DHW. The CHP requires a boiler house inside or very close to the apartment block. The investment costs of CHP are relatively high compared to individual HP, but relatively low compared to LTDH. Criel, Sourbron & Breesch (2022) researched with the use of a case study that the occupancy profiles in apartment buildings has a significant impact on the required sizing of CHP systems. Currently, CHP are massively over dimensioned, and adjusting this could lead to lower investment costs making it a more attractive option for stakeholders.

Heat Pumps	Pros	Cons
Air Source Heat Pump	Simple operation and low installation costs Less primary energy consumption and GHG emissions than conventional fossil-fuel-based systems	Frost formation on the outside evaporator at low ambient temperatures Heating capacity and COP may decrease under cold climates.
Water Source Heat Pump	Can utilize heat from abundant sources, such as rivers, ponds, and lakes Higher COP and energy efficiency ratio (EER) than ASHPs	Surface water temperature is affected by climate variations. Low water quality may cause the blockage, corrosion, and fouling of heat exchangers. Water availability can restrict the use of WSHPs.
Ground Source Heat Pump	Highly efficient systems Higher COP and greater energy savings than ASHPs More suitable to be applied in than ASHPs in cold climates Significant GHG emissions reductions compared to fossil-fuel-based systems.	High installation costs or land requirement Potential leaks of refrigerant and antifreeze solutions Metal corrosion of GHEs System performance may be affected by underground heat accumulation and depletion.
Solar Assisted Heat Pump	Significant environmental benefits 70% of energy savings can be achieved. Higher-temperature heat being delivered to heat pumps	Solar intermittency restricts the system performance Requires complex control system Relatively high installation costs
Cascade Heat pump	Higher heating capacity and COP than single-stage heat pumps Can operate efficiently under cold climates Great GHG emissions reduction compared to fossil-fuel-based systems	Higher installation cost, Higher operating costs than fossil-fuel-based systems Hard to add a four-way valve to achieve heating or cooling
Two Stage Heat Pump	Higher COP and heating capacity than conventional ASHPs Can operate efficiently under cold climates	Significantly higher costs than ASHPs Requires appropriate control logic

Table 2.1.2 Summary of pros and cons of various heat pumps. Taken from *State of the Art on Heat Pumps for Residential Buildings* (p.19) by Wang et al., 2021.

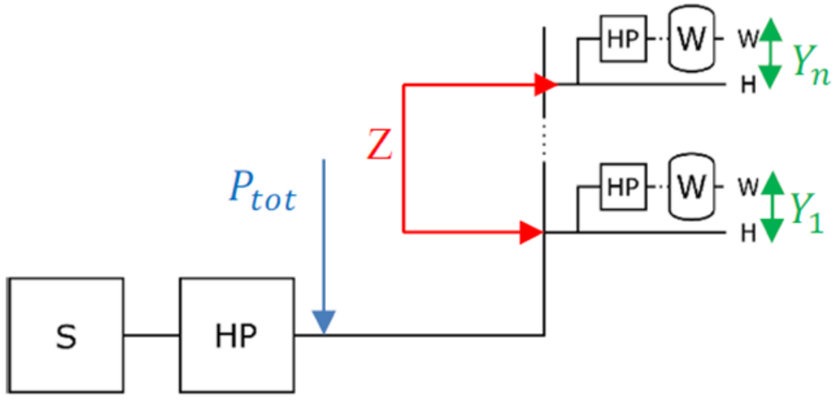


Figure 2.1.4 Schematic drawing of the CHP-system. Taken from *Sizing a collective heat pump system in an apartment building: impact of occupancy profiles* (p.3) by Criel, Sourbron & Breesch, 2022.

2.1.3 Strengths & Weaknesses of LTH systems

Although LTDH, HP and CHP are all energy efficient heating systems, their suitability is highly dependent on scale. LTDH and CHP benefit the most from dense urban areas with stacked buildings, whereas HP is more suitable for ground-level buildings in either urban or rural areas. LTH has the potential to become a key contributor to the energy transition in the building sector, but also comes with challenges that this thesis will address. The identified strengths and weaknesses from chapter 2.1.1 and 2.1.2 are summarized in table 2.1.3. To guarantee the energy efficiency of LTDH, HP and CHP systems a LT heat delivery system is required. Chapter 2.2.1 will elaborate on the different types of heat delivery systems.

LTH system	Strengths	Weaknesses
LTDH	• Renewable sources widely available and non-weather dependent • Energy efficient system, especially when combined with energy storage, low transmission losses • Underground infrastructure, leaving valuable space for other renewable energy producers like wind and solar • After initial investment energy costs are much lower compared to traditinal gas heated systems	• Availability of source is location dependent, limited transportation distances • Requires large underground infrastructure, leading to high investment costs • Likely to require (extensive) renovation measures to compensate difference in heating demand and heating capacity caused by lowering the supply temperature • Requires booster for DHW to prevent legionella
HP	• Renewable sources widely available, ground variant is non-weather dependent, water variant is season dependent • Energy efficient system, can become self-sufficient if combined with PV-panels and storage • HP has the potential for cooling as well as heating • After initial investment energy costs are much lower compared to traditinal gas heated systems	• Air and solar variant are weather/season dependent, influencing the energy effiency • Requires electrical energy, contributing to the risk of grid congestion • HP requires aditional space for indoor & outdoor units • Likely to require (extensive) renovation measures to compensate difference in heating demand and heating capacity caused by lowering the supply temperature • Requires booster for DHW to prevent legionella • Outdoor units can produce up to 40 dB, risk for noise pollution • Most refrigerants used in HPs have a negative environmental impact
CHP	• Renewable sources widely available, ground variant is non-weather dependent, water variant is season dependent • Energy efficient system, can become self-sufficient if combined with PV-panels and storage • CHP has the potential for cooling as well as heating • After initial investment energy costs are much lower compared to traditinal gas heated systems	• Air and solar variant are weather/season dependent • Requires electrical energy, contributing to the risk of grid congestion • CHP requires large boiler house for technical installations • Likely to require (extensive) renovation measures to compensate difference in heating demand and heating capacity caused by lowering the supply temperature • Requires booster for DHW to prevent legionella • High investment costs, but correct sizing of CHP could reduce this • Most refrigerants used in HPs have a negative environmental impact

Table 2.1.3 Strengths & Weaknesses of LTH systems

MAIN FINDINGS 2.1

- Low-temperature = 30-55 °C
- Common heating system in NL is central heating with natural gas source
- LTH heating systems can be applied on individual scale (Heat Pump), collective scale (District Heating) or hybrid scale (Collective Heat Pump)
- Each LTH system has its own strenghts and weaknesses, context is an important factor in detemening the type of system

2.2 State-of-the-art renovation measures for LTH

In order to enable LTH in existing dwellings while providing a reasonable level of thermal comfort, a variety of renovation measures can be implemented. Chapter 2.2.1 elaborates on the type of measures, categorized in measures on the building envelope scale and building installations. Chapter 2.2.2 elaborates on two methods for a costs analysis which can be used to estimate the financial benefits of the presented renovation measures.

2.2.1 State-of-the-art renovation measures

The renovation measures on the building envelope scale aim to reduce the heating demand by improving the insulation values of the dwelling, thereby reducing transmission losses. The renovation measures on the building installation scale aim to improve the heating capacity and efficiency. This way, the resulting gap between heating demand and heating capacity caused by a lower supply temperature will be solved, contributing to LT-ready renovation scenarios.

Building Envelope

Bone (2009), Hirvonen et al. (2018), Konstantinou & Knaak (2013), Netherlands Enterprise Agency (n.d.), Wahi et al. (2023b) and Wang & Holmberg (2014) generally suggest the same type of renovation measures to reduce the buildings transmission and infiltration losses occurring in the building envelope. Two distinct approaches can be identified. The first is an insulation approach where roof, wall & floor surfaces, and thermal bridges are retrofitted by adding insulation material to achieve a higher R-value, while doors and windows are replaced to achieve a lower U-value. The second strategy is an airtight approach where gaps near windows and doors are sealed, and ventilation grills are replaced by demand driven or pressure regulated grills to reduce the infiltration rate. An overview of these measures is provided in table 2.2.1. An illustration of the placement for the roof, wall and floor insulation can be found in figure 2.2.2. Figure 2.2.1 shows an example of air tightness improvement.

In order to determine to what extent the renovation measures need to be implemented, the Netherlands Enterprise Agency (2023) published de Standaard en Streefwaarden voor Woningisolatie, which encompasses limit values and indications for insulation thickness as well as recommendations for ventilation systems that will be sufficient to enable LTH.



Figure 2.2.1 Air tightness improvement by adding draft excluders to window frame. Taken from *https://heemstededuurzaam.nl/het-abc-van-de-tochtstrip-2/*

Building Envelope

Renovation Measures	Roof		Wall		Floor		Façade openings		Air tightness	
	Flat roof interior insulation	1, 2, 3, 5, 6	Cavity insulation	1, 4, 5	Crawl space insulation	1, 3, 4, 5	Glass replacement [double glazing or triple glaing/HR++]	1, 3, 4, 5, 6	Improved air tightness façade openings	1, 4, 5, 6
	Flat roof exterior insulation	1, 2, 3, 4, 5, 6	Wall interior insulation	1, 2, 3, 4, 5, 6	Insulation on top of floor	1, 3, 4, 5, 6	Frame replacement	1, 3, 5	Improved air tightness roof	1, 4
	Pitched roof attic insulation	1, 3, 4, 6	Wall exterior insulation	1, 2, 3, 4, 5, 6			Window replacement	2, 4, 5, 6	Improved air tightness wall-ground floor	6
	Pitched roof interior insulation	1, 2, 3, 4, 5, 6					Insulated door	2, 4, 5		
	Pitched roof exterior insulation	1, 2, 3, 4, 5, 6					Insulated panels	1, 4		
							Balcony/Gallergy sealing [joints & intersections sealing or building envelope integration]	3, 4, 5, 6		

Ref nr.	Author
1	Bone (2009). *Basisboek Isoleren*
2	Hirvonen et al. (2018). *Towards the EU emissions targets of 2050: optimal energy renovation measures of Finnish apartment buildings*
3	Konstantinou & Knaak. (2013). *An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate*
4	Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO). (n.d.). *Kostenkentallen.*
5	Wahi et al. (2023b). *Lower-Temperature-Ready Renovation: An approach to identify the extent of renovation interventions for lower-temperature district heating in existing Dutch homes*
6	Wang & Holmberg. (2014). *A methodology to assess energy-demand savings and cost-effectiveness of retrofitting in existing Swedisch residential buildings*

Table 2.2.1 Renovation measures at Building Envelope scale

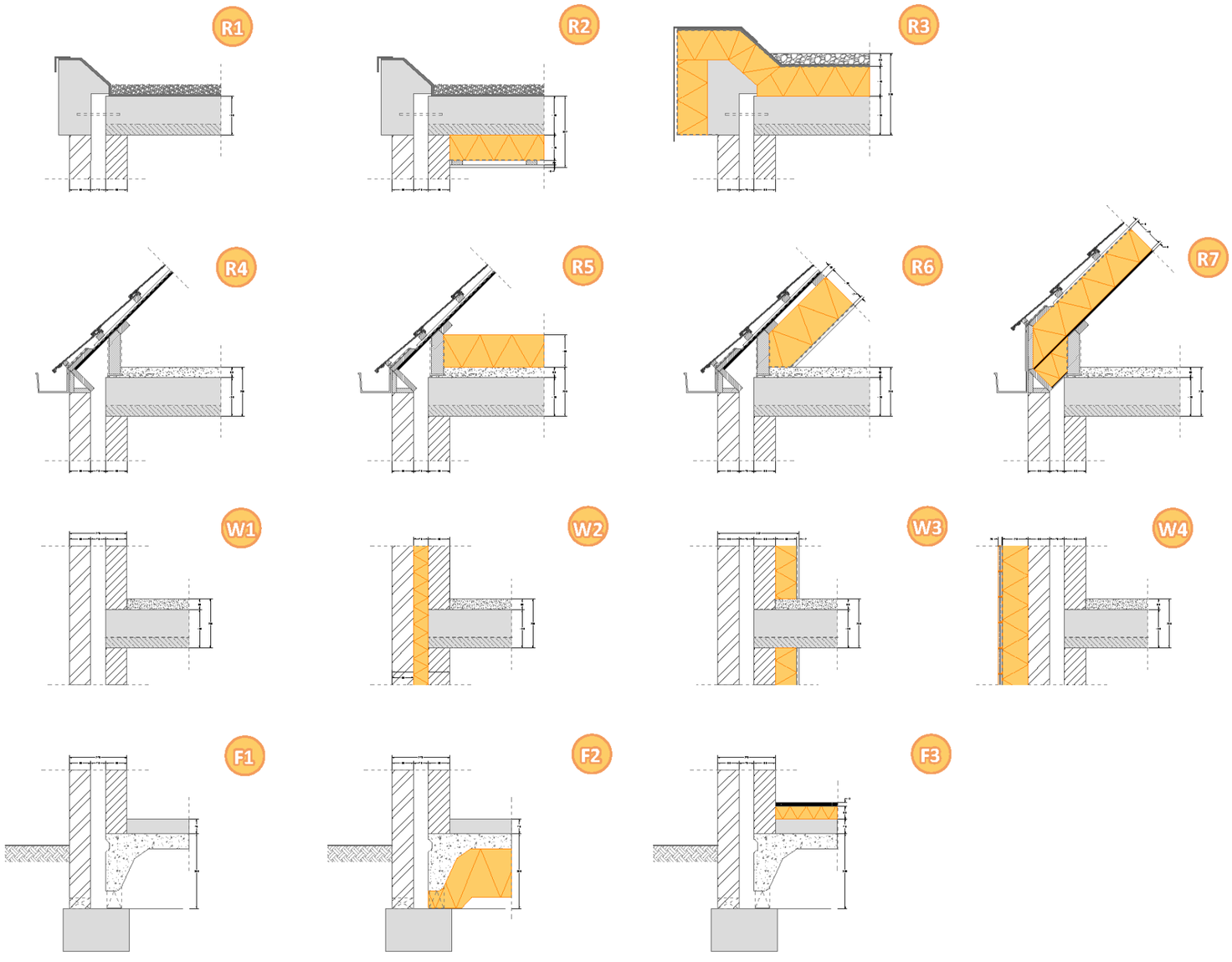


Figure 2.2.2 Insulation placement for roof, wall and floor renovation measures. Based on underlay SBR-referentiedetails Woningbouw 101.0.3.01; 301.0.3.01; 401.0.3.01; 409.0.3.01.T1

Building Installations

Apart from lowering the heating demand through reducing transmission and infiltrations losses, increasing the heating capacity and improving heating efficiency also contributes to enabling LTH. The heating capacity can be increased by enlarging the heat emitting surface area or enhancing the heat transfer coefficient (Hesaraki, Ploskic & Holmberg, 2015). Changing the heat delivery system from existing radiators to large surface emitters like underfloor, wall or ceiling heating, or introducing LT-radiators will therefore increase the heating capacity. Instead of changing the whole heating system, adding one or two radiators to the existing systems could also provide the needed increase in heating capacity. For peak moments like cold winter days an extra heating element might be necessary to provide comfort, for example an infrared panel in the living room (Milieu Centraal, n.d.-B).

The heating efficiency can be improved by changing the existing ventilation system to a demand-driven system with heat recovery, or a balanced ventilation system (Hesaraki, Ploscik & Holmberg, 2015; Hirvonen et al., 2018; Konstantinou & Knaak, 2013; Milieu Centraal, n.d.-C; Wahi et al., 2023b). Ventilation systems can be either centralized or decentralized systems for air inlet and outlet. A decentralized system has an individual air inlet/outlet per room with its own connection to the exterior, a centralized air inlet/outlet means one sub-inlet/outlet per room that is connected to the main air inlet/outlet that connects to the exterior. A system can be completely (de)centralized, or have for example a decentralized inlet with a centralized outlet (ISSO – Kleintje Ventilatie, 2023). It is common for dwellings built before 1970 to have a natural ventilation system (VST1), and common for dwellings built after 1970 to have an exhaust ventilation system (VST3-4). Balanced ventilation systems (VST5-6) are relatively new and were applied from 2010 onwards, in addition to VST3-4. Ventilation system type B (VST2) with mechanical supply and natural exhaust is very uncommon in the Netherlands (Netherlands Enterprise Agency, 2022). Table 2.2.3 shows the average insulation values of the building envelope and implemented ventilation type relative to the building typology and construction period.

A ventilation radiator is a heat delivery system that combines ventilation with heating, by placing an air inlet in the wall behind the radiator. The cold air is preheated by the radiator reducing cold drafts, while the forced convection reduces thermal stratification (Hesaraki, Ploskic & Holmberg, 2015; Wang & Holmberg, 2014).

Another option to improve the heating efficiency is to apply additions to the existing heat delivery or ventilation system. For example adding pressure regulated grills, implementing heat reflective foil between the outside wall and the radiators, or reducing thermal stratification by applying forced convection through add-on fans. Those add-on fans can improve the heat delivery by 20% (Milieu Centraal, n.d.-A), but do produce noise up to 24 dB (Milieu Centraal, n.d.-B). Heat reflective foil reduces transmission losses through the wall behind the radiator, with an estimated annual saving effect of 10 m^3 natural gas per square meter (Milieu Centraal, n.d.-A). Integrating smart control systems that anticipate the moment of heat demand based on the current weather forecast, or peak shaving control systems can improve the heating efficiency (Lund et al., 2014). Lowering the indoor operative temperature from 21-22 to 19-20 °C would reduce the heating demand without any interventions (Milieu Centraal, n.d.-A; Wahi et al., 2023b), but could require a form of behavioural thermoregulation like putting on an additional sweater to provide comfort to the occupant. Heating pipes that encounter unheated spaces like the crawl space can be insulated to reduce transmission losses. It is estimated that the addition of 2 cm insulation per meter pipe would save 3 m^3 natural gas per year (Milieu Centraal, n.d.-A).

Table 2.2.2 provides an overview of renovation measures at building installation scale that increase the heating capacity and efficiency. For a clear overview, the ventilation system types as described in literature are divided into ventilation system types as found in ISSO – Kleintje Ventilatie (2023).

Renovation Measures							
Building Installations							
Heat Delivery System		**Ventilation System**			**Additions**		
Existing radiators	3, 4a, 7	VST1 (A) - Natural ventilation	Natural supply, natural exhaust	6	Heat reflective foil (radiators, LT-radiators)	4b
Underfloor heating	1, 2, 4a, 5, 7	VST2 (B) - Mechanical ventilation	Mechanical supply (wet & dry spaces), natural exhaust		Add-on fan radiator (radiators, LT-radiators)	2, 4a, 4b, 7
Wall heating	1, 2, 4a, 5	VST3 (C4a) - Exhaust ventilation wet spaces	Natural supply (dry spaces), mechanical exhaust (wet spaces), CO2-driven	3, 5, 6, 7	Ventilation grills (pressure grills, CO2 driven)	5
Ceiling heating	2	VST4 (C4c) - Exhaust ventilation all spaces	Natural supply (dry spaces), mechanical exhaust (wet & dry spaces), CO2-driven	3, 5, 6, 7	Smart control (anticipating weather, peak shaving, indoor operative temperature control to 19-20 °C)	4b, 7
LT-radiators	1, 3, 5, 7	VST5 (D3/D5a) - Centralized balenced ventilation	Mechanical supply (dry spaces), mechanical exhaust (wet spaces), central system, heat recovery, CO2-driven	1, 2, 3, 5, 7	Insulation of heating pipes	4b, 5
Convectors/baseboard radiators	1, 4a, 7	VST6 - Decentralized balanced ventilation	Mechanical supply (circulation space), mechanical exhaust (wet & dry spaces), decentral system, CO2-driven, heat recovery	2, 3, 5, 7	Additional radiator	4a
Air heating	1, 2	VST7 (X1) - Hybrid ventilation	Mechanical supply (dry spaces), mechanical exhaust (wet spaces & dry spaces, combined central & decentral), optional hybrid system combination with VST3-4 or VST1, optional heat recovery, optional humidity/ CO2-driven	5		
LT-ventilation radiators	2, 5, 7					
Infrared panels	4a, 7					

Ref nr.	Author
1	Cauberg-Huygen Raadgevende Ingenieurs bv, & Boerstra, A.C. (2001). *LTV voor nieuwbouw en renovatie: Méér comfort met minder energie*
2	Hesaraki, Ploskic & Holmberg. (2015). *Integrating Low-temperature Heating Systems into Energy Efficient Buildings*
3	Hirvonen et al. (2018). *Towards the EU emissions targets of 2050: optimal energy renovation measures of Finnish apartment buildings*
4a	Milieu Centraal. (n.d.). *Lage temperatuur verwarming (ltv)*
4b	Milieu Centraal. (n.d.). *Bespaartips verwarming.*
5	Netherlands Enterprise Agency (Rijksdienst voor Ondernemend Nederland, RVO). (n.d.). *Kostenkentallen.*
6	Konstantinou & Knaak. (2013). *An approach to integrate energy efficiency upgrade into refurbishment design process, applied in two case-study buildings in Northern European climate*
7	Wahi et al. (2023b). *Lower-Temperature-Ready Renovation: An approach to identify the extent of renovation interventions for lower-temperature district heating in existing Dutch homes*

Table 2.2.2 Renovation measures at Building Installations scale

Voorbeeldwoningen 2022 Building type	Ground floor Rc-value [m²K/W]	Wall Rc-value [m²K/W]	Roof Pitched Rc-value [m²K/W]	Roof Flat Rc-value [m²K/W]	Window U-value [W/m²K]	Door U-value [W/m²K]	Ventilation type [ISSO ventilatie]	Average heat demand [kWh/m²]	De Standaard [kWh/m²]	Deviation from 'de standaard' [kWh/m²]
Detached										
before 1965	**0,15**	0,35	2,50	0,85	1,80	3,40	VST1	213,6	92,8	120,8
1965-1974	**0,17**	0,43	0,86	0,86	2,90	3,40	VST1	204,9	87,8	117,1
1975-1991	**0,52**	1,30	1,30	1,30	2,90	3,40	VST1	157,3	90,3	67,0
1992-2005	**2,50**	2,50	2,50	2,50	2,90	3,40	VST3-4	122,2	90,2	32,0
2006-2014	**2,50**	2,50	2,50	2,50	1,80	3,40	VST3-4	104,4	84,7	19,7
2015-2018	**3,50**	4,50	6,00	6,00	1,80	3,40	VST3-4	91,4	93,6	-2,2
Semi-detached										
before 1965	0,15	0,35	0,72	2,50	1,80	3,40	VST1	197	80,5	116,5
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST1	183,5	75,8	107,7
1975-1991	1,30	1,30	1,30	1,30	2,90	3,40	VST1	139,1	79,2	59,9
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	108	78,0	30,0
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	94,3	76,1	18,2
2015-2018	3,50	4,50	6,00	6,00	1,80	2,00	VST3-4	72,2	64,2	8,0
Terraced middle										
before 1946	0,15	0,35	2,00	0,35	2,90	3,40	VST1	160,7	107,8	52,9
1946-1964	0,15	0,35	0,72	0,72	2,90	3,40	VST1	162,5	61,6	100,9
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST1	141,9	57,5	84,4
1975-1991	0,52	1,30	1,30	1,30	2,90	3,40	VST3-4	108,4	57,0	51,4
1992-2005	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	81,4	61,0	20,4
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	74,5	58,3	16,2
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST3-4	68,8	62,0	6,8
Terraced corner										
before 1946	0,15	0,35	0,22	0,35	2,90	3,40	VST1	259,6	169,2	90,4
1946-1964	0,15	0,35	0,85	0,35	1,80	3,40	VST1	208,2	84,2	124,0
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST1	183,6	75,6	108,0
1975-1991	0,52	1,30	1,30	1,30	2,90	3,40	VST3-4	132,3	75,8	56,5
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	110,7	81,8	28,9
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	91,8	76,9	14,9
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST3-4	79,4	76,7	2,7
Maisonette										
before 1965	0,15	0,19	0,35	0,35	2,90	3,40	VST1	154,9	45,0	109,9
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST1	157,7	50,8	106,9
1975-1991	1,30	1,30	1,30	1,30	2,90	3,40	VST3-4	93,6	47,6	46,0
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	76	45,0	31,0
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST5-6	58,8	48,2	10,6
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST5-6	51,2	48,2	3,0
Gallery apartment										
before 1965	0,15	0,35	0,72	0,72	2,90	3,40	VST1	144,4	45,0	99,4
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST3-4	111,2	45,0	66,2
1975-1991	0,52	1,30	1,30	1,30	2,90	3,40	VST3-4	90,2	45,0	45,2
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	75,4	45,0	30,4
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	66	45,0	21,0
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST5-6	35	45,0	-10,0
Staircase apartment										
before 1946	0,15	0,19	0,35	0,35	2,90	3,40	VST1	176,6	104,4	72,2
1946-1964	0,15	0,35	0,72	0,72	2,90	3,40	VST1	154,2	55,7	98,5
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST3-4	120,7	45,4	75,3
1975-1991	0,52	1,30	1,30	1,30	2,90	3,40	VST3-4	98,3	49,1	49,2
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	79,3	48,0	31,3
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	73,7	48,3	25,4
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST3-4	83,8	59,7	24,1
Apartment (other)										
before 1965	0,65	0,35	0,72	0,72	2,90	3,40	VST1	121	45,0	76,0
1965-1974	0,17	0,43	0,86	0,86	2,90	3,40	VST3-4	118,3	45,0	73,3
1975-1991	0,52	1,30	1,30	1,30	2,90	3,40	VST3-4	85,1	45,0	40,1
1992-2005	2,50	2,50	2,50	2,50	2,90	3,40	VST3-4	75,9	45,0	30,9
2006-2014	2,50	2,50	2,50	2,50	1,80	3,40	VST3-4	65,6	45,0	20,6
2015-2018	3,50	4,50	6,00	6,00	1,80	3,40	VST3-4	56,5	45,0	11,5

Table 2.2.3 Average insulation values, ventilation type & heat demand based on data from Netherlands Enterprise Agency (2022). The last column indicates the improvement required in kWh/m² to meet De Standaard. Red = deep renovation, orange = moderate renovation, yellow = light renovation, green = no renovation.

2.2.2 Cost of Renovation Measures

A cost-benefit analysis [CBA] can provide useful insights for the decision making process when selecting a renovation strategy. It is an approach that can be used to evaluate which interventions provides the highest value for the costs associated, often expressed over a certain time span (e.g. lifetime of renovation measure). A CBA assigns monetary value to both costs and benefits. The benefits in this case are the energy saving benefits of the renovation measures, which can be quantified through calculating the expected effect on the heat losses. This requires comparing the original energy performance values to the new renovated values.

There are multiple types of cost-benefit analysis, of which payback period [PP] and net present value [NPV] are commonly used in energy renovation projects (Belaïd et al., 2021). All incorporate the total investment costs as a factor. The investment costs itself is an important indicator to determine economic feasibility. When these costs exceeds the available investment budget, those renovation options can be eliminated from the decision-making process.

Payback Period

The payback period is a quick and simple technique to expresses the length of time it takes to recover the cost of a renovation measure ($P_{investment}$) through the annual energy savings generated by that measure ($E_{savings}$). The annual energy savings can also be expressed as net cash flow over the first year ($CF_{i=1}$). The Netherlands Enterprise Agency (n.d., Kostenkentallen) provides data on the investment costs of different renovation measures. A low PP value indicates a short payback period, which is often the preferred option. Profitability and time value of money is not incorporated in this type of cost analysis (Belaïd et al., 2021). The PP can be calculated by following formula 2.1-2.4.

$$PP = \frac{P_{investment}}{E_{savings}} = \frac{P_{investment}}{CF_{i=1}} \quad (2.1)$$

PP = payback period [years]

$P_{investment}$ = initial investment cost of renovation measure [€] per unit area [€/m²]

$E_{savings}$ = annual energy saving benefits of renovation measure [€/m²]

$CF_{i=1}$ = net cash flow of year *i* of renovation measure, *i=1* [€]

$$E_{savings} = S_{natural\ gas} * P_{natural\ gas} \quad (2.2)$$

$S_{natural\ gas}$ = annual volume of natural gas saved per unit area [m³/m²]

$P_{natural\ gas}$ = cost of natural gas per unit volume [€/m³]

$$S_{natural\ gas} = \frac{\Delta Q_{heat\ loss}}{CV_{natural\ gas} \cdot \eta_{boiler}} \quad (2.3)$$

$\Delta Q_{heat\ loss}$ = reduced annual heat losses per unit area [MJ/m²]

$CV_{natural\ gas}$ = caloric value natural gas [MJ/m³] = 35,2

η_{boiler} = boiler efficiency [%] = 90

The caloric value of natural gas ($CV_{natrual\ gas}$) is assumed to be constant, a typical CV for natural gas in the Netherlands is 35,2 MJ/m³. The boiler efficiency is also assumed constant, with a typical value of 90%. The total annual heat loss reduction can be expressed as followed:

$$\Delta Q_{heat\ loss} = Q_{heat\ loss\ original} - Q_{heat\ loss\ renovated} \quad (2.4)$$
$$= (\Delta Q_{trans} + \Delta Q_{vent} + \Delta Q_{inf}) \cdot \Delta T_{heating\ season} \cdot t_{heating\ season}$$

ΔQ_{trans} = transmission heat loss difference between original and renovated scenario

ΔQ_{vent} = ventilation heat loss difference between original and renovated scenario

ΔQ_{inf} = infiltration heat losss difference between original and renovated scenario

$\Delta T_{heating\ season}$ = average indoor outdoor temperature difference of heating season [°C]

$t_{heating\ season}$ = duration of heating season [Ms]

The transmission, ventilation and infiltration losses can be calculated according to chapter 2.3 Energy Performance formula 2.12-2.14. $\Delta T_{heating\ season}$ multiplied by $t_{heating\ season}$ is also know as the time accumulated temperature difference. This is assumed constant with a typical value of 238 [K·Ms] (N5128, n.d.). If required the time accumulated temperature difference can also be calculated for specific values.

Example: the average heating season in the Netherlands starts in October and ends in April. This leads to a $t_{heating\ season}$ = 211 days = 18,23 Ms. Assuming the average indoor temperature during heating season is T_{in} = 20 °C, and the average outdoor temperature during heating season is T_e = 6,13 °C. This results in a time accumulated temperature difference of (20 - 6,13)·18,23 = 253 [K·Ms]. It can be concluded that a higher average indoor temperature leads to a higher time accumulated temperature difference.

Net Present Value

The NPV is a more complex technique that expresses the difference between the present value of cash inflows and outflows over a period of time. In this case the present value of cash inflows represents the energy saving benefits, while the present value of cash outflows represents the investment costs, with the time period being the lifetime of the renovation measure. A positive NPV is an indicator for economic viability, suggesting that the project's benefits outweigh its costs. Conversely, a negative NPV implies a deficit in overall value. Investments with a higher NPV are more profitable compared to those with a lower NPV (Belaïd et al., 2021). The most important limitations of a NPV is that the input values like investment cost and discount rate are all estimations. The NPV can be calculated by following formula 2.5-2.8..

$$NPV(\tau)_{dwelling} = \sum_{i=1}^{n} NPV(\tau)_{measure,\ n} \quad (2.5)$$

$$NPV(\tau)_{measure} = -I_0 + \sum_{i=1}^{\tau}\left(\frac{CF,i}{(1+d)^i}\right) \quad (2.6)$$

$NPV(\tau)_{measure}$ = Net Present Value over period of time τ per measure

τ = calculation period, lifetime of renovation measure

I_0 = investment cost of renovation measure per renovated surface [€]

CF,i = net cash flow of year i per measure (energy saving benefits) [€]

d = discount rate [%] = 4

When summing the NPV of each measure, the calculation period (τ) has to be the same. The discount rate is a constant value, Belaïd et al. (2021) have used a discount rate of 4%.

$$I_0 = P_{investment} * A_{renovation} \quad (2.7)$$

$P_{investment}$ = initial investment cost of renovation measure per unit area [€/m²]

$A_{renovation}$ = surface area of renovation [m²]

An accurate indication of the investment costs ($P_{investment}$) per measure can be found on the Kostenkentallen site from the RVO (Netherlands Enterprice Agency, n.d.).

$$CF,i = S_{natural\ gas} * P_{natural\ gas,i} * A_{renovation} \quad (2.8)$$

$S_{natural\ gas}$ = annual volume of natural gas saved per unit area [m³/m²] (see formula 2.3)

$P_{natural\ gas,\ i}$ = cost of natural gas per unit volume of year *i* [€/m³]

$A_{renovation}$ = surface area of renovation [m²]

It is relevant to note that a cost-benefits analysis is just one part of the decision-making process regarding the selection of a renovation scenario. The renovation measures with an individual long PP or low NPV can still be excellent performing measures on other criteria like energy performance, aesthetics or renovation duration. A decision matrix can evaluate all those decision criteria at the same time, which will be elaborated upon in chapter 4.

2.3 Evaluating LT-Readiness

2.3.1 Static vs. Dynamic calculations

There are two main methods to estimate the effect of a renovation measure on the heating demand or respectively the heating capacity. The first method involves a stationary model, the second method is a dynamic model. Both models calculate approximations of the real-world scenario, each with their own benefits and limitations.

Stationary models use steady-state heat flows, where temperatures and heat fluxes are assumed constant over time. This type of model significantly simplifies the real-world scenario, because in reality the temperatures differ per season and day/night cycle, leading to transient heat fluxes instead of steady-state heat fluxes (Bokel, 2016, LECTURE 01). Therefore, the results that stationary models provide should always be interpreted with regards to the made assumptions and simplifications. However, the simplification leads to relatively easy calculations, providing a quick overview of the potential effect of a renovation measure.

Dynamic models are often used for computational simulations, incorporating dynamic heat flows, with heat fluxes that are time dependent (non-stationary). Factors like temperature fluctuations, solar load, internal heat gain and heat storage in mass over time are considered, giving a more accurate approximation and provide a wider range of knowledge on the effects of the renovation measures over time (Bokel, 2016, LECTURE 03-04). However, dynamic models are more complex, leaving more room for error and risk of misinterpretation of results. This complexity also leads to a more time-consuming calculation than what can be expected of stationary models.

The aim for this thesis is to develop a framework that supports the decision-making process on selecting a renovation scenario, which requires providing a quick overview of multiple criteria in a concise manner. To estimate the energy performance of the renovation scenarios, this research makes use of the LTH-Rhino/grasshopper tool developed by P. Wahi. This tool combines static and dynamic calculations, ensuring a fast but relatively accurate estimation on the heating demand and thermal discomfort.

2.3.2 Stationary heat balance

A stationary heat balance is based on the principles of the energy conservation law (First Law of Thermodynamics), meaning that energy can only be converted or transferred, but is never created or destroyed. This comes down to the sum of heat flows having to be zero, see formula 2.9.

$$\sum Q = 0 \quad (2.9)$$

The heat outflux should be equal to the heat influx to create a heat balance. In a dwelling the heat outfluxes are considered heat 'losses', which sounds contradictory to the first law of thermodynamics, but it refers to a form of unwanted heat transfer since the aim in winter is to keep the heat inside the house. In order to provide a comfortable indoor temperature the heating capacity ($Q_{capacity}$) of a dwelling should be equal or higher to the heating demand (Q_{demand}) of that dwelling. This is expressed by formula 2.10:

$$Q_{demand} \leq Q_{capacity} \quad (2.10)$$

Heating Demand

The maximum required heating capacity depends on the heating demand during peak moments (e.g. a cold winter day). The heating demand can be determined by adding all the heat losses and subtracting them with all the heat gains of the dwelling. Transmission (Q_{trans}), ventilation (Q_{vent}) and infiltration (Q_{inf}) are the most important heat losses occurring in a dwelling. Internal (Q_{int}) and solar gains (Q_{solar}) are the most important heat gains to consider. The heating demand can be expressed by equation 2.11:

$$Q_{demand}\ [\mathrm{W}] = Q_{trans} + Q_{vent} + Q_{inf} - Q_{int} - Q_{solar} \quad (2.11)$$

Transmission losses occur through wall, floor and roof surfaces and façade openings like windows and doors. During winter, heat transfers from the indoor space through the building envelope into the outdoor space. How much heat is lost depends on the heat transfer coefficient and the surface area of the building element, and the indoor-outdoor temperature difference. The transmission losses can be determined by equation 2.12:

$$Q_{trans}\ [\mathrm{W}] = \sum_i U_i A_i (T_{in} - T_e) \qquad (2.12)$$

U_i = heat transfer coefficient of element i [W/m²K]

A_i = surface area of element i [m²]

T_{in} = interior temperature [°C]

T_e = exterior temperature [°C]

Ventilation losses occur through the exchange of air between the indoor and outdoor environment, either by natural or mechanical systems, or a combination of both. The amount of heat loss depends on the air change rate, the volume of ventilation and the indoor-outdoor temperature difference. A temperature correction factor should be incorporated if the ventilation system has a heat recovery system (ISSO-51, 2017). The ventilation losses can be determined by equation 2.13:

$$Q_{vent}\ [\mathrm{W}] = \frac{\rho c\ n_v V_v\ f_v}{3600} \cdot (T_{in} - T_e) \qquad (2.13)$$

ρ = specific density of air =1 ,27 [kg/m³]

c = specific heat capacity of air = 1000 [J/kgK]

n_v = air change rate [h⁻¹]

V_v = ventilation volume [m³]

f_v = temperature correction factor [-]

T_{in} = interior temperature [°C]

T_e = exterior temperature [°C]

Infiltration losses occur through cracks and seams in the building envelope, often found around façade openings. The heat loss through infiltration depends on the air tightness of the building, which depends on the infiltration rate, infiltration volume and the indoor-outdoor temperature difference. An infiltration fraction should be incorporated based on the building type (ISSO-51, 2017). The infiltration losses can be determined by equation 2.14:

$$Q_{inf}\ [\mathrm{W}] = \frac{\rho c\ n_{inf} V_{inf}\ z}{3600} \cdot (T_{in} - T_e) \qquad (2.14)$$

ρ = specific density of air =1 ,27 [kg/m³]

c = specific heat capacity of air = 1000 [J/kgK]

n_{inf} = infiltration rate [h⁻¹]

V_{inf} = infiltration volume [m³]

z = infiltration fraction [-] = 0.5

T_{in} = interior temperature [°C]

T_e = exterior temperature [°C]

The infiltration fraction is 0.5 for multi-family buildings like gallery apartments and portiekwoningen, according to the NTA8800.

Internal gains is heat produced through occupancy, lighting and equipment. The internal gains can be determined by equation 2.15:

$$Q_{int}[\mathrm{W}] = Q_{occupancy} + Q_{lighting} + Q_{appliances} \qquad (2.15)$$

$Q_{occupancy}$ = heat generated by people [W]

$Q_{lighting}$ = heat generated by lighting [W]

$Q_{appliances}$ = heat generated by equipment [W]

Solar gains is heat acquired through solar radiation on the windows. Solar gain is dependent on the total surface area of glass, the intensity of solar radiation and the solar heat gain coefficient. The solar gains can be determined by equation 2.16:

$$Q_{solar} = q_{solar} \cdot A_{glass} \cdot g \qquad (2.16)$$

q_{solar} = level of solar radiation on the glass [W/m²]

A_{glass} = surface area of glass [m²]

g = solar heat gain coefficient [-]

When considering LT-renovations, internal gains and solar gains are beneficial towards a lower heating demand during winter. However, during summertime these gains could cause the building to overheat. These gains can be reduced through the use of external sun shading and windows with a low g-factor, or compensated by increasing the ventilation. This thesis does not incorporate overheating calculations during summertime since it is out of scope (focus is on comfortable heating with LTH during winter periods), but this is something that should always be checked before selecting a final renovation scenario.

Heating Capacity

The heating capacity needs to meet the heating demand to provide comfort. There are multiple types of heat emitters, like radiators and floor heating. The heating capacity of a radiator can be calculated by equation 2.17-20. (Johansson & Wollerstrand, 2010).

$$Q_{capacity} = \dot{m}_s \cdot c_p (T_s - T_r) = k \cdot A \cdot \Delta\theta \qquad (2.17)$$

m_s = mass flow [kg/s]

c_p = heat capacity [J/kgK]

T_s = supply temperature [°C]

T_r = return temperature [°C]

k = heat transfer coefficient [W/m²K]

A = surface area of heat emitter [m²]

$\Delta\theta$ = logarithmic mean temperature difference [K]

$$\frac{1}{k} = \frac{1}{\alpha_{water-metal}} + \frac{\delta_{metal}}{\lambda_{metal}} + \frac{1}{\alpha_{conv} + \alpha_{rad}} \qquad (2.18)$$

$\alpha_{water\text{-}metal}$ = heat transfer coefficient between water and radiator [W/m²K]

δ_{metal} = thickness of metal radiator plate [m]

λ_{metal} = conductivity of metal radiator plate [W/mK]

α_{conv} = heat transfer coefficient of convective parts

α_{rad} = heat transfer coefficient of radiative parts

Convection and radiation are the most significant parameters when calculating the capacity of a radiator. Therefore, formula 2.17 can be simplified to the following equation:

$$\begin{aligned} Q_{capacity} &= Q_{rad} + Q_{conv} \\ &= \alpha_{conv} \cdot A_{conv} \cdot \Delta\theta + \alpha_{rad} \cdot A_{rad} \cdot \Delta\theta \end{aligned} \qquad (2.19)$$

α_{conv} = heat transfer coefficient of convective parts

A_{conv} = surface area of convective parts

A_{rad} = surface area of radiative parts

α_{rad} = heat transfer coefficient of radiative parts

$\Delta\theta$ = logarithmic mean temperature difference [K]

$$\Delta\theta = \frac{T_s - T_r}{\ln \frac{T_s - T_i}{T_r - T_i}} \qquad (2.20)$$

T_s = supply temperature [K]

T_r = return temperature [K]

T_i = indoor (ambient) temperature [K]

Switching from HT to LT lowers the supply and return temperature, which lowers the logarithmic mean temperature difference and thus decreases the heating capacity. To compensate this, either the surface area need to be increased and/or the heat transfer coefficient needs to be increased. This can be realised through renovation measures like replacing the existing radiators with radiators that have an additional panel, or switching to an underfloor heating system. Adding a radiator fan to the original radiators could also increase the heat output, which allows for a lower supply temperature (Johansson & Wollerstrand, 2010), potentially eliminating the need to replace the existing radiators.

2.3.3 Thermal Comfort

Thermal comfort is the state of mind that expresses satisfaction with the surrounding thermal environment. According to Auliciems & Szokolay (2007) there are environmental, personal and contributing factors that can influence thermal comfort. The environmental factors are the air temperature (dry bulb), air movement (velocity), humidity (relative, absolute or moisture content) and radiation (mean radiant temperature (MRT)). Personal factors considered are the metabolic rate and clothing, while the contributing factors considered are food & drink, acclimatization, body shape, subcutaneous fat, age & gender and state of health. These factors make thermal comfort a subjective matter. This implicates that, when there are multiple people present in the same space, it is very well possible that one person perceives the space as too cold while another perceives it as too hot.

Fanger developed the Predicted Mean Vote (PMV) model to measure thermal comfort. The PMV predicts the average thermal sensation of a group of people exposed to a certain thermal environment, ranging from -3 (cold) to 0 (neutral) to +3 (hot). The model relies on the steady-state heat balance of the human body and incorporates various environmental factors, including air temperature, MRT, air velocity, relative humidity, metabolic rate and clothing (Peeters et al., 2009). Where PMV predicts the average thermal

sensation, the Predicted Percentage of Dissatisfied (PPD) can quantify the extent of discomfort based on that sensation. The PPD is thus derived from the PMV and indicates the expected level of dissatisfaction among people. Figure 2.3.1 shows the relation between PMV and PDD. International standards like ISO 7730 and ASHRAE 55 incorporate PMV and PDD for defining what are acceptable thermal environments.

However, since the PMV and PDD model are based on steady state laboratory experiments, this is not an entirely accurate representation of the real-world, especially when considering residential buildings (Peeters et al., 2009). Therefore, the Adaptive Temperature Limits model (ATG in Dutch) was developed, which considers the occupants ability to adapt their thermal environment. This adaptation can exist of behavioural changes (e.g. adjusting clothing, opening windows), physiological changes (e.g. acclimatization) and psychological adjustments (e.g. altered thermal expectations based on previous experiences). The adaptive model accounts for variations in thermal comfort over time and different conditions, unlike the static assumptions of the PMV/PDD model. Figure 2.3.2 illustrates the temperature thresholds based on outdoor temperature for various acceptability levels.

In this thesis, when evaluating the thermal comfort of a renovation scenario, the number of hours below 20% PPD (underheated hours) are calculated for the living room during occupancy, based on the adaptive temperature model that Peeters et al. (2009) presents.

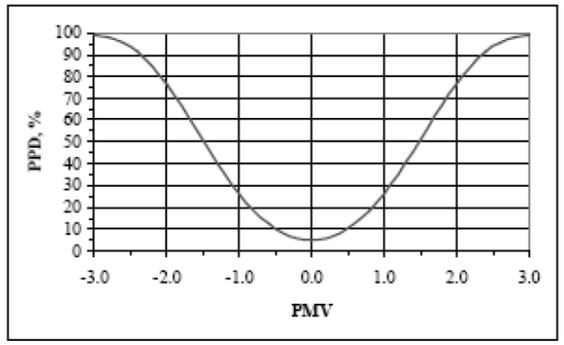


Figure 2.3.1 Predicted Percentage of Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV). Taken from *Thermal comfort in residential buildings: Comfort values and scales for building energy simulation* (p.34) by Peeters et al., 2009.

Thermal comfort with LTH systems

Low temperature heating systems provide primarily radiant and conductive heat, which is generally perceived as more pleasant compared to the primarily convective and radiant heat produced by traditional HT radiators (Cauberg-Huygen Raadgevende Ingenieurs & Boerstra, 2001). LTH systems gradually warms up surrounding surfaces where HTH directly heats the air in the room. This lack of convection (circulation patterns) in LTH leads to slower, but very consistent heat distribution, improving the indoor comfort (Hesaraki et al., 2015). LT underfloor heating provides a consistent near-optimal floor surface temperature. The relatively low surface temperature prevents dust particles from burning, reducing odour nuisances and respiratory problems, as well as

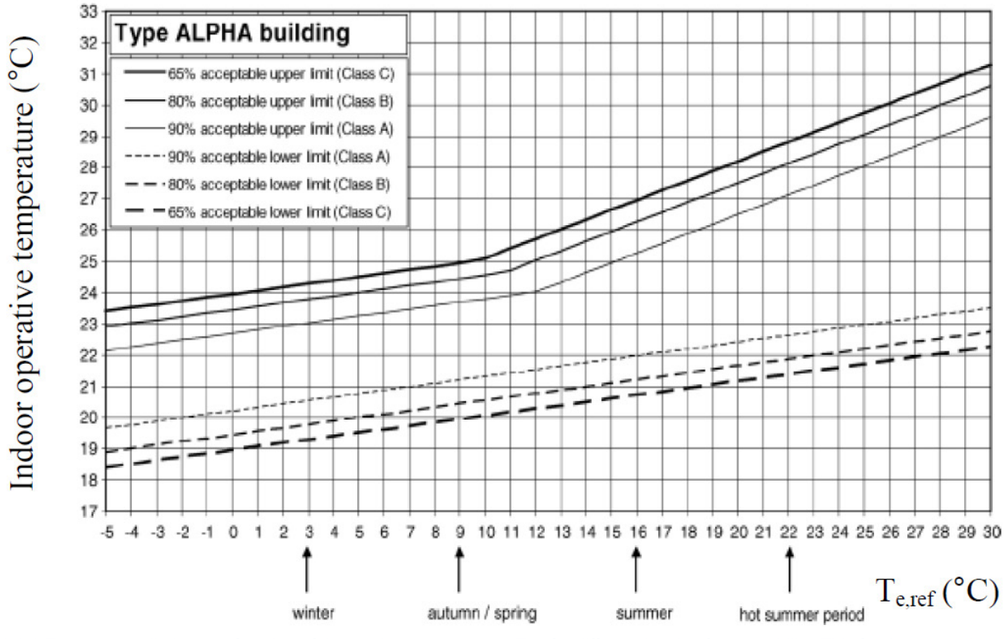


Figure 2.3.2 Temperature limits as a function of the outdoor temperature $T_{e,ref}$ for different levels of acceptability. This for the general case of persons dressed according to the season and performing office-like activities. Taken from *Thermal comfort in residential buildings: Comfort values and scales for building energy simulation* (p.35) by Peeters et al., 2009.

eliminating the risk of burn due to touch (Cauberg-Huygen Raadgevende Ingenieurs & Boerstra, 2001).

LTH also has some challenges in terms of comfort. One of the significant issues is the presence of cold drop near windows, especially with older windows. Traditionally, this cold drop is countered by placing HT radiators near the windows, but LTH lacks the power to oppose this cold drop. However, the issue can be mitigated by replacing the windows with HR++ glass, increasing the density of underfloor heating directly beneath the windows or placing additional LT-radiators near the windows (Cauberg-Huygen Raadgevende Ingenieurs & Boerstra, 2001). LTH systems also have a relatively slow warm-up time compared to the direct feedback HTH systems. This 'slow response' can be addressed by modern control systems that anticipate the moment of heat demand based occupancy patterns and on weather forecasts (Lund et al., 2014).

While HTH systems can heat spaces quickly, they are less energy efficient and less comfortable due to temperature fluctuations and drafts. LTH systems are likely to provide more comfort than HTH, due to its even heat distribution, enhanced indoor air quality and improved safety. Integrating smart control systems combined with clever placement of heat emitters can enhance the effectiveness of LTH systems, ensuring a comfortable, healthy and safe indoor environment.

2.3.4 LT-Ready

In order to determine if a building is ready to be heated with a LT-supply temperature, the LT-readiness needs to be evaluated. In this research, a building is considered LT-ready when the following conditions are reached at a supply temperature between 30-55°C:

1. $Q_{capacity_LT} \geq Q_{demand}$
2. $Q_{demand_LT} \leq Q_{demand_original}$
3. $\textbf{Thermal comfort}_{LT} \geq \textbf{Thermal comfort}_{original}$

The heating capacity with the lowered supply temperature has to meet the heating demand of the building (figure 2.3.3). The new heating demand should be at least equal but preferably lower to the original heating demand. At the lower supply temperature the thermal comfort should be improved compared to the original thermal comfort in the living room.

Østergaard & Svendsen (2018) found that roughly 80% of the existing heating systems are over-dimensioned relative to their present-day design heat load. This overcapacity finds its origin in extreme design conditions or is created through previous energy renovations. Dwellings with this overcapacity can be heated with a supply temperature below 60°C for most of the year for Danish dwellings. Pothof, Vreeken & van Meerkerk (2023) state that the supply temperature for 60% of existing Dutch dwellings can be below 55 °C. This indicates that LTH might be possible without any renovation. A LT-ready check at the beginning of the project where the heating capacity with LT supply is compared to the original heating demand without any renovation measures can provide important insight on the necessity of the renovation plans. If there is not enough overcapacity to compensate for the lowered supply temperature, renovation measures are a necessity. The following three approaches are presented to solve the discrepancy between the heating demand and the heating capacity.

Three approaches to enable LTH:

1. Reduce Q_{demand} by reducing transmission, ventilation and infiltration losses until $Q_{capacity}$ is sufficient
2. Increase $Q_{capacity}$ by increasing heating area or heat transfer coefficient until Q_{demand} is met
3. Combination of lowering Q_{demand} and increasing $Q_{capacity}$

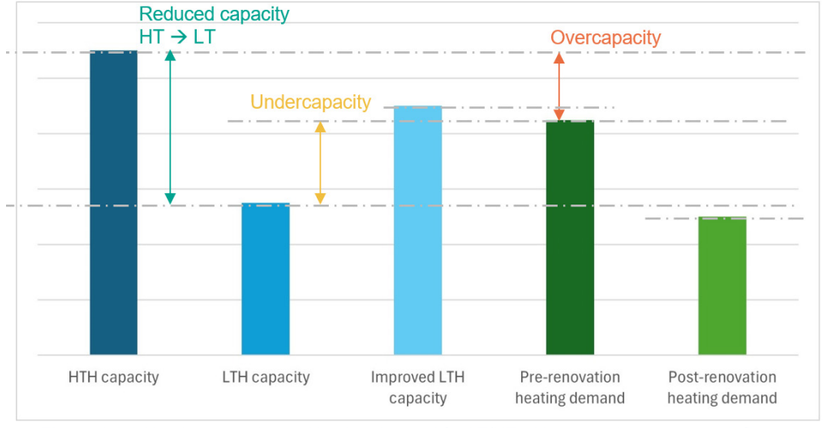


Figure 2.3.3 Heating capacity vs. Heating demand for LT/HT with renovation measures influence

EXPLORATION DECISION SUPPORT

3. DECISION SUPPORT

Decision making process

Decision-making is deeply intertwined with daily life. Some decisions are simple with low stakes, like deciding which pair of socks to put on in the morning. In contrast, other decisions require a thorough analysis due to the high stakes involved, like deciding on a university that will probably determine your future career path. Complex decisions occur when there are multiple, possibly conflicting decision objectives and solutions to the problem, accompanied by a level of uncertainty and/or risk. This requires careful consideration, especially when the outcome has a significant impact.

Energy renovation projects involve complex decision-making. These projects often involve multiple stakeholders, resulting in diverse decision objectives, which in turn generate various and sometimes conflicting decision criteria. Additionally, there are numerous renovation scenarios available, each with its own unique effect, that will meet the decision objectives in one way or another. The conflicting criteria can either originate from the different perspectives and interests of the involved stakeholders (see Chapter 5. Stakeholders), or can be conflicting by their nature. For instance, maximizing energy savings almost always lead to higher investment costs, while both maximizing energy savings and minimizing costs is the objective. Energy renovations often have high stakes, with large investment costs involved and where the estimated lifespan of the renovation stetches over decades (see Chapter 2. LTH), contributing to elements of uncertainty and risk. Given the complex nature of energy renovation projects, decision support would be beneficial, both for the overall decision-making process as well as the specific selection of a renovation scenario.

This thesis applied the following approach to gain insight into how a decision-making process for LT-renovation projects can be supported. The first step contains a literature research aimed at identifying the general phases of a decision-making process. After that, additional research is conducted to identify any phases or action points unique to the decision-making process for LT-energy renovations. This way, the first draft of the LT-decision support framework is developed. The next step is an in-depth literature review of existing decision support methods commonly used in energy renovations, comparing their ease of use, advantages and limitations. After this comparison, suggestions are made for selecting a suitable method when aiming to support the decision on the selection process of different renovation scenarios.

3.1 Phases of the Decision-Making Process

Amorocho & Hartmann (2022), Pohekar & Ramachandran (2004) and Zardari et al. (2014) all provide their own version of a general decision-making framework, containing overlap in multiple steps. Figure 3.1.1 illustrates the three versions of a general decision-making framework of the aforementioned authors. Figure 3.1.2 is this authors' interpretation of a general decision-making framework based on the reviewed literature mentioned above. The next paragraph describes the phases as illustrated in Figure 3.1.2.

1. Problem Definition

The first phase of a general decision-making process is problem identification, which contributes to recognizing the need for a decision and aims to gain insight into the scope of the problem. Both Amorocho & Hartmann (2022) and Zardari et al. (2014) acknowledged the importance of this step.

2. Establishing objectives & criteria

The second phase establishes the decision objectives and criteria, which sets clear goals regarding the preferred outcome (Amorocho & Hartmann, 2022; Pohekar & Ramachandran, 2004; Zardari et al., 2014).

3. Criteria weighting

The third phase involves criteria weighting, where the relative importance of the decision parameters (=objectives + criteria) can be incorporated (Amorocho & Hartmann, 2022).

4. Alternatives Generation

The fourth phase consists of generating multiple alternatives which could all be potential solutions to the identified problem, and will be subjected to performance comparison in a later phase (Amorocho & Hartmann, 2022; Pohekar & Ramachandran, 2004;

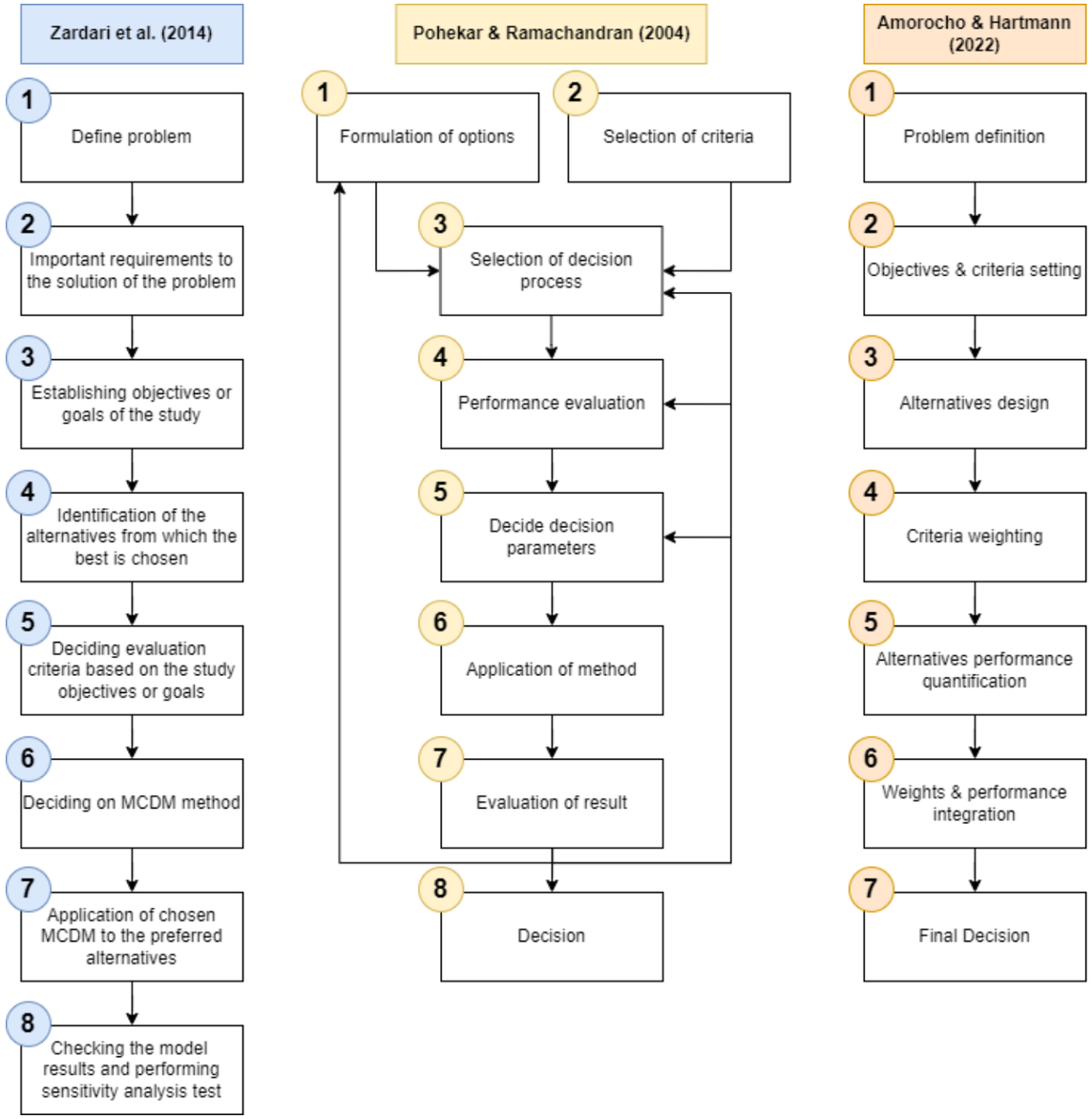


Figure 3.1.1 General decision-making frameworks of Amorocho & Hartmann (2022), Pohekar & Ramachandran (2004) and Zardari et al. (2014).

Zardari et al., 2014).

5. Performance quantification

The fifth phase encompasses quantifying performance, where the assessment methods of the decision criteria are determined, to quantify the performance of the alternatives regarding the selected decision criteria (Amorocho & Hartmann, 2022).

6. Application of MCDM method

The sixth phase consists of selecting and applying a suitable MCDM method to compare the solutions and produce a ranking of alternatives (Zardari et al., 2014). This happens through normalization and aggregation, which converts the quantified criteria values of the previous phase into comparable units and cluster them into a single composite score. This way, every alternative can be represented through a single score, which allows for a simple ranking of the alternatives. Amorocho & Hartmann (2022) describe this as 'weights & performance integration'. The ranking subsequently provides insight in to the alternatives' performance based on the predetermined decision criteria and chosen quantification method.

7. Evaluation of Result

The seventh phase is where the evaluation of the results takes place. This evaluation is two-fold: the first one consists of a sensitivity analysis to check the robustness of the obtained values and ranking (Zardari et al., 2014), whereas the second one is more of a reflection to check if the results provide the desired outcome (Pohekar & Ramachandran, 2004).

8. Final Decision

When the results are robust and desirable a final decision can be made, which is the concluding eighth phase of a general decision-making process.

Although this description of phases could be interpreted as a linear process, this is not the case. As long as the results are not desirable, there will be an iterative flow between the phases, until a desirable outcome is reached or the decisionmaker concludes on abandoning the decision. Pohekar & Ramachandran (2004) illustrate this iterative process of steps in their framework. Another possibility for non-linearity of the process occurs when new information about the problem has come to light. In that case, it is possible to return to any previous phases (Zardari et al., 2014). Figure 3.1.2 shows the iterative process of decision-making through dotted lines.

3.2 Phases of the Decision-Making Process

The next step is placing this general framework into the specific context of energy renovations, so that the unique decision-making aspects or phases occurring in those types of renovations can be identified.

Nielsen et al. (2016) reviewed 43 decision-support tools for renovation projects and identified six areas in the renovation decision-making process where those tools can support decision-makers. The identified areas are goal setting, criteria weighting, building diagnosis, design alternatives generation, performance estimation and evaluation of design alternatives.

Amorocho & Hartmann (2022) developed an MCDM framework for residential building renovations to support the decision-making process. They identified specific decision-making aspects related to energy renovations as the identification of stakeholders, building diagnosis, identification of renovation requirements through the setting of objectives and criteria (supported by a decision-tree), development of multiple renovation scenarios and quantifying the performance of the designed renovation scenarios by utilizing energy calculation software.

Wahi et al. (2023b) presented a two-step approach to identify the extent to which building renovations are required to enable LTH through district heating. The first step of the method encompasses the evaluation of the suitability of using LTH. In this step the benchmark performance of the original HT situation is calculated for the determined LT-Ready criteria, which are 'annual space heating demand' and 'occupied hours too cold'. Following that, the LT-Ready criteria are recalculated for both MT and LT situations, and compared with the benchmark performance values. The recalculated values that satisfy the benchmark performance are considered MT or LT-Ready, respectively. Those that do not satisfy the benchmark performance require renovation solutions, following with the second step of filtering of potential solutions. A suggestion for a renovation solution space is presented, where the process of developing renovation scenarios, strategies and measures is illustrated and categorized in relation to their level of intervention (basic, moderate, deep). According to the presented method, filtering the renovation alternatives takes place through quantifying them on the annual space heating demand and occupied hours too cold, and comparing them to the benchmark performance.

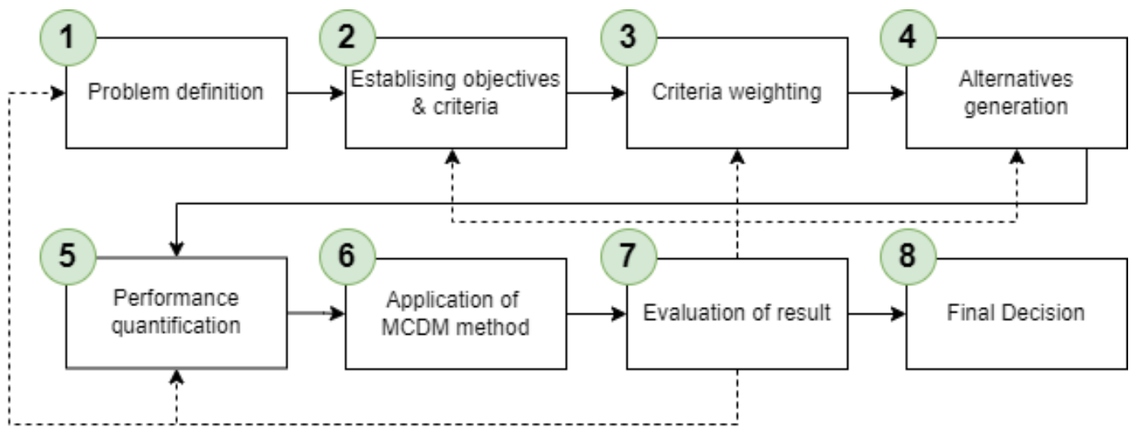


Figure 3.1.2 Framework for general decision-making process

Only the alternatives that show a reduction on both criteria compared to the benchmark are considered desirable solutions.

When reviewing the literature of Amorocho & Hartmann (2022), Nielsen et al. (2016) and Wahi et al. (2023b) and comparing it to the presented general decision-making framework as presented in figure 3.1.2, the following decision-making aspects specific to LTH renovations are identified.

Aspects like stakeholder identification and project characterization are relevant elements in the problem definition phase. This includes actions like building diagnosis, exploration of project limitations and local regulations (Amorocho & Hartmann, 2022). Chapter 5.1 'Stakeholders: role & influence' identifies stakeholders in energy renovations. Wahi et al. (2023b) display the importance of benchmarking the original energy performance, which could be considered a part of building diagnosis, and evaluate the necessity of renovation by recalculating the MT/LT performance. This provides essential insight into the required renovation intervention, if any.

Representing stakeholders' interest is an important aspect in energy renovations and takes place through establishing objectives and criteria (Amorocho & Hartmann, 2022; Nielsen et al., 2016). These interests are made explicit through a set of criteria, which are highly likely to be based on the concept of sustainability, covering economic, environmental and social aspects. It is standard to represent the set of objectives and criteria in a so-called 'decision-tree' (Nielsen et al., 2016). Wahi et al. (2023b) define energy efficiency and thermal comfort as LT-Ready criteria. When developing a decision-support framework specific to LT-renovations, those two criteria should always be included in the comparison, and the quantified performance values of the alternatives may not exceed the benchmark performance values. Chapter 4. Decision Parameters will elaborate on objectives and criteria within energy renovation projects.

Within energy renovations, it is expected to have an imbalance of importance for certain decision parameters, impacting how a final decision is made (Nielsen et al., 2016). Criteria weighting can capture the relative importance of decision parameters. Existing criteria weighting methods like pairwise comparison are often used to analytically obtain criteria weights (Amorocho & Hartmann 2022; Nielsen et al., 2016). Chapter 5.2 Balancing Stakeholders' Interests elaborates on this criteria weighting method.

Designing multiple renovation scenarios as a solution to the identified objective is one of the most common aspects of energy renovations. This phase is often supported through software tools and relies on expert knowledge (Nielsen et al., 2016). Due to the almost endless possibilities of renovation measures, determining the required renovation level can help pre-select the more suitable renovation scenarios (Wahi et al, 2023b). Generated alternatives should always be checked to see if their expected performance complies with the set objectives and existing building limitations. Non-satisfactory alternatives should be eliminated from the process.

The quantification of alternative performance for energy renovations can be done through estimations, calculations and assumptions with the support of spreadsheets, software tools and existing methods to perform calculations like LCA, LCC building energy and costs analysis (Amorocho & Hartmann, 2022; Nielsen et al., 2016). The implemented method and level of expertise involved influence the accuracy of the quantification. For quantification of soft criteria, descriptive scales can be used. Chapter 4.3 elaborates on the approach of performance quantification.

Applying an MCDM method provides a ranking of the renovation alternatives. Some MCDM methods are better suited to the context of energy renovations than others. Chapter 3.3 elaborates on which methods can best support the selection of the generated renovation alternatives.

Discussing the results as a part of decision analysis between stakeholders is a relevant aspect of the evaluation phase, as it can potentially lead to adjustments in the decision parameters and/or on the renovation scenarios (Amorocho & Hartmann, 2022; Nielsen et al. 2016). The final ranking leads to an overview of more and less desirable renovation alternatives, supporting the stakeholders to make a better informed decision when selecting a renovation scenario (Amorocho & Hartmann, 2022).

Based on the reviewed literature on general decision-making processes and specific aspects of said process in LTH/energy renovations, a first draft of the decision support framework for LT-renovations is developed. Chapter 6.1 illustrates and elaborates on this framework development.

3.3 Multi-Criteria Decision-Making (MCDM)

Multi-criteria decision-making (MCDM) is an analytical way of comparing multiple alternatives by evaluating multiple criteria when making a complex decision (Pohekar & Ramachandran, 2004). The main objective of MCDM is to support decision-makers in selecting the alternative that best represents their preferences within given constraints (Zardari et al., 2014). MCDM methods encompass multi-objective optimization, enhancing the quality of a decision by improving clarity, efficiency and applying logic to the problem. It also creates the opportunity for negotiation, quantification and communication (Pohekar & Ramachandran, 2004), contributing to a better informed decision. However, MCDM methods are also criticized for their susceptibility to manipulation and potential for inaccuracies: critics of MCDM argue that different methods lead to different final outcomes, making the outcome unreliable (Mutikanga et al., 2013). Besides that, in compensatory methods, important information could get lost or present difficulties in eliciting subjective information (Zardari et al., 2014). As long as the users of the methods are aware that MCDM provides a simplification of the decision problem and that the outcome of the method is not the absolute truth but an approach to get clarity on their problem and preferences and how it relates to the included solutions.

An MCDM problem can be represented through a decision matrix (*D*). The amount of alternatives (*m*) and the number of performance criteria (*n*) can be described by a matrix with *m*×*n* elements. Each element (X_{ij}) is a single numerical value that represents the performance of an alternative (A_i) when it is assessed for a criterion (C_j), as expressed in formula 3.1.

Many different terms for MCDM are mentioned in literature and sometimes used interchangeably. The most common terms are Multi-Criteria Decision Analysis (MCDA), Multi-Attribute Decision Making (MADM), Multi-Objective Decision Making (MODM) and Multi-Objective Decision Analysis (MODA).

A clear distinction can be made between MODM and MADM. In MODM, the decision-making process involves optimizing a set of objective functions while considering a set of constraints to find the most satisfactory and efficient solution (Pokehar & Ramachandran, 2004). It is about finding the best solution by balancing different objectives, even if improving one objective means degrading the performance of another. MODM is used for decision problems where the decision space is continuous (Kamari et al., 2018), meaning that the decision variables can take on any value within a range.

On the other hand, in MADM, several alternatives are evaluated against a set of criteria. These criteria are often difficult to quantify. The best alternative is selected by comparing the alternatives based on each criterion (Pohekar & Ramachandran, 2004). MADM is used for decision problems where the decision space is discrete (Kamari et al., 2018), meaning that specific alternatives are presented, and the decision is made among those alternatives.

Thus, MODM is used to optimize objectives within given constraints, while MADM is used to evaluate alternatives based on specific criteria. For this thesis, MADM methods are fit to support the decision-making process of selecting LT-renovation scenarios since this requires the evaluation of multiple alternatives against a set of (conflicting) criteria.

Within these two main groups of methods, unique characteristics can be found in each method. They are typically classified as deterministic, stochastic or fuzzy (Pohekar & Ramachandran, 2004). The core of MCDM is deterministic: algorithms and models are used to analyze the decision problem and generate (near-)optimal solutions. The input is precise, and the method assumes that the relationship between criteria and alternatives can be accurately quantified. Modifying existing MCDM to stochastic or fuzzy methods can help capture the decision-makers' uncertainty, imprecision and subjectivity. Stochastic methods are more usable for quantifiable uncertainties like randomness, whereas fuzzy methods are more useful for qualitative uncertainties like handling subjective linguistic information.

$$D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccc} C_1 & \dots & C_n \end{array} \\ \begin{bmatrix} X_{1,1} & \cdots & X_{1,n} \\ \vdots & \ddots & \vdots \\ X_{m,1} & \cdots & X_{m,n} \end{bmatrix} \end{array} \qquad (i = 1, 2, 3, \dots, m \text{ and } j = 1, 2, 3, \dots, n) \tag{3.1}$$

3.4 MCDM in Energy Renovations

MCDM is widely used for decision support in fields like energy planning and energy renovations. Siksnelyte-Butkiene et al. (2021) reviewed 12 common MCDM methods that can aid the challenge of selecting the best-fitting thermal insulation material, Ozorhon, Batmaz & Caglayan (2018) explored how MCDM can support decision-making for renewable energy investments, while Afsordegan et al. (2016) applied MCDM to support the selection process of a sustainable energy alternative. Based on the reviewed literature of Amorocho & Hartmann (2022), Kamari et al. (2018) and Passoni et al. (2021), using MCDM is also a good approach to support the selection process of a renovation scenario.

There are many different MCDM methods, with their advantages and limitations. The most popular methods applied in energy renovation and energy planning are identified through reviewing papers on MCDM applied to those fields.

Siksnelyte-Butkiene et al. (2021) systematically reviewed 18 papers on the application of MCDM methods to support the selection of building insulation materials. They found that 33% of the papers used the MCDM method Analytical Hierarchy Process (AHP), and 28% used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

Pohekar & Ramachandran (2004) and Kumar et al. (2017) both reviewed an almost identical set of 8 MCDM methods common in (sustainable) energy planning. Kumar et al. (2017) came to the same conclusion as Pohekar & Ramachandran (2004), which is that AHP is still the most popular MCDM method in energy planning, followed by PROMETHEE and ELECTRE.

AHP was developed by Saaty in the 1970s and is considered a value measurement model (Kumar et al., 2017). The approach of this method is based on the hierarchical structuring of the complex problem by dividing it into top-to-bottom levels of objectives, criteria and sub-criteria, with the alternatives at the bottom level (Pohekar & Ramachandran, 2004). AHP simplifies the multi-criteria problem through pairwise comparisons, which obtains criteria weights for ranking the alternatives. According to Kumar et al. (2017), AHP is considered one of the simplest calculation techniques among the different MCDM methods, where results can be quickly acquired. The method is also deemed easy to adapt. However, this method relies heavily on the decision-makers' experience for obtaining the criteria weights, which may complicate the evaluation process when there are multiple decision-makers. AHP also requires an additional sensitivity analysis to validate the results (Siksnelyte-Butkeine et al., 2021). Besides that, an interdependency between the objectives and the alternatives can lead to inaccurate results (Kumar et al., 2017).

The TOPSIS method was developed by Hwang and Yoon in 1981 and is considered a goal programming model (Kumar et al., 2017). The approach of the method is based on identifying the closest Euclidean distance to the theoretical positive ideal solution (PIS) and the furthest distance to the theoretical negative ideal solution (NIS) in a multi-dimensional space. The positive ideal solution is the theoretical optimum, representing the highest performance value over all criteria. The negative ideal solution is the inverse of the positive ideal, thus representing the lowest performance value over all criteria. The alternatives are ranked based on their relative closeness to the positive ideal solution, where the first-ranked alternative has the shortest distance (Pohekar & Ramachandran, 2004). The TOPSIS method is considered logical and easy to understand, with relatively simple calculations that quickly obtain results. The results are easy to interpret for the method users (Siksnelyte-Butkiene et al., 2021). Amorocho & Hartmann (2022) mention that TOPSIS can maintain a consistent number of method steps irrespective of the quantity of alternatives, which is considered an asset in solving renovation projects. However, it is essential to note that TOPSIS requires an understanding of the ideal and negative ideal solutions. For example, an ideal solution for the criteria of 'total investment cost' is likely to have the lowest possible value, whereas 'net present value' ideal solutions would be the ones with the highest possible value. Also, a significant deviation from the ideal solution within a criterion can significantly impact the final ranking. When the performance values within a single criterion differ significantly, the method becomes less reliable (Siksnelyte-Butkiene et al., 2021).

PROMETHEE was developed by Brans & Vincke in 1985 and is considered an outranking model since it ranks alternatives based on preference functions (Kumar et al., 2017). The PROMETHEE method has evolved over time into a group of methods and is widely acknowledged as one of the most accurate MCDM methods (Siksnelyte-Butkiene et al., 2021). The method involves pairwise comparison and calculates the preference degrees for each alternative relative to others, considering both positive and negative aspects of each criterion (Pohekar & Ramachandran, 2004). The method allows for incorporating both quantitative and qualitative information and uncertain and fuzzy information. Besides that, the method also allows for group-level decisions (Kumar et al., 2017). PROMETHEE is a non-compensatory method that is robust to outliers, unlike the TOPSIS method (Siksnelyte-Butkiene et al., 2021). Although the PROMETHEE group is considered a very accurate MCDM technique, it is also considered the most complex in terms of calculations. And contributes to a more lengthy process of obtaining results. Due to the complexity of the method, it is often only used by professionals with a deep understanding of the mathematics of the method (Siksnelyte-Butkiene et al., 2021). In contrast to the TOPSIS and AHP methods, the PROMETHEE lacks a clear objective structuring (Kumar et al., 2017).

ELECTRE was developed by Benayoun et al. in 1966 and is considered an outranking model similar to PROMETHEE discussed above. The main difference is that the ELECTRE method ranks the alternatives based on predefined thresholds instead of preference functions (Kumar et al., 2017). The method involves complex calculations and requires decision-makers' input to set threshold values (Siksnelyte-Butkiene et al., 2021). In essence, the method ranks alternatives based on how well they meet certain qualitative and quantitative criteria. The aim is to find alternatives that perform well across most criteria without causing unacceptable discontent. By identifying concordance and discordance indices, graphs can be developed to illustrate the strong and weak relationships, supporting the ranking of alternatives. However, ELECTRE might not always pick the best solution, but it highlights the top alternatives. This method simplifies decision-making by narrowing down the options, which is especially useful when considering many alternatives (Pohekar & Ramachandran, 2004). Siksnelyte-Butkiene et al. (2021) recognize that an additional sensitivity analysis is required to validate the obtained results when using the ELECTRE method.

An overview of these four most popular MCDM methods with a short description, steps, advantages, limitations and ease of use can be found in Table 3.4.1.

Determining which MCDM method would be the most suitable to support the selection process of a LT-renovation scenario can be considered a multi-criteria decision problem in itself. Kumar et al. (2017) state that it is impossible to determine the 'best or worst' method, and that this highly depends on the application of the method and the objective.

From the literature, it can be concluded that all presented MCDM methods can potentially support the decision-making process of selecting a renovation scenario. It is up to the user of the method to determine which one would be preferred. What could potentially influence the preference is the ease of use of the method and the characteristics of the problem. This includes the amount of criteria and alternatives that require consideration, the level of uncertainty, the type of data and the availability of recourses. However, based on the assumption that multiple stakeholders will be involved in the decision-making process and that they are no experts in the field of MCDM, the most obvious choice would be the TOPSIS method. Therefore, this thesis adopts the TOPSIS method to support the decision-making process of selecting an LT-renovation concept.

MCDM Method	Description	Steps of method as described by Kumar et al. (2017)	Advantages	Limitations	Ease of Use
AHP	Developed by Saaty in the 1970's. AHP is considered a value measurement model, and ranks alternatives by determining criteria weights.	1. Defining objective into a hierarchical model. 2. Determining weights for each criteria. 3. Calculating score of each alternative considering criteria. 4. Calculating overall score of each alternative.	• Easy to calculate • Easy to adapt • Each criterion is compared to every other criterion based on a hierarchial structure, leading to a focussed and transparent process	• Additional sensitivity analysis is required validate results • Requires subjective assumptions of decisionmaker to assign weights (pairwise comparison) • Method is less suitable when multiple decisionmakers are involved • Hierarchy structure can lead to inaccurate results if there is an interdependency between objectives and alternatives	Relatively easy, obtaining results is a relatively quick process
TOPSIS	Developed by Hwang et Yoon (1981). TOPSIS is considered a goal programming model, and ranks alternatives based on their distance to the ideal and negative ideal solutions.	1. Calculation of matrices 2. Normalised and decision 3. Calculation of positive and negative ideal solutions 4. Calculation of separation and relative closeness.	• Easy to calculate • Results are easy to interpret • Comprehensible logic of calculations • Positive ideal and negative ideal leads to fundamental and transparent ranking process • Can handle large set of alternatives	• Requires understandig of what the 'positive ideal' and 'negative ideal' is • Significant deviations of performance values in a single criterion can lead to out of proportion ranking results	Relatively easy, obtaining results is a relatively quick process
ELECTRE	Developed by Benayoun et al. (1966). ELECTRE is considered an outranking model, and ranks alternatives based on predefined thresholds.	1. Based on three pillars: a. Determination of threshold function. b. Concordance index and Discordance index. c. Outranking degree. 2. Assigning rank based on above calculation	• Allows for quantitative and qualitative criteria • Non-compensatory • Can narrows down large set of alternatives	• Requires deep understandig of the decision problem due to complexity of method • Additional sensitivity analysis is required validate results • Requires subjective assumptions of decisionmaker to assign weights (pairwise comparison) • Might not provide a clear ranking	Relatively complex, obtaining results is a lengthy process
PROMETHEE	Developed by Brans et Vincke (1985). PROMETHEE is an outranking model, and ranks alternatives based on preference functions.	1. Finding evaluation matrix and comparing them pairwise considering every single criteria 2. Assignment of preference function with values from 0 to 1 depending on the difference between pairs 3. Calculation of global matric and determining the rank by adding the column which express the supremacy of one alternative over the other	• Non-compensatory • Robust to outliers • Allows for group level decisions • Allows for quantitative and qualitative criteria • Incorporates uncertain and fuzzy information	• Complex calcualtions that require experts • Lacks structuring of the objective • Requires subjective assumptions of decisionmaker to assign weights (pairwise comparison)	Very complex, obtaining results is a lengthy process

Table 3.4.1 Review of MCDM methods in Energy Renovations

3.5 TOPSIS CALCULATION METHOD

For the decision-maker(s) to obtain a ranking of alternatives based on the selected decision criteria, a decision analysis needs to be performed. After constructing the decision matrix as presented in formula 3.1, the following steps should be completed to acquire a ranking according to the TOPSIS method (Triantaphyllou, 2000):

1. Construct the normalized decision matrix (*R*). This step converts varying criteria units into dimensionless criteria. Each element (R_{ij}) can be calculated through equation 3.2

$$R_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} X_{ij}^2}} \tag{3.2}$$

2. Construct the weighted normalized decision matrix (*V*) by calculating the weighted normalized vectors (V_{ij}). The equations for calculating the criteria weights (W_j=w_k) can be found in chapter 5.2, equation 5.2, and are obtained through pairwise comparison.

$$V = \begin{bmatrix} V_{1,1} & \cdots & V_{1,n} \\ \vdots & \ddots & \vdots \\ V_{m,1} & \cdots & V_{m,n} \end{bmatrix} = \begin{bmatrix} W_1 R_{1,1} & \cdots & W_n R_{1,n} \\ \vdots & \ddots & \vdots \\ W_1 R_{m,1} & \cdots & W_n R_{m,n} \end{bmatrix} \tag{3.3}$$

$$(i = 1, 2, 3, \dots, m \text{ and } j = 1, 2, 3, \dots, n)$$

$$V_{ij} = W_j \cdot R_{ij} \tag{3.4}$$

3. Derive the Positive Ideal and Negative Ideal Solutions through equations 3.5 and 3.6. The theoretical Positive Ideal Solution (A^+) value represents the best performance over all criteria, the theoretical Negative Ideal Solution (A^-) value represents the worst performance over all criteria. A correct analysis must determine whether each decision criterion's highest or lowest value is considered positive or negative.

$$A^+ = \{V_1^+, V_2^+, \dots, V_n^+\} \tag{3.5}$$

$$A^- = \{V_1^-, V_2^-, \dots, V_n^-\} \tag{3.6}$$

4. Determine the distances (S_i^+ and S_i^-) of each alternative from the PIS (A^+) and NIS (A^-) by equation 3.7 and 3.8:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^+)^2} \qquad (i = 1, 2, 3, \dots, m) \tag{3.7}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_j^-)^2} \qquad (i = 1, 2, 3, \dots, m) \tag{3.8}$$

5. Calculate the relative closeness index (C_i^+) to the PIS (A^+)

$$C_i^+ = \frac{S_i^-}{(S_i^+ + S_i^-)} \tag{3.9}$$

6. Rank the alternatives where the highest relative closeness index (C_i^+) represents the best-performing alternative, and the lowest represents the worst-performing alternative. The highest (C_i^+) value has the shortest distance to the PIS

After following these steps, the decision-maker(s) will have a clear overview of the performance of alternatives evaluated against their selected decision criteria, gaining insight into the suitability of the presented scenarios. The final ranking could lead to a focused discussion where trade-offs are made explicit, and objectives become more precise, essentially supporting the decision-maker(s) in their decision-making process for selecting an alternative.

4. DECISION PARAMETERS

Decision Parameters in Energy Renovations

Energy renovations are pivotal in the transition towards a more sustainable built environment. These renovations aim to improve the energy efficiency, reduce the environmental impact while promoting the use of renewable resources. This leads to buildings that have a lower energy consumption and produce fewer greenhouse gas emissions without compensating on comfort. However, the decision-making process for selecting suitable energy renovation concepts is complex, particularly for integrating LTH systems.

The previous chapter shows that establishing decision objectives and criteria is an important part of the decision making process. Decision criteria can enable evaluation of the renovation alternatives through quantification of performance. Adding structure and hierarchy to the decision parameters helps to make the decision making process more explicit. The aim of this chapter is to identify the key decision parameters occurring in energy renovation projects. This is done through a literature study, a meta-review on 5 papers that have reviewed common decision parameters in the field of sustainable energy and energy renovations. The decision criteria that are deemed most influential are determined out of that set, and summarized into a criteria decision tree. The second part of the chapter presents an approach on how to analytically assess the selected set of decision criteria.

4.1 Decision objectives & Criteria

Before diving into the decision objectives and criteria, it is important to clarify the terminology, since there is no clear consensus in literature on what a decision objective and what a decision criterion encompasses. Terminology like category, cluster, objective, criteria, factor, indicator, sub-indicator as well as key performance indicator (KPI) are interchanged, causing noise for the structuring of decision parameters.

In this research, at the top of the hierarchy there are the sustainability pillars, also known as sustainability categories, which includes environmental, economic and social. This is the first step towards determining the scope of the decision-making process. Amorocho & Hartmann (2022) and Jafari & Valentin (2018) adopt the exact same hierarchy while Afsordegan et al. (2016) expands the categorization with a technical pillar (but calls it ‘criteria’, followed by ‘indicators’). Kamari, Corrao & Kirkegaard (2017) adopt a different categorization, and uses functionality, accountability and feasibility at the top of the hierarchy. Wahi et al. (2023a) adopts the same categorization as Kamari, Corrao & Kirkegaard (2017), with the exception of the accountability category. The sustainability pillars allow for the categorization of the decision objectives, placed at the second level, which represents the aim/goal of the renovation. The third level contains the decision criteria, which is the indicator on how to reach the renovation objective. Every sustainability pillar leads to one or more objectives, and an objective leads to one or more decision criteria. Although the terminology differs per author, most strive for a holistic decision approach. Incorporating decision parameters from every sustainability pillar ensures a holistic decision-making approach, leading to a better informed decision.

The papers from the above mentioned authors are reviewed to identify the most common decision objectives and criteria in energy renovations. Decision objectives and criteria represent the aspect of interest for the decision, which are determined by decision-maker(s). Table 4.1.1 provides an overview on the decision parameters, categorized by the presented structure of category-objective-criteria.

Environmental

Objectives	Criteria	Author
Energy Efficiency & Savings	Renewable energy	2
	Energy savings	2
	Operational primary energy demand	2
	Total energy demand	2
	Final energy consumption	5
	Total primary energy consumption	5
	Energy efficiency	1, 4
	Exergy	1
	Energy payback time	1
	Prebound effect	5
Environmental impact	(embodied) global warming potential	2
	CO2 emissions	1, 3, 5
	NOx emissions	1
	CO emissions	1
	Suspended particulate matter emission	1
	Environmental impact	3, 5
	Pollution	4
	Fossil fuel conservation	3
	Embodied energy and GHG emissions	5
	Land use	1
	Environmental risk	1
Resource efficiency	Material & waste	4
	Total water consumption	2
	Water efficiency	4
	Break-even years	5
Quality & reliability	Technical reliability	1
	Technical risk	1
	Capacity	1
	Quality of services	4, 5
	Noise	1
	Supply/return temperatures	5

Economic

Objectives	Criteria	Author
Financial feasibility	Investment cost	1, 2, 3, 4, 5
	Availability of funds	1
	Financial structures	4
	Financial incentives	2
Cost efficiency	Life cycle cost (LCC)	2, 3
	Operational & Maintenance cost	1, 2, 3, 4
	Net present value (NPV)	1, 5
	Internal rate of return (IRR)	1
	Payback period	1, 2
Social-economic impact	Energy consumption cost	3
	Fuel poverty	2
	Rent increment	2
	Property tax	3
	Property value increment	2, 3

Social

Objectives	Criteria	Author
Indoor comfort	Visual comfort	2, 3, 4
	Acoustic comfort	2, 3, 4
	Indoor air quality	2, 4, 5
	Thermal comfort	2, 3, 4, 5
Health and Safety	Health risk	1, 3
	Fatal accidents	1
	Security	3, 4
	Social reputation	2
Social & Community impact	Social acceptability	1, 3
	Job creation	1
	Community impact	3
	Building impact	3
	Pride and satisfaction	3
Renovation effectiveness & feasibility	Productivity	3
	Sociality	4
	Accessibility	2
	Aesthetic	2, 4
	Identity	4
	Integrity	4
	Spatial	4
	Durability	2
	Renovation time	2
	Covered scope	2
	Innovation	4
	Flexibility & Management	4
	Stakeholder engagement & education	4

Topic of papers	Authors	Reference number
Decision making in sustainable energy alternatives	Afsordegan et al. (2016)	1
MCDM framework for building renovation	Amorocho & Hartmann (2022)	2
Decision making in building energy retrofits	Jafari & Valentin (2017)	3
Decision making in building renovation	Kamari, Corrao & Kirkegaard (2017)	4
Decision making parameters review for LTH renovations	Wahi et al. (2023)	5

Table 4.1.1 Common Decision Parameters in Energy Renovations

As shown in table 4.1.1 some decision criteria, like investment cost and thermal comfort, are mentioned by (almost) every author. This indicates that this decision criteria is very relevant to the decision-making process in energy renovations. Some criteria are worded differently, but quite comparable in what they represent.

Providing a tool which helps set decision criteria and objectives to stakeholders can support them in their decision-making process. A common approach to this is the decision-tree (Amorocho & Hartmann, 2022). Therefore a decision-tree is developed for this research, which is illustrated in figure 4.1.1. Comparable objectives and criteria are combined into a clear and concise list of decision parameters. Objectives and criteria that were deemed less relevant in the context of LTH-renovations are not represented in the decision-tree. However, the decision-tree is merely a suggestion to support the decision making process. Decision-makers are free to adapt the decision-tree to their interests and needs. Nevertheless, to ensure that the decision-making process related to the enablement of low-temperature heating, there are two non-negotiable criteria. These are heating demand and thermal comfort, since those are the criteria on which the LT-Ready definition from Chapter 2.3 is based. Chapter 4.2 elaborates on what the decision criteria entails.

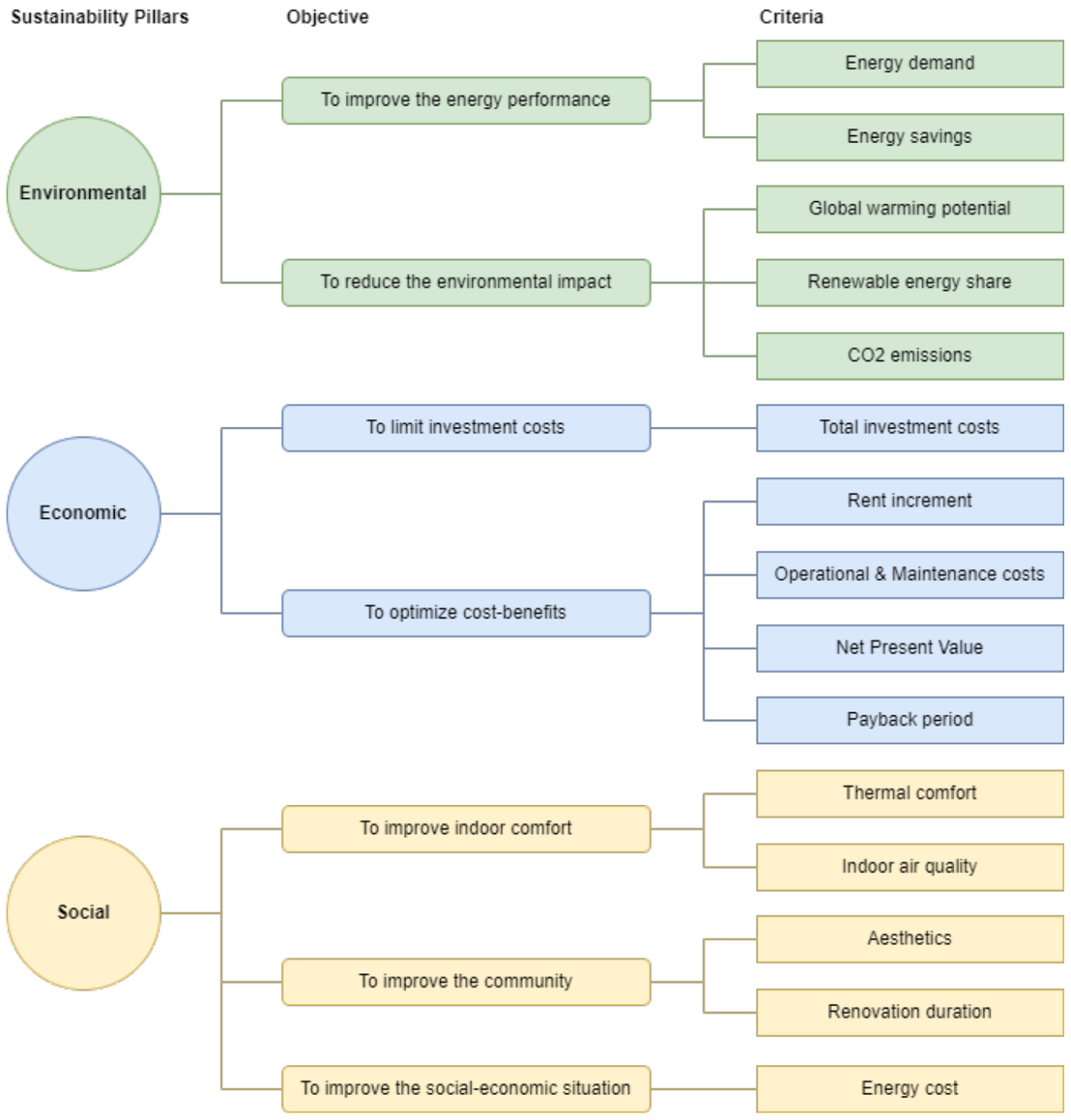


Figure 4.1.1 Decision-tree for LTH energy renovations

4.2 Decision criteria in LTH energy renovations

4.2.1 Environmental Decision Criteria

Energy demand

Energy demand relates to the total amount of energy required to operate the building. This includes thing like space heating & cooling, lighting and appliances. However, in this research energy demand relates specifically to the heating demand as defined according to chapter 2.3, so that LT-readiness can be evaluated.

Energy savings

Energy savings encompass the reduction in energy consumption achieved through the energy renovation measures of the renovation scenario, evaluating the effectiveness of the scenario. This can be expressed through gas or electricity savings.

Global warming potential (GWP)

GWP assess the impact of the renovation measures on climate change. It measures the CO2 emission from both making and using building materials and systems, incorporating emissions from the start of production until installation. This criteria evaluates the environmental impact of the production and installation of the renovation measures.

Renewable energy share

The renewable energy share indicates the part of the energy consumption that is provided by renewable energy sources, like solar panels and heat pumps. This criterion also evaluates on the environmental impact of the renovation alternative.

CO2 emissions

The CO2 emissions represent the amount of carbon dioxide reduction caused by the renovation measures reducing the energy demand.

4.2.2 Economic Decision Criteria

Total investment cost

This covers the estimated initial investment costs of a renovation scenario. This includes project costs related to labour, building material, equipment, engineering and taxes.

Rent increment

Most multi-family buildings are occupied by tenants, therefore it is relevant to include the criterion of rent increment. This evaluates the potential increase in rent due to improved energy performance and comfort. It can be used as a strategy to cover the costs of the renovation measures and levels the (potential) property value increment.

Operational & maintenance cost

This includes all costs related to the daily functioning and upkeep of the selected renovation measures for a scenario. The scenario with an implementation of a heat pump with a balanced ventilation system will have higher O&M costs than the scenario that only includes insulation measures.

Net Present Value

The NPV calculates the difference between the cash inflows and cash outflows over the renovation project's lifespan. The cash inflows represent the energy saving costs, the cash outflow represent the investment costs. The lifespan is dependent on the type of renovation measures included. The NPV can help evaluate the financial viability of a renovation scenario. A positive NPV means that the scenario is economically viable, the higher the better.

Payback Period

The simple payback period is the amount of time it takes for the investment costs of the renovation scenario to be recovered through its energy savings. This criterion assess the risk of the investment: a short payback period is more desirable and a long payback period.

4.2.3 Social Decision Criteria

Thermal comfort

Thermal comfort expresses the occupants satisfaction with the indoor thermal environment. In this research thermal comfort is quantified as thermal discomfort: the amount of hours that the dwelling is underheated (compared to setpoint temperature) in the living room. This is a non-negotiable criterion that, together with the heating demand criterion, evaluates LT-readiness. Other ways to quantify the thermal comfort is through the predicted mean vote or the floor surface temperature.

Indoor air quality

The indoor air quality expresses the cleanliness of the air, ensuring a healthy living environment. This can be quantified through aspects like CO2 concentrations and relative humidity.

Aesthetics

The criterion aesthetics relates to a subjective perception of the building, expressing how pleasing its appearance will be after renovation. For example, when the original façade has discoloured panelling with graffiti on it, and the renovation measure of exterior wall insulation leads to a renewed façade finish of neat bricks, it is likely that the perception of the aesthetics of the building is improved. Renovation measures like placing new radiators do not affect the aesthetics of the building. If the building has an

architectural value, renovation measures that impact this value negatively should be assigned a low score. Aesthetics is a qualitative criterion that can be quantified through developing a descriptive scale representing numerical ranking values.

Renovation duration
This is the (estimated) renovation time of the implementation phase for the renovation scenario.

Energy cost
This criterion expresses the reduction in energy cost, like a utility bill, due to the energy savings caused by the renovation measurements of a scenario. It evaluates social-economic benefits.

All these decision criteria can be quantified in multiple ways. The approach on how to quantify the criteria depends on the decision-makers' aim and interests. Criteria can be both quantitative and qualitative, but all criteria should be expressed in a quantitative way to provide the required input for decision support tool. The next sub-chapter elaborates on how to approach this quantification.

4.3 Approach to quantify decision criteria

Each criterion has to be quantified into a numerical value as input for the TOPSIS method. Some criteria can be assessed in multiple ways, but one method needs to be selected per criterion. For example, thermal comfort can be expressed through the amount of hours a space is underheated or overheated given the heating capacity and demand, but thermal comfort could also be expressed through the amount of hours the floor surface temperature is within a comfortable range. How a criterion is assessed, depends on what the decisionmakers wants to evaluate and what resources are available for the quantification. For example, when the decisionmaker has access to energy simulation software that can calculate the share of renewable energy expressed in a percentage of the total energy use, it is wise to use that instead of trying to express the amount of renewable energy in kWh/m^2. The following approach can be used to determine the quantification of performance per criterion:

1. Determine how to assess the criterion
2. Determine the data requirements to complete the assessment
3. Determine method of calculation for the assessment
4. Determine when the performance value of the criterion complies with the renovation goals by benchmarking the criterion

A clear definition of the criterion often helps to determine how to assess it. The data requirements are dependent on what needs to be assessed, but the availability of data could also influence the assessment of criterion. The method of calculation is often based on existing methods or software in case of quantitative criteria. In case of qualitative criteria, a descriptive scale linked to a numerical value can be developed to assess the criterion in a quantitative manner. However, when there are many qualitative criteria, the decision analysis could benefit from a fuzzy model, but for this thesis that is out of scope. Quantifying criteria with varying levels of accuracy on the performance values can impact the reliability of the ranking. It is important to benchmark each criterion, so that renovation alternatives that underperform on a criterion can be eliminated from the comparison. The next paragraph illustrates an example of the quantification of the criterion 'initial investment cost'.

Assessment
The criterion is evaluated by determining all cost aspects of the renovation scenario. This includes material, labour and equipment cost per renovation measure. The Netherlands Enterprise Agency/ RVO (n.d.) provides an up-to-date cost overview of common renovation measures which includes material, labour and equipment. It is common in the Netherlands to have subsidies available for energy renovation, either locally (municipality) or regional (province or government).

Data requirements
An overview of the renovation measures per scenario is necessary, along with the numbers on the total dwelling units and surface areas of different building elements. The cost per measure can be predicted based on the Kostenkentallen database from the Netherlands Enterprise Agency. An example is provided in table 4.2.1. If available, the amount of subsidies per renovation scenario also needs to be inquired.

Method of Calculation
Sum up all the costs of renovation measures per renovation scenario, and subtract any available subsidies. Table 4.2.2 shows an example of the initial investment costs (no subsidies available).

Benchmark
It is common to have a limit in terms of investment budget. For example, a social housing company has a renovation budget of €300.000,-. This is the benchmark. If the social housing association has no flexibility in its budget, scenario 2 should be eliminated from the comparison since it clearly exceeds the benchmark.

The investment cost of the scenarios are the performance values which can be used in the TOPSIS. The performance quantification of some other criterion, like heating demand, payback period and NPV can be found in Chapter 2.2 and 2.3 of this thesis.

Data requirements	RVO Kostenkentallen		
Cavity Insulation	WB009b EPS pearls	22,76	€/m^2
Exterior wall insulation	WB369 Wood fiber + plaster finish	299,56	€/m^2
Window replacement	WB401 HR++ wooden frame	748,68	€/m^2
Heat pump placement	WB107 collective HP air-water	16.897,93	€/dwelling
Heat pump placement	WB181 collective HP ground closed	28.600,77	€/dwelling
Balanced ventilation	WB156 balanced ventilation with WTW	5.133,82	€/dwelling
Amount of dwellings		10	units
Surface area wall		189	m^2
Surface area window		50	m^2

Table 4.2.1 Data requirements to calculate initial investment costs

	Renovation measures	**Investment Costs**	
Scenario 1	Cavity + window + HP air-water	€	210.714,94
Scenario 2	Exterior wall + window + HP ground	€	380.058,54
Scenario 3	Cavity + window + balanced vent + HP air-water	€	262.053,14

Table 4.2.2 Initial investment costs per renovation scenario

5. STAKEHOLDERS

Stakeholders in Residential Energy Renovations

To comprehend how the decision-making process of residential energy renovations can be supported, it is essential to determine the parties involved and their specific role. Section 5.1 elaborated on the determination of how and to what extent different stakeholders influence the final decision, which is significant in gaining insight into the relative importance of their interests. Furthermore, section 5.2 elaborates on how criteria weighting methods can balance stakeholders' interests with varying influence on the decision-making process.

5.1 Stakeholders: role & Influence

Energy renovations are complex as they involve various stakeholders with their perspectives on the renovation process. These different perspectives often lead to contradicting or conflicting goals that require a systematic approach to address them. Few studies in the literature address this challenge by developing decision-support tools tailored to particular stakeholder groups . For instance, Jafari & Valentin (2018) developed a decision matrix for four different types of investors to illustrate which economic, environmental and social benefits could apply to them when energy retrofitting a building. The four identified types of investors are owner-occupant, absent-owner, leaser and external stakeholder, all considered decision-makers.

Jensen and Maslesa (2015) developed the RENO-EVALUE decision support tool, which provides early-stage decision support to stakeholders in sustainable renovation projects. The stakeholders identified as target group for their tool are social housing associations, client organizations, estate administrators and managers in project, design or facility functions. Other identified stakeholders are developers, landlords, consultants, designers and representatives of building users.

Amorocho and Hartmann (2022) developed a multi-criteria decision-making framework to support a group of stakeholders in deciding on residential building renovations. The mentioned stakeholders are single/multiple owner(s), experts, multiple investors, tenants and external stakeholders like municipalities.

From the above-mentioned studies, it can be observed that not every stakeholder has an equal influence on the final decision . For a final decision, there needs to be at least one decision maker, which is most likely the stakeholder that funds the renovation (Jafari & Valentin, 2018). There are also stakeholders (e.g. experts, managers) who inform the decisionmaker(s) with relevant knowledge (Amorocho & Hartmann, 2022; Jensen & Maslesa, 2015), thereby influencing the decision while not being considered decision-makers. Furthermore, external stakeholders are involved in the decision-making process who are responsible for enacting policies, plans, rules and regulations (Amorocho & Hartmann, 2022; Jafari & Valentin, 2018). They can be considered authorizers to the decisionmakers. Besides decisionmakers, informants and authorizers, there are also stakeholders who are responsible for the implementation of the renovation project. Implementers often appear at a later stage, limiting their influence on the already advanced decision process.

It is possible for a stakeholder to have a combined influence profile on the decision-making process. In energy renovations there are two stakeholders with this combined profile, requiring some additional explanation. The first one are tenants, who can be both informants as well as authorizers. Since tenants are end-users of the building, their interests and preferences are often inquired by the decisionmaker to make an informed decision, making tenants informants. But, for example in case of a social housing corporation with tenants, the tenants are also authorizers to the housing corporation. In case of a multi-family building with a minimum of 10 apartments, at least 70% of the occupant-tenants need to agree with the plans of the corporation before they are allowed to start the renovation process (Ministry of the Interior and Kingdom Relations (BZK), 2023).

The second one are net operators, who can be both informants as well as implementers. Net operators are responsible for the development of (underground) infrastructure based on demand and are thus by nature implementers. However, for LT-renovations in particular, net operators can have a big influence on the timespan of the renovation implementation. For example, when the renovation approach with heat pumps requires reinforcement of the existing electricity grid, the net operator informs the decisionmaker that this adaption of the grid can be done in 2-10 years. This timespan uncertainty could cause a practical limitation, influencing the feasibility of the renovation approach. This makes the net operator therefore an important informant to the decisionmaker. For an effective decision-making process is it thus relevant to collaborate and discuss operational possibilities at an early stage between the decisionmakers and implementers. Understanding the roles and specific influence on the decision-making process is essential when deciding whose preferences to incorporate when evaluating the renovation alternatives.

Table 5.1.1 provides an overview with role description of the in literature identified stakeholders in residential energy renovations, completed with stakeholder suggestions based on the semi-structured interviews the author had with project managers in the energy renovation field. The stakeholders are categorized based on their function and their influence on the decision-making process. For clarification purposes the Dutch description title of the stakeholder is also mentioned.

Figure 5.1.1 illustrates the hierarchy structure of stakeholders and their influence on the final decision.

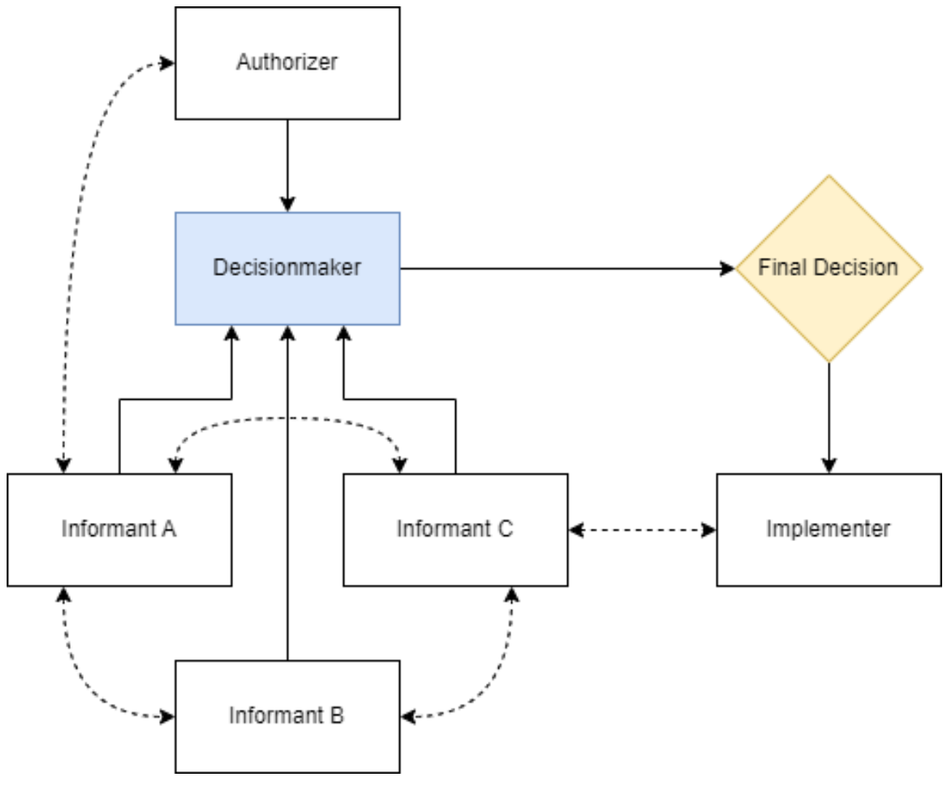


Figure 5.1.1 Stakeholders' hierarchy structure and influence on the final decision

Nr.	Function	Stakeholder	Literature ref.	Dutch definition	Role description	Influence on decision-making process
1	Owner	Social housing corporation	1, 3, 4	Woningcorporatie	Organisation with the aim to provide affordable housing for low to middle-income households.	Decision-maker
2		Investor	1, 2, 3	Investeerder	Person or company that invests money in real estate with the aim to make a profit	Decision-maker
3		Private owner(s)	1, 2	Particuliere eigenaar	Person who owns a residential building for private use	Decision-maker
4	Occupant	Owner	1, 2, 3	Eigenaar	Owner-occupant, end-user of the residential building	Decision-maker
5		Tenant	1, 2, 3, 4	Huurder	Occupant, end-user of the residential building	Informant and/or authorizer
6	Project Management	Project manager	1, 3, 4	Projectleider	Person who supervises and manages the planning and organisation of the renovation project, coordinator of stakeholders	Informant
7		Developer	3, 4	Projectontwikkelaar	Person who develops and initiates the renovation project, collaborate closely with architects, engineers, contractors and project manager	Informant
8		District manager	3, 4	Wijkbeheerder	Communicator between the social housing corporation and the tenants on building and/or neighbourhood level	Informant
9		Community representative	3, 4	Bewonersvertegenwoordiger	Spokesman for the tenants, usually a tenant who represents the combined interests of all tenants	Informant
10	Advisor	Expert consultant	1, 3, 4	Adviseur	Companies that provide expertise required to guarantee feasibility of the renovation project, like energy companies, financial institutions and fire safety experts	Informant
11		Engineer	1, 4	Ingenieur	Provides technical expertise to the project, for example building physics or structural engineer	Informant
12		Architect	1, 3	Architect	Translates clients desires and project requirements into design options, informed by experts	Informant
13	Operator	Net operators	4	Netbeheerder	Companies that manage and develop the (underground) infrastructure like the heat and electricity network. Provide information on operational possibilities of the renovation options. Redevelop infrastructure.	Informant and/or implementer
14	Policy	Municipality	1, 2, 4	Gemeente	Public institution that regulates policies, provides local grants, and provides authorization of the renovation project on a local scale (e.g. city and surrounding areas)	Authorizer
15		Public institutions	2, 4	Publieke sector	Public institutions like the provinces (provincies) and government (Rijksoverheid) that regulate and develop policies and grants on a national and regional scale, based on agreements like the Climate Agreement	Authorizer
16	Implementation	Contractor	3, 4	Aannemer	Companies that are in charge of the implementation of renovation project, hiring sub-contractors and/or technicians for specific renovation task like demolition and façade renovation	Implementer
17		Technician	4	Installateur	Executing specific renovation tasks like heat pump installation and roof insulation	Implementer
18		Supplier	4	Leverancier	Supply materials and products required to execute the renovation project, like insulation material and HVAC elements	Implementer

Ref nr.	Author
1	Amorocho & Hartmann (2022). *A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods*
2	Jafari & Valentin (2018). *Selection of optimization objectives for decision-making in building energy retrofits*
3	Jensen & Maslesa (2015). *Value based building renovation - A tool for decision-making and evaluation*
4	Gathered through semi-structured interview

Table 5.1.1 Stakeholder identification in residential energy renovations

5.2 Balancing Stakeholders' Interests

From chapter 5.1 it becomes evident that there are many stakeholders involved in the decision-making process of energy renovations, with varying influence on the final decision. The different roles can lead to different perspectives, prompting a wide variety of interests. These interests can be conflicting in nature, for example the building owner who wants to minimize investment costs while maximizing property value, while the tenants wish for a more comfortable living place with a short renovation time, while the municipality wants to prioritize energy savings in their city as a part of their political agenda. It is also common to have different or conflicting interests within one stakeholder, for example the social housing corporation who wants to minimize investment and operational costs, but also prioritize energy savings to lower the energy bills for the tenants while reaching the required energy label as imposed by the government. Some of these interest might have a larger impact on the final decision than others, introducing the aspect of relative importance in the decision making process.

Compromises are unavoidable in these kind of complex decisions. As elaborated in Chapter 3.3, MCDM is a peer-reviewed method that can support the making an informed decision when multiple conflicting/hard to compare criteria and multiple solutions/alternatives are present. In MCDM, stakeholders' interests are represented through a selection of decision parameters (see Chapter 4.1), and the relative importance of those interests can be represented through criteria weighting. The action of assigning weights to all criteria is up to the decisionmakers. How the weights are determined can be done through existing criteria weighting methods, or decided by the decisionmakers (Nielsen et al., 2016).

There are two main approaches in criteria weighing: equal weights and rank-order weights. Equal weights do not allow for relative importance of criteria, while rank-order weights do allow for prioritization. Within rank-order weighting the approach can be subjective, objective or combined. In the subjective approach the decisionmaker ranks the criteria based on their preferences, while the objective approach is based on mathematical models. (Zardari et al., 2014).

Within energy renovation projects an important aspect in the decision-making process is balancing the stakeholders interests. The process can be best supported by incorporating a criteria weighting method that has a subjective rank-order approach, since this could capture the different perspectives of the stakeholders in a logical and transparent way.

Examples of commonly used subjective weighting methods in energy renovations are the pairwise comparison and Delphi method (Amorocho & Hartmann, 2022; Nielsen et al., 2016, Siksnelyte-Butkiene et al., 2021). The Delphi method provides more flexibility than the pairwise comparison, but quantifying the perspectives of the stakeholder is a lot harder than with the pairwise comparison. The pairwise comparison provides a high level of transparency, but is sensitive to inconsistencies. Analytic Hierarchy Process (AHP) is one of the most applied MCDM methods that uses pairwise comparison as the foundation for the decision analysis, making the pairwise comparison a method that has been widely tested both theoretically and empirically for a wide range of decisions (Zardari et al., 2014).

Pairwise comparison originates as a psychometric technique with the function to order a set of criteria. Within this method each criterion is compared to every other criterion in a set of two (Zardari et al., 2014). This forces the decisionmaker to thoroughly consider all decision parameters, which can be especially helpful for non-expert decisionmakers who potentially struggle with comprehending their own preferences (Amorocho & Hartmann, 2022).

The amount of comparisons to be made based on a set of criteria can be calculated through formula 5.1 (Zardari et al., 2014).

$$o = \frac{n(n-1)}{2} \qquad (5.1)$$

o = number of comparisons

n = number of criteria

This formula shows that the more criteria are considered, the more comparisons need to be made. To prevent a time-consuming decision-making process it is therefore important to somewhat limit the number of criteria.

Criteria weights can be calculated through pairwise comparison consisting of the following three steps (Zardari et al., 2014):

1. Construct the criterion matrix and fill in the matrix by determining the relative importance of each criterion based on the 1-9 scale that Thomas L. Saaty developed in 1980
2. Normalize the relative importance values and calculate the criteria weights
3. Calculate the consistency ratio (CR) of the criteria weights

An example of these steps is illustrated in figure 5.2.1. When assigning the relative importance values, the diagonal comparison between the same criterion always have a value of 1 (equal importance). The assigned values are inversely proportional since the matrix is reciprocal. The 1-9 scale of Saaty is illustrated in table 5.2.1. For example, when criterion 1 (C1) has a moderate importance compared to criterion 3 (C3), the assigned value is 3 in the top right part (green accent). This automatically leads to a relative importance of 1/3 when comparing C3 to C1 in the bottom left part (blue accent).

1) Construct matrix, assign relative importance value

	C1	C2	C3	C4
C1	1	2	3	3
C2	1/2	1	4	2
C3	1/3	1/4	1	1/3
C4	1/3	1/2	3	1

2) Normalize matrix & Calulate criteria weights

	C1	C2	C3	C4
C1	1	2	3	3
C2	1/2	1	4	2
C3	1/3	1/4	1	1/3
C4	1/3	1/2	3	1
SUM	2,17	3,75	11,00	6,33

	C1	C2	C3	C4	Wk
C1	0,462	0,533	0,273	0,474	0,435
C2	0,231	0,267	0,364	0,316	0,294
C3	0,154	0,067	0,091	0,053	0,091
C4	0,154	0,133	0,273	0,158	0,179

n=4

3) Check consistency ratio

	C1	C2	C3	C4
Wk	0,435	0,294	0,091	0,179
C1	1	2	3	3
C2	1/2	1	4	2
C3	1/3	1/4	1	1/3
C4	1/3	1/2	3	1

	C1	C2	C3	C4		
Wk	0,435	0,294	0,091	0,179	rj	CVj
C1	0,435	0,588	0,273	0,538	1,835	4,216
C2	0,218	0,294	0,364	0,359	1,235	4,197
C3	0,145	0,074	0,091	0,060	0,369	4,060
C4	0,145	0,147	0,273	0,179	0,745	4,150

λ_{max}	4,156	n=4
CI	0,0519	
CR	0,0576	

Figure 5.2.1 Example of generating criteria weights based on pairwise comparison with a set of 4 criteria

Relative importance	Assigned value
Equal importance	1
Equal to moderate importance	2
Moderate importance	3
Moderate to strong importance	4
Strong importance	5
Strong to very strong importance	6
Very strong importance	7
Very strong to extreme importance	8
Extreme importance	9

Table 5.2.1 Saaty's 1-9 scale of relative importance

The criteria weights can be calculated by summing the values in each column (*i*), dividing each relative importance value (a_{kj}) by the column total ($\sum^{n}_{i=1} a_{ij}$), and dividing the summation of the normalized scores for each row (*j*) by the total number of criteria (*n*). This is expressed in formula 5.2.

$$w_k = \frac{1}{n} \cdot \sum_{j=1}^{n} \left(\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}} \right) \qquad (5.2)$$

w_k = criteria weights for k = 1, 2, 3, …, *n*

n = number of criteria

a_{kj} = relative importance value

To check if the outcome of the criteria weights are robust, a consistency check is required. The consistency is expressed by the consistency ratio (CR) and refers to the degree to which the decisionmakers judgements are coherent. The CR can be calculated by dividing the consistency index (CI) with the random index (RI). The random index is a predetermined set of values and can be found in table 5.2.2. λ_{max} is the maximum eigenvalue of the matrices, which can be calculated by summing the consistency vectors and dividing them by the amount of criteria (*n*). The consistency vector (CV) can be calculated by dividing the weighted sum value (r_j) with the calculated criteria weights (w_k). r_j is calculated by multiplying the relative importance values with the according criteria weights per column, and summing the row values.

The CR can be calculated through formula 5.3-5.7.

$$CR = \frac{CI}{RI} \qquad (5.3)$$

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad (5.4)$$

$$\lambda_{max} = \frac{\sum_{i=1}^{n} CV_{ij}}{n} \qquad (5.5)$$

$$CV_j = \frac{r_j}{w_k} \qquad (5.6)$$

$$r_j = \sum_{j=1}^{n} a_{kj} * w_k \qquad (5.7)$$

A common threshold value for the CR is 10%, but if less precision is required the threshold value can be higher, or lower if more precision is required. When the calculated CR is lower than the threshold value the criteria weights are robust enough to be implemented (CR<0,10). If the calculated CR exceeds the threshold value (CR>0,10), the decisionmakers' judgement is likely to be inconsistent (Zardari et al., 2014).

The pairwise comparison has the advantage of being relatively simple to use, since only two criteria are compared at a time. However, the method is limited when large sets of criteria should be compared, since this leads to numerous time-consuming individual comparisons. There is also a fuzziness in this method, since different stakeholders can interpret the 1-9 scale of Saaty differently, resulting in different criteria weights. Nevertheless, when trying to balance (subjective) perspectives there will always be a risk of bias and a certain amount of fuzziness. As long as the users of the method are aware of these shortcomings, the pairwise comparison is very suitable to balance the subjective perspectives in a simple, efficient, transparent and analytical way.

The pairwise comparison is suitable for both single-user as well as multi-user. In case of a single-user, for example just one decisionmaker, the user assigns the relative importance values based on their own preferences. In case of multi-user, for example one decisionmaker that is informed by three other stakeholders, all four users require to do an individual pairwise comparison based on their preferences. The decisionmaker can decide to take the average value of the obtained criteria weights to make an informed

	Wk C7	Wk C8	Wk C9	Wk C10
S1	9%	18%	44%	29%
S2	15%	21%	39%	25%
S3	10%	30%	25%	35%
S4	18%	8%	50%	24%
Balanced	13%	19%	40%	28%

Table 5.2.3 Aggregated criteria weights of 4 different stakeholders (S1-S4) for a set of 4 criteria (C7-C10)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49

Table 5.2.2 Random Index values

decision, or just use them as reference and only implement their own criteria weights, disregarding the interests of the other stakeholders. Table 5.2.3 shows an example of the aggregated criteria weights. Doing a separate pairwise comparison and then combining them into a collective weighting score provides transparency on the influence the informants have on the decisionmaker, as well as balancing the variety of interests different types of stakeholders can have.

After obtaining the aggregated criteria weights, they can be applied to the determined decision parameters. Aiming for a holistic and sustainable decision requires the three main categories (environmental, economic, social) to be weighted equally (33% each). All objectives originating from the same category can be assigned weights through the pairwise comparison method. Each branch of criteria related to a specific objective can also be assigned weights through pairwise comparison. This leads to a comparison of criteria within the same objective instead of a comparison between the complete set of criteria, limiting the total amount of individual comparisons to be made. An example based on the presented criteria tree from chapter 4.1 is illustrated in figure 5.2.2.

The identified stakeholders and their influence on the decision-making process from chapter 5.1 and the criteria weighting methods to balance the stakeholders interests from chapter 5.2 are essential to develop an informed decision support framework specified to LT-renovation projects. The first sub-chapter provides useful information about the potential target audience (users) of the intended decision support framework. A distinction is made between decisionmakers, informants, authorizers and implementers, creating potential for a more transparent and structured decision-making process. The second sub-chapter provides an easy to use and widely validated method to balance the stakeholders interests.

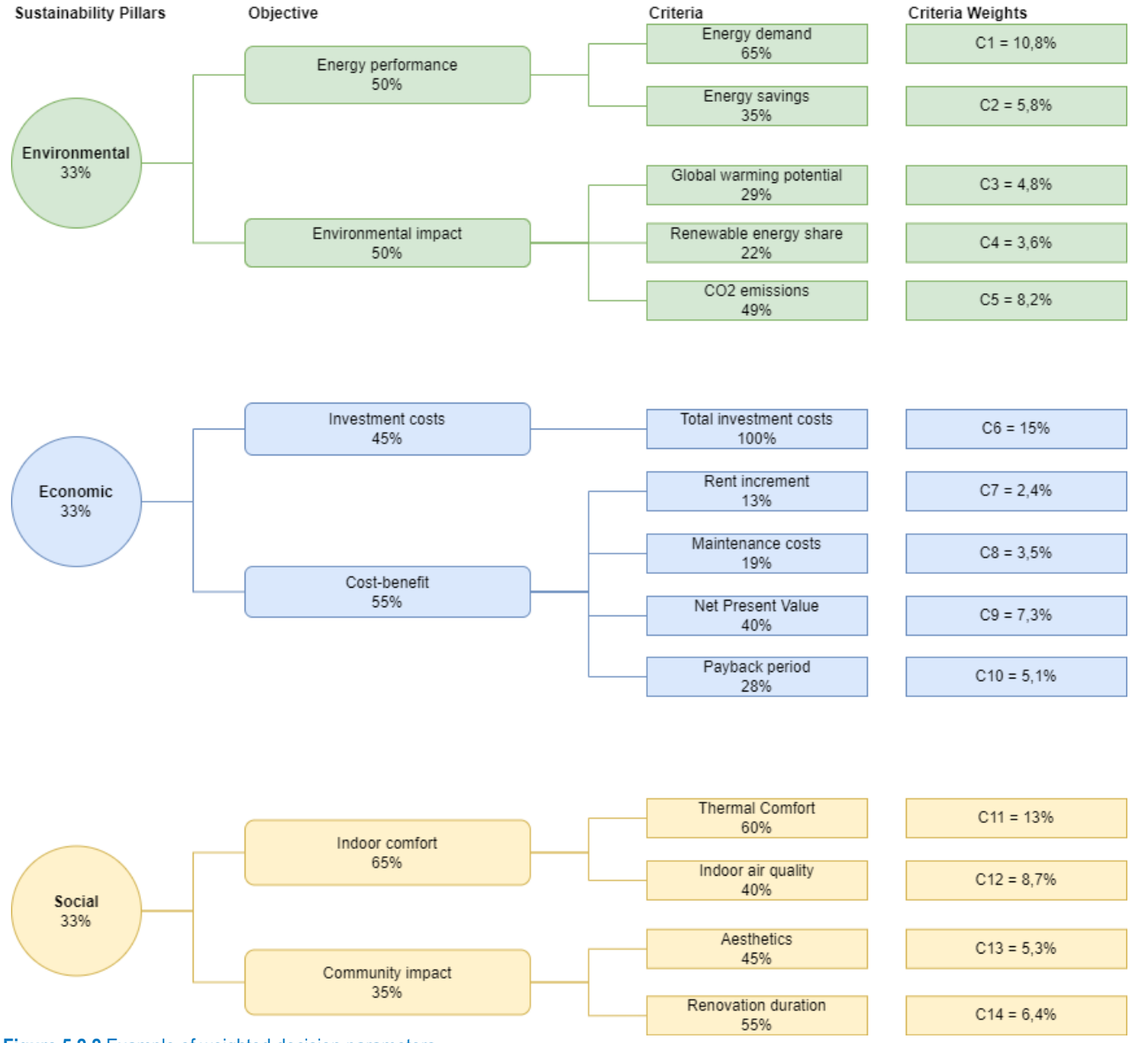


Figure 5.2.2 Example of weighted decision parameters

FRAMEWORK & TOOL DEVELOPMENT

6. FRAMEWORK & TOOL

Development of LTH-DS Framework & Tool

A scientific approach to supporting the selection of a LTH-renovation scenario is through structuring the decision-making process and providing a way to ease the implementation of the identified steps in the process. A logical approach to this is to develop a decision support framework accompanied by a decision support tool. The insights on the requirements to enable LTH in residential buildings from chapter 2, combined with the insights on decision support in energy renovations from chapter 3, 4 and 5 provides the knowledge base for the development of an informed decision support framework for LTH renovations. The MCDM TOPSIS method from chapter 3.5 and the pairwise comparison method from chapter 5.2 provides the methodological base for the development of the decision support tool.

Chapter 6.1 elaborates on the framework development, Chapter 6.2 elaborates on the tool development.

6.1 Framework Development

The framework is developed over different phases of the research, and adapted based on new acquired insights from literature and obtained feedback during presentations. The base of the framework is the framework for general decision-making processes as presented in chapter 3, figure 3.2. For clarity purposes only the final version of the developed decision support framework is presented and discussed.

6.1.1 Objective

The main aim of the framework is to provide early stage decision-support for the selection of LTH renovation concepts for residential dwellings by simplifying the decision-making process. The framework aims to provide this simplification by structuring the decision-making process of multiple stakeholders who try to reach a consensus on the selection of a LTH renovation scenario. It attempts to balance the stakeholders' interests by providing a decision support tool based on a transparent and empirically tested multi-criteria decision-making method. The framework in combination with the tool aims to identify and rank suitable renovation scenarios based on the balanced interests of the involved stakeholders and the scenarios performance of decision criteria. The framework includes an element of decision parameters identification with the aim to incorporate a holistic approach towards the decision-making process. Current decision support for energy renovations is often limited to optimizing cost versus energy benefits. However, chapter 4.1 illustrates that there are many different decision criteria, and that a well-balanced decision should include environmental, economic as well as social decision parameters. Incorporating a holistic approach towards decision-making can nudge the decisionmakers towards a better informed, more sustainable decision widening their perspective to the definition of the 'optimal solution'.

The overarching aim of the framework is to contribute to the acceleration of the energy transition by expediting the rate of renovation and preparing existing dwellings for gas free heating.

6.1.2 Hypothesis

The hypothesis of this framework is that by evaluating the performance of LT-renovation alternatives across decision criteria from all three pillars of sustainability, alternatives that initially appear inferior (e.g. higher costs, less ideal energy performance) may ultimately prove to be optimal from a holistic perspective. This broadens the scope of evaluation. The hypothesis suggests that when ranking alternatives by evaluating all these diverse criteria, a different, non-obvious scenario may emerge as the best option. By quantifying and making intangible aspects tangible, a more balanced and informed decision can be achieved.

6.1.3 Boundaries & Conditions

The target audience that the framework aims for are stakeholders with experience in residential energy renovation projects and decision-making processes. The framework allows for balancing stakeholders preferences who have varying levels of influence on the final decision. The framework can be used by a single or multiple decision-maker(s). The starting point of the framework is that a LTH connection is aimed for, either through heat pumps or district heating. The following framework boundaries are applicable:

- The framework is specific to identify the most optimal renovation scenario to enable low-temperature heating. To ensure LT-readiness, heating demand and thermal discomfort are non-negotiable decision criteria.
- The framework is designed from the perspective of multi-family buildings.
- The framework can be applied to cases in the Netherlands or other places with comparable climate.
- The framework supports informed, holistic decision-making, therefore criteria from every pillar of sustainability should be included in the decision analysis.

6.1.4 LTH DS Framework

The framework is based on a general MCDM framework. It is then tailored specifically to LTH by incorporating several key steps, as identified in chapter 2-5. These steps include assessing LTH readiness, incorporating specific LTH decision parameters, and implementing a criteria weighting method to represent multiple stakeholders, thus facilitating multi-stakeholder involvement. Additionally, the framework generates renovation alternatives that aim to make buildings compatible with LTH and filters out scenarios that are not compatible with LTH. Based on the frameworks' objective, hypothesis and boundaries the following low-temperature heating decision support framework is proposed (figure 6.1.1):

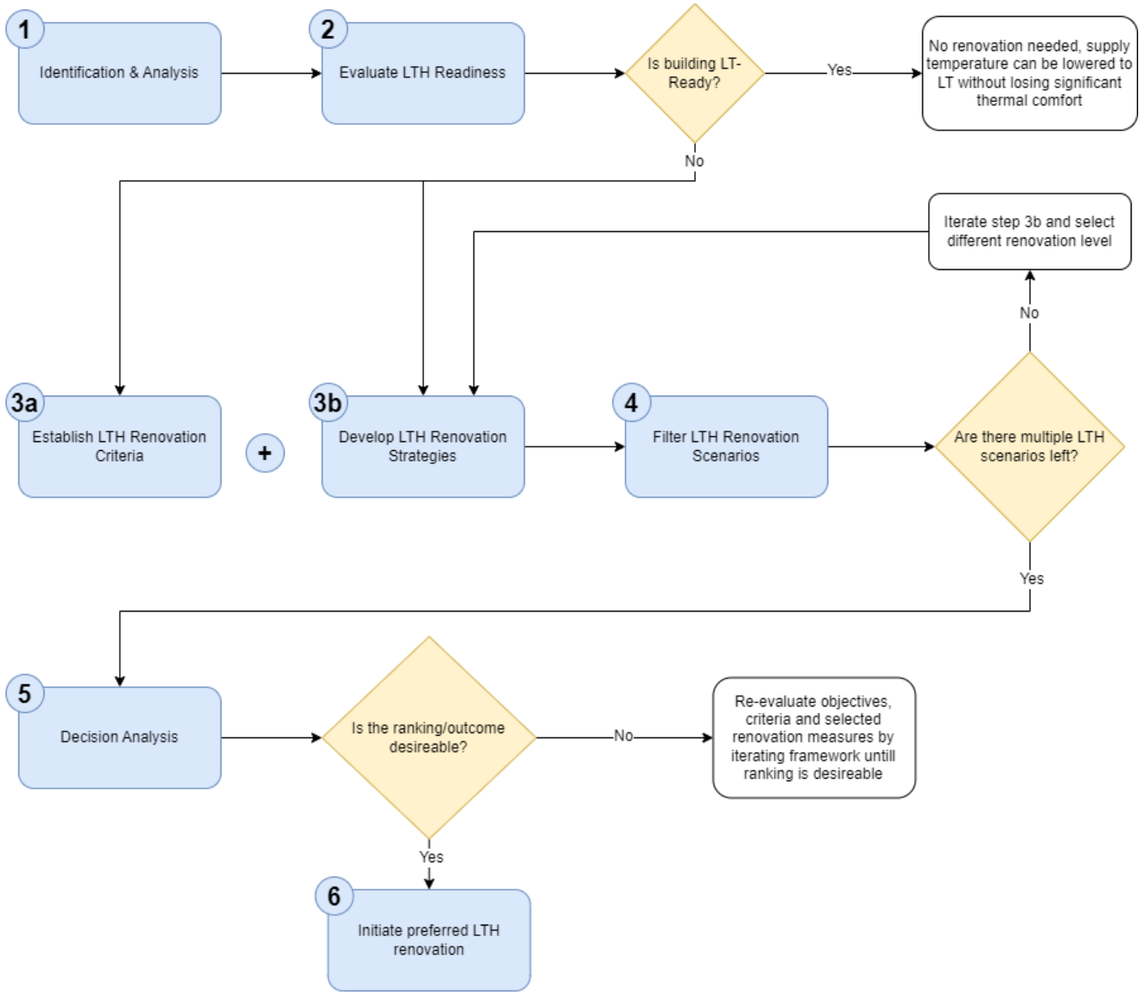


Figure 6.1.1 Low-temperature heating decision support framework

6.1.4.1 Step 1 - Identification & Analysis

The first step in the low-temperature heating decision support framework encompasses identification and analysis. This foundational step involves defining the 'problem', the reason for the renovation initiative. This could be a natural renovation moment, like the end-of-life of a heating system or rotten window frames. This can lead to the identification of additional renovation objectives, like improving the energy performance of the building or improve the neighbourhood cohesion. Chapter 4.1 provides an overview of common LTH renovation objectives. For a holistic, informed renovation project it is important to have objectives that relate to all three pillars of sustainability. Another important identification aspect is stakeholder identification: who are involved, which role do they have and what influence do they have on the decision-making process. Besides identification, analysis is required to gain insight into the specific context of the project. This involves the gathering of information on social, economic and environmental aspects to identify project limitations, (tenants) wishes and complaints, and to benchmark the state of the building (data collection). An example of a renovation limitation can be the absence of a cavity, or a ventilation system that has not yet reached its end-of-life. An example of a tenants wish can be the placement of PV panels, or a complaint about cold drafts. This provides valuable information to develop suitable renovation alternatives. It creates the boundary condition, the framework for the renovation project. The technical data is used to calculate the benchmark of the original situation, which is required to assure that the to be developed renovation alternatives will be an improvement on all decision criteria compared to the original situation. The LTH-grasshopper tool, developed by P. Wahi, can be utilized to simulate the original heating demand as well as existing thermal (dis)comfort for the original HT situation.

By completing this step, a comprehensive understanding of the initial conditions is established, and clear objectives for the renovation project are set. This foundational work ensures that subsequent steps in the framework are based on accurate information and well-defined goals.

6.1.4.2 Step 2 - Evaluate LTH Readiness

The second step of the framework is to evaluate the LTH readiness of the building. In order to do this, a clear definition of what LT-readiness encompasses needs to be defined. For this research, LT-readiness is measured based on annual heating demand (kWh/m^2) and thermal discomfort (hours underheating in living room) at a heating supply temperature of 30-55 °C. A new simulation for the 6 different apartment positions with the LTH-grasshopper tool where the parameters are exactly the same, except the change of supply temperature from HT to LT, can show the LTH-performance of the building. If both performance values are equal or lower to the original HT benchmark, the building is LT-ready. This LT-ready check is essential, since a lot of buildings have an overcapacity in the existing heating system, which can compensate for a lower heat output of a LT-supply temperature, eliminating the need for extensive renovation. If the building is LT-ready at this check, the building can be connected to a LTDH or HP system without additional renovation measures to complete the heating transition for the project. If the building is not LT-ready, the development of the renovation project should continue, which can be supported by following the next steps in the framework.

6.1.4.3 Step 3a - Establish LTH Renovation Criteria

Based on the established objectives in the first step of the framework, decision criteria can be extracted. The criteria decision tree from chapter 4.1 can be used as a support tool to establish those criteria. In theory there is no limit to the amount of decision criteria for comparison in the decision analysis, but it should be noted that the decision support tool is developed to compare 15 decision criteria (5 in each category). More criteria leads to the need of quantifying the performance of the alternatives on more aspects, leading to a more extensive and time-consuming decision analysis. Less decision criteria thus leads to less extensive, shorter decision analysis, but also represents a less informed ranking of the alternatives. The minimum required amount of decision criteria is 1 per renovation objective. There are two non-negotiable decision criteria for this LTH-DS framework: heating demand and thermal comfort. These are non-negotiable since this measures if the renovation alternatives are LT-ready or not, and prevents the risk of selecting a renovation scenario that is not sufficient on those aspects. It is recommended to determine a quantification method per criteria that can be executed within available resources (like specific energy simulation software). For qualitative decision criteria descriptive scales can be developed to estimate the performance. Setting benchmark values for the decision criteria can support the filter of renovation alternatives: scenarios that do not reach the benchmark values for one or more decision criteria should be eliminated from the comparison. For the function of the decision support tool, it is important to determine if the maximum or minimum of the quantified performance value is beneficial. For example, when considering the decision criteria investment costs (€), the beneficial value is the minimum value. When considering the decision criteria gas savings (m^3), the maximum value is the beneficial value.

After the decision criteria and method of quantification are sorted, the relative importance of selected decision criteria can be determined. Assessing the relative importance of decision criteria is done by quantifying stakeholders' preferences through pairwise comparison. The decision support tool can be used for this. In case of multi-stakeholders, individual pairwise comparisons should be made obtaining individual criteria weights (representing individual preferences), after which the individual weights are combined into balanced criteria weights for each criteria.

6.1.4.4 - Step 3b Develop LTH Renovation Scenarios

The identified renovation measures from Chapter 2.2 provides the start for the development of the renovation alternatives. To determine which measures can be combined for a suitable renovation scenario the following aspects have to be taken into consideration:

1. Building context. The identified renovation objectives, building limitations, end-of-life elements and (tenants) renovation wishes/ complaints from step 1 can provide valuable information in terms of selection or elimination of certain renovation measures. For example, no cavity eliminates the renovation measure cavity insulation, and the renovation objective improve coherence of neighbourhood could lead to the measure of exterior façade insulation since this also creates the opportunity to improve the appearance of the building.
2. Level of LT-Readiness. The calculated LTH-performance value from step 2 provides valuable information to estimate the extent to which renovation measures are necessary in order to become LT-ready. For example, an exceedance of 50 hours underheated compared to the benchmark requires a lighter renovation approach than an additional 500 hours.
3. Performance benchmarks. The identified benchmark values for the decision criteria from step 3, the performance values that are aimed for, provide valuable information on the extent to which the renovation measures need to be applied.

The approach for developing the renovation scenarios should be based around these aspects to increase the changes of designing fitting solutions.

6.1.4.5 - Step 4 Filter LTH Renovation Scenarios

After developing the renovation alternatives it is crucial to assess the LT-Readiness of the new scenarios. Each developed alternative requires a LT-ready check for all 6 apartment positions when dealing with multi-family buildings. This has to do with the difference in compactness ratio, and if the building envelope is connected to the exterior or to another apartment, influencing the heat losses. The 6 unique positions are illustrated in figure 6.1.2.

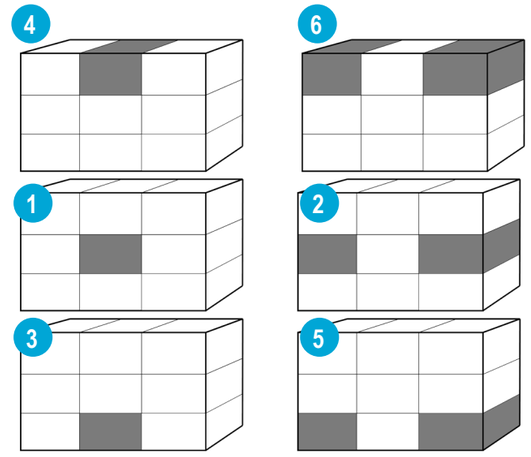


Figure 6.1.2 Six unique positions for multi-family buildings

The LTH-grasshopper tool can be used to calculate the new heating demand and thermal discomfort. For a theoretically true LT-ready scenario, all 6 apartment positions should perform equal or better than the benchmark for the corresponding position. Scenarios that do not reach this goal should be eliminated from the comparison for the decision. In practice, it could be sufficient to design scenarios that make the complex on average LT-ready. The few corner-ground or corner-roof apartments that are not LT-ready can be made ready locally by placing an additional radiator to increase the heating capacity for that apartment, without requiring additional measures on building level. It is recommended to consult with experts before considering including these almost LT-ready renovation scenarios into the comparison for the decision.

The values of the 6 positions for heating demand and thermal discomfort as simulated by the LTH-grasshopper tool need to be averaged to obtain one value on heating demand and one value on thermal discomfort per renovation scenario. This averaged value is the quantified performance value for the decision criteria, which is an required input for the decision analysis tool.

If there are none, or just a single scenario left after this LT-ready check, it is important to develop some more alternatives that are LT-ready so that there are enough alternatives for the comparison. In theory there is no limit to the amount of renovation alternatives that can be compared in the decision analysis. However, the more renovation alternatives are incorporated into the analysis, the more

alternatives require calculations/estimations for the performance quantification, which could extend the process. The decision support tool is currently limited to 6 renovation alternatives, but can be easily adapted to compare more alternatives.

6.1.4.6 - Step 5 Decision Analysis

For the remaining scenarios it is essential to quantify the performance for every decision criterion, using the determined approach from step 3a. This quantification can be supported by simulation and calculation software, as well as by experts who can make accurate estimations. However, the ranking results are as reliable as the data input provided: rough estimations or calculations can introduce inconsistency, providing a rough direction for decision support, while data with a higher accuracy can provide more definitive decision support.

When incorporating the aspect of relative importance to the decision criteria (by incorporating criteria weights obtained from the pairwise comparison), each quantified criterion needs to have a comparable level of accuracy in the data. If this accuracy is not comparable, and C1 has a criterion weight of 3% with high accuracy data, while C2 has a criterion weight of 21% with low accuracy data, the low accuracy criterion would have an out of proportion effect on the ranking. This can lead to a situation where an alternative is ranked higher or lower, not due to its true performance, but due to the inconsistency in the data. This compromises the final ranking, potentially providing misleading results. Low accuracy data with a high weight lead to less reliable results, while high accuracy data with a high weight can lead to a more reliable ranking. A sensitivity analysis can help understand how changes in the data accuracy can affect the final ranking, providing insight into the robustness of the decision. A sensitivity analysis on the criteria weights is built in into the decision support tool for the pairwise comparison.

After obtaining all required data (quantified values + criterion weights), the decision support tool can be used to gather a ranking of the renovation alternatives based on the expected performance and stakeholders' preferences, utilizing the TOPSIS method. It should be noted that the decision support tool is just that, and not a decision replacement tool. An evaluation of the ranking is therefore required: if the outcome of the ranking is desirable, the last step of the framework can be taken. If the outcome of the ranking is undesirable, a targeted discussion can be held on why the outcome is undesirable. The framework steps can be iterated with the new acquired insights from this targeted discussion, to adjust for example the decision parameters or renovation alternatives, until a desirable outcome has been reached.

6.1.4.7 - Step 6 Initiate preferred LTH renovation

The last step of the framework is to initiate the renovation process, and prepare the building for gas free heating by renovating the building to enable low-temperature heating.

6.1.4.8 Final LTH-DS framework

This leads to the final low-temperature heating decision support framework. In this framework, the decision-making process is structured, the complex renovation problem is clearly identified, and stakeholders' preferences are balanced through criteria weighting. Renovation scenarios are developed and filtered based on the specific context, then assessed and ranked according to their expected performance and the stakeholders' preferences, all within the context of enabling low-temperature heating. Figure 6.1.3 illustrates the final LTH-DS framework.

The next step in the research is validating if the developed framework functions in the way it is designed for by fitting it to a real-world scenario, which will be explained in Chapter 7. Chapter 6.2 will first elaborate on the development of the decision support tool itself.

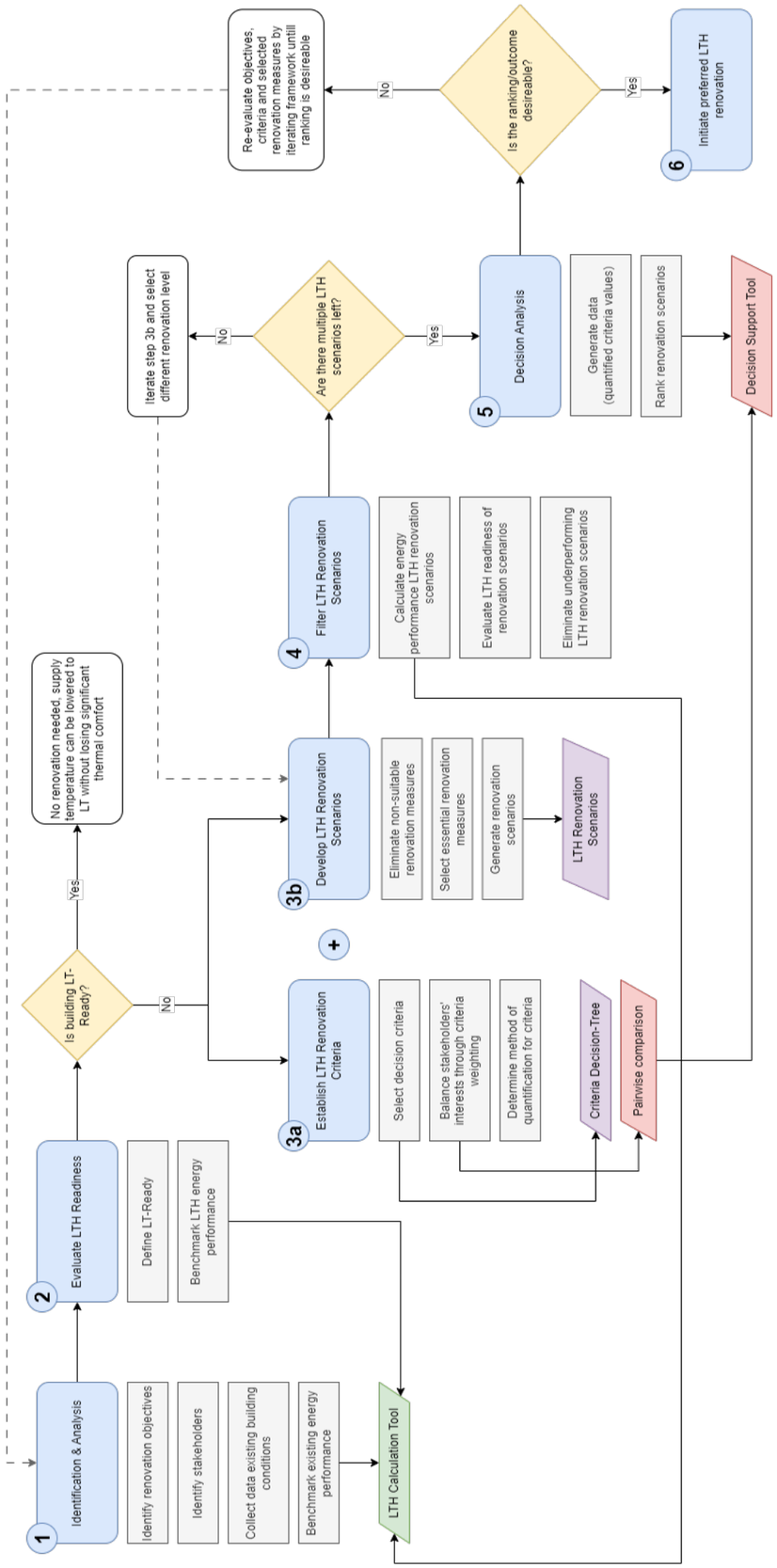


Figure 6.1.3 Final LTH-DS framework

6.2 Tool Development

6.2.1 Concept of Decision Support Tool

To assist in the completion of the frameworks' steps a decision support tool has been developed. This tool has the aim to aid the identification of the most optimal LTH-renovation alternative out of a finite set of renovation scenarios compared to a set of decision criteria. To capture the stakeholders preferences the tool adopts the pairwise comparison method to obtain balanced criteria weights. To acquire a ranking of the alternatives based on the performance of the set of decision criteria the TOPSIS method is adopted. The balanced criteria weights from the pairwise comparison are integrated into the TOPSIS calculation for a preference integrated performance based final ranking.

The target audience for the tool are the stakeholders who are decisionmakers and informants with an influence on the final decision. The tool can be used for multiple decision support approaches. For example, a single decisionmaker could use the tool to obtain a ranking based on their own preferences, while a group of informants could use the tool to obtain a ranking based on their combined preferences. If desired, the tool can also provide a ranking based on the combined preferences of both the decisionmaker and the informants. If the interests of the stakeholders differ, it is likely that the tool will provide a different result for each approach, meaning diverse rankings where a different optimal alternative is suggested. Comparing those results among the stakeholders can lead to useful insights on who prefers what, which can lead to a focussed and targeted discussion. This can narrow down the amount of alternatives to consider, and support the decision on the selection of a final alternative.

To achieve these ranking results, the tool requires certain input from its users. Chapter 6.2.2 expands on the tool components, the interface and the different input requirements. Chapter 6.2.3 discusses the current limitations of the tool. Chapter 6.2.4 suggests future improvements for the tool.

6.2.2 Decision Support Tool

The decision support tool is an Excel based tool, making it widely accessible. The following sub-paragraphs elaborate on the different components of the tool and the input required of its users. Reasonable random numbers are provided to showcase the function of the tool. For a real-world case study application of the tool, the validation chapter 7.3.3 can be consulted.

6.2.2.1 Project Description

The decision support tool starts with an information tab. The users of the tool can input a short description of relevant project information which can be used as reference throughout the process to provide structure and overview. Table 6.2.1 illustrates how a project description can look.

Project	Specifics
Name of Project	
Complex no.	
Location	
Owner(s)	
Building Characteristics	**Specifics**
Building Type	e.g. detached house, semi-detached house, terraced house, corner house, maisonnette, staircase apartment, gallery apartment, flat, other
Construction year	
Number of floors	Including attics and cellar
Total amount of dwelling units	
Number of rooms per dwelling	e.g. 10 two-bedroom apartments, 35 three-bedroom apartments
Other building specifics	e.g. routing, spaces in building with function other than living (e.g. bicycle storage, recreational space), place of boiler room, etc.
Orientation	Position of blocks, building orientation of long side of façade
Previous renovations	e.g. mechanical exhaust ventilation placed in 2008, cavity insulation 6cm EPS added in 2016
Additional Project Information	**Specifics**
Energy efficiency	e.g. energy label, energy-index, BENG performance, EPG
Building installations	Heating system type (e.g. collective HT space heating boilers from 2004 with radiator type 22) Ventilation system type (e.g. C1 natural supply, central mechanical exhaust) Domestic hot water (e.g. collective HR boilers from 2007)
Planned major maintenance	e.g. end-of-life heating boiler, planned replacement 2024
Occupancy profile	Age group (e.g. elderly people), gender (e.g. 19% male, 70% female, 1% other), occupancy (e.g. 20% living together, 80% single)
Other specifics	e.g. fire safety, asbestos, flora & fauna, residents wishes & complaints

Table 6.2.1 Project description Decision Support Tool

6.2.2.2 Stakeholder Identification

To support one of the action points of the first step of the framework, the next tab of the tool involves another information summary, this time for stakeholder identification. Table 6.2.2 illustrates the stakeholder identification tab. This identifies the total number of stakeholders whose preferences need to be incorporated into the decision analysis, providing overview and understanding of each other's role and influence. This can remove noise from the decision making process.

6.2.2.3 Decision Parameters

To support the identification of decision objectives and criteria from framework step 1 and 3 a decision parameters tab is included in the tool (Table 6.2.3). This is based on the literature research of Chapter 4. The required input are all identified decision objectives with their accompanying decision criteria. The number of objectives can be flexible, as long as there is a minimum of 1 objective per category to guarantee a holistic decision-making process. The tool is currently limited to exactly 5 decision criteria per category. The two non-negotiable criteria are C1 energy demand and C11 thermal comfort, since those measure LT-readiness. Users of the tool are allowed to tailor the other decision criteria to their needs. Next, the users need to determine their method of quantification for every decision criterion, as elaborated upon in Chapter 4. C1 and C11 are quantified through the LTH-grasshopper tool. If there are benchmarks for certain decision criteria, they can be written down in the next column. As a final action for this tab, the users are required to determine for every decision criterion if the minimum performance value or maximum performance value is beneficial. This is needed to calculate the Positive Ideal Solution and Negative Ideal Solution for the TOPSIS method in the decision analysis tab of the tool.

6.2.2.4 Pairwise Comparison

To support the frameworks' step of identifying the stakeholders preferences, a pairwise comparison calculation is incorporated into the decision support tool. The users of the tool are required to scale the relative importance of each decision criterion from one category to every other criterion in the same category by sliding the bar in the position that represents their preference. Every stakeholder performs their own comparisons in individual Excel files. Table 6.2.4 shows the 9 point scale of Saaty, which is used as the base for table 6.2.5, which provides a filled out example of these pairwise comparisons. The example of the first comparison in the environmental category shows that C2 is equal to moderate important compared to C1. It is important for the users to be consistent in their answers to obtain reliable criteria weights. This means that if

Name	Role	Organisation	Influence on the Decision	Incorporate preferences into decision?
	e.g. social housing corporation, investor, private owner		e.g. decision-maker, informant, authorizor, implementer or combination	yes/no
	e.g. owner, tenant			
	e.g. project manager, developer, district manager, community representative,			
	e.g. expert consultant, engineer, architect, net operator			
	e.g. municipality, public institutions			
	e.g. contractor, technician, supplier			
	other			

Table 6.2.2 Stakeholder Identification Decision Support Tool

Category (sustainability)		Objective		Criteria		Quantification	Benchmark	Min or max value beneficial?
S1	Environmental	O1	Improve the energy performance	C1	Energy demand	annual kWh/m^2	< original HT situation	Min
				C2	Energy savings	annual kWh/m^2		Max
		O2	Reduce the environmental impact	C3	Global warming potential	kg CO2/m^2		Min
				C4	Renewable energy share	annual kWh/m^2		Max
				C5	CO2 emission reduction	CO2		Max
S2	Economic	O3	Limit investment costs	C6	Total investment costs	€		Min
		O4	Optimize cost-benefits	C7	Rent increment	€/year		Max
				C8	Maintenance costs	€		Min
				C9	NPV	€		Max
				C10	Payback period	years		Min
S3	Social	O5	Improve indoor comfort	C11	Thermal Comfort	hours too cold	< original HT situation	Min
				C12	Indoor air quality	CO2 concentration		Min
		O6	Improve community	C13	Aesthetics	Descriptive scale		Max
				C14	Renovation duration	days		Min
		O7	Improve social-economic situation	C15	Energy costs (bill)	€/year		Min

Table 6.2.3 Decision Parameters Decision Support Tool

C1 is valued extremely important compared to C2, and C1 is moderate important compared to C3, when comparing C2 to C3 it'd be expected that C3 has a higher relative importance compared to C2, based on their relative importance to C1.

Relative Importance	Assigned value
Inverse extreme importance	1/9
Inverse very strong to extreme importance	1/8
Inverse very strong importance	1/7
Inverse strong to very strong importance	1/6
Inverse strong importance	1/5
Inverse moderate to strong importance	1/4
Inverse moderate importance	1/3
Inverse equal to moderate importance	1/2
Equal importance	1
Equal to moderate importance	2
Moderate importance	3
Moderate to strong importance	4
Strong importance	5
Strong to very strong importance	6
Very strong importance	7
Very strong to extreme importance	8
Extreme importance	9

Table 6.2.4 Saaty's 1-9 scale of relative importance

ENVIRONMENTAL

	Extreme importance	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extreme importance	Score
C1																	C2	1/2
C1																	C3	3
C1																	C4	4
C1																	C5	5
C2																	C3	6
C2																	C4	4
C2																	C5	7
C3																	C4	1/3
C3																	C5	1/2
C4																	C5	4

ECONOMIC

	Extreme importance	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extreme importance	Score
C6																	C7	4
C6																	C8	2
C6																	C9	3
C6																	C10	1
C7																	C8	1/3
C7																	C9	1/2
C7																	C10	1/4
C8																	C9	1
C8																	C10	2
C9																	C10	1/2

SOCIAL

	Extreme importance	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extreme importance	Score
C11																	C12	1/4
C11																	C13	1/5
C11																	C14	1/5
C11																	C15	1/2
C12																	C13	2
C12																	C14	3
C12																	C15	1
C13																	C14	1/2
C13																	C15	2
C14																	C15	3

Table 6.2.5 Pairwise comparison – user input example Decision Support Tool

6.2.2.5 Individual Criteria Weights

The next tab in the decision support tool is the pairwise comparison matrix tab, where individual criteria weights are obtained, which is shown in table 6.2.6-7. This is a calculation tab, where the input from the previous tab automatically fills in the matrices. The users of the tool can check their own consistency ratio here: when the criteria weights are marked red (like the social weights in the figure), this indicates an inconsistency higher than the standard threshold consistency ratio of 10%. From this point there are two approaches:

1. Review the input of pairwise comparison for the category that is inconsistent until all criteria weights are within the consistency ratio of 10%.
2. Up the threshold of the consistency ratio by sliding the bar to a higher percentage.

The first approach allows for reasonable reliability of the individual criteria weights. The second approach decreases the reliability of the weights. However, it is possible that the users of the framework are not particularly good at reflecting on their own consistency, leading to endless reviewing of the comparisons without reaching the wanted consistency. This can be obstructing to the process, missing the point of decision support. Being inconsistent is also part of being human, therefore upping the threshold to a slightly higher consistency ratio might be beneficial to the decision-making process. It remains important to be aware of the influence on the reliability of the results when choosing this approach.

6.2.2.6 Balanced Criteria Weights

The individual criteria weights acquired through the previous tab are automatically filled out in the next tab with the balanced criteria weights at the position of stakeholder 1. The individual Excels can now be combined into one final document to calculate the balanced criteria weights. The users only have to copy-paste their (consistent) individual criteria weights into the corresponding row. The balanced criteria weights are automatically calculated by the tab. Depending on which preferences the users want to have balanced, different combinations can be made. The decisionmaker decides on which preferences needs to be balanced. The tool is currently limited to balancing criteria weights of 1 till a maximum of 5 stakeholders.

6.2.2.7 Renovation Scenarios

The developed renovation alternatives can be put into the renovation scenarios tab of the decision support tool (table 6.2.9). Per renovation alternative the correct renovation measures can be selected. When analysing the results of the TOPSIS ranking, this functions as a reference to what measures occur in which alternative.

	Criteria Weights														
	Environmental					Economic					Social				
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Stakeholder 1	28%	45%	6%	14%	7%	33%	7%	23%	14%	24%	6%	33%	20%	27%	15%
Stakeholder 2	3%	4%	40%	22%	31%	41%	2%	24%	13%	20%	51%	23%	2%	12%	12%
Stakeholder 3	14%	41%	8%	23%	14%	26%	9%	41%	13%	11%	26%	13%	12%	31%	18%
Stakeholder 4	22%	25%	23%	17%	13%	13%	11%	32%	18%	26%	43%	16%	21%	17%	3%
Stakeholder 5	5%	9%	15%	13%	58%	6%	14%	45%	7%	28%	39%	9%	13%	8%	31%
Balanced Criteria Weigths	14%	25%	18%	18%	25%	24%	9%	33%	13%	22%	33%	19%	14%	19%	16%
Final Balanced Criteria Weights	4,8%	8,2%	6,1%	6,0%	8,2%	7,9%	2,9%	11,0%	4,3%	7,3%	11,0%	6,3%	4,5%	6,3%	5,2%

Table 6.2.8 Balanced Criteria Weights Decision Support Tool

	Building Envelope							Building Installations									Other
	Insulation			Façade openings			Air tightness	Heat delivery system		Ventilation System				Additions			
	Roof insulation	Wall insulation	Floor insulation	Windows	Doors	Joints sealing		Underfloor heating	LT-radiators	Mechanical exhaust	Balanced ventilation	Heat recovery	CO2-driven	Radiator foil	Add-on radiator fan	Smart control	
A1	☐	☑	☐	☑	☐	☐	☑	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐
A2	☑	☑	☐	☑	☐	☐	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐
A3	☑	☐	☑	☐	☐	☐	☑	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐
A4	☐	☑	☑	☐	☐	☐	☑	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐
A5	☐	☑	☐	☑	☐	☐	☑	☑	☐	☑	☐	☐	☐	☐	☐	☐	☐
A6	☑	☑	☑	☑	☐	☐	☑	☐	☑	☑	☐	☐	☐	☐	☐	☐	☐

Table 6.2.9 Renovation Scenarios Overview Decision Support Tool

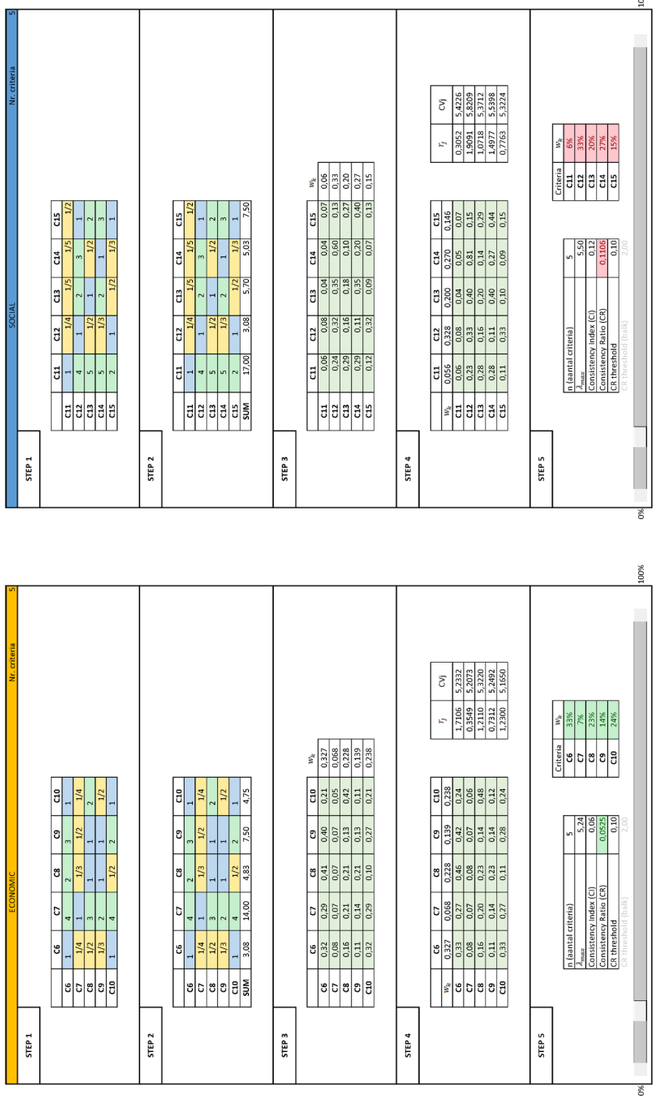


Table 6.2.6 Pairwise comparison matrices – individual criteria weights Decision Support Tool

n	Random Index (RI)
1	0,00
2	0,00
3	0,58
4	0,90
5	1,12
6	1,24
7	1,32
8	1,41
9	1,45
10	1,49

Table 6.2.7 Random index values & abbreviations for pairwise comparison matrices

	weighted sum value
w_k	criteria weights
CVj	Consitency Vector
CR	Consistency Ratio
CI	Consistency Index
RI	Random Index
r_j	

6.2.2.8 Quantification of Scenarios

Every renovation alternatives needs have a quantified performance value for every decision criterion. These values can be obtained by other tools, such as the LTH-grasshopper tool and the LCC and Energy Index tool. The users of the decision support tool need to manually filter LT-ready scenarios based on the simulation data and the benchmark performance of the LTH-grasshopper tool. If the users decided on additional benchmark values, for example a maximum of €4.500.000,- for the total investment costs, scenarios that exceeds those benchmarks have to be manually eliminated as well. The users should input the remaining renovation scenarios with their accompanying performance values into the quantification tab of the decision support tool, as the example in table 6.2.10 shows. The current decision support tool is limited to the comparison of exactly 6 alternatives for the decision analysis.

6.2.2.9 TOPSIS Decision Analysis

The performance values, the balanced criteria weights, and the beneficial direction of the values are directly linked to the decision analysis tab. The decision analysis is done according to the MCDM TOPSIS method. A numerical ranking is provided (table 6.2.11), as well as a graphical representation (figure 6.2.12). This tab present the results, the suggested optimal renovation alternative based on the performance incorporated with the stakeholders' preferences. No input is required from the users.

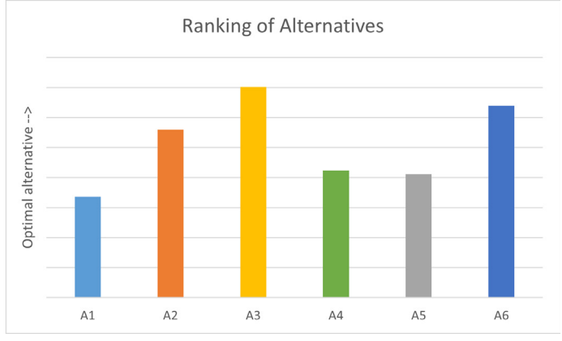


Figure 6.2.12 Weighted TOPSIS Ranking - Decision Support Tool

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
	Energy demand	Energy savings	Global warming potential	Renewable energy share	CO2 emission reduction	Total investment costs	Rent increment	Maintenance costs	NPV	Payback period	Thermal Comfort	Indoor air quality	Aesthetics	Renovation duration	Energy costs (bill)
	annual kWh/m^2	annual kWh/m^2	kg CO2/m^2	%	%	€	€/year	€	€	years	hours too cold	CO2 concentration	desireable = 5, undesireable = 1	days	€/year
A1	254	56	3502	12%	35%	€ 1.350.250	€ 40	€ 16.512,00	€ 145.621	23	765	1025	2	30	€ 250
A2	235	51	4652	16%	21%	€ 2.350.252	€ 51	€ 16.525,00	€ 135.852	11	265	856	5	45	€ 165
A3	105	52	1200	26%	19%	€ 3.546.982	€ 53	€ 21.352,00	€ 126.842	8	34	1862	2	28	€ 135
A4	198	42	1358	24%	26%	€ 1.685.492	€ 35	€ 20.215,00	€ 185.620	21	568	1568	5	48	€ 354
A5	137	60	5865	29%	31%	€ 3.198.756	€ 48	€ 18.635,00	€ 168.456	16	865	1358	4	19	€ 235
A6	97	45	2135	19%	18%	€ 4.001.256	€ 58	€ 19.520,00	€ 125.657	12	132	765	1	56	€ 189

Table 6.2.10 Quantification of Renovation Alternatives Decision Support Tool

Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1	254	56	3502	0,12	0,35	1350250	40	16512	145621	23	765	1025	2	30	250
A2	235	51	4652	0,16	0,21	2350252	51	16525	135852	11	265	856	5	45	165
A3	105	52	1200	0,26	0,19	3546982	53	21352	126842	8	34	1862	2	28	135
A4	198	42	1358	0,24	0,26	1685492	35	20215	185620	21	568	1568	5	48	354
A5	137	60	5865	0,29	0,31	3198756	48	18635	168456	16	865	1358	4	19	235
A6	97	45	2135	0,19	0,18	4001256	58	19520	125657	12	132	765	1	56	189
	445	126	8726	0,53	0,63	7000780	118	46245	366568	39	1321	3184	9	98	569

Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1	0,571	0,445	0,401	0,225	0,554	0,193	0,339	0,357	0,397	0,583	0,579	0,322	0,231	0,308	0,439
A2	0,528	0,405	0,533	0,299	0,333	0,336	0,433	0,357	0,371	0,279	0,201	0,269	0,577	0,461	0,290
A3	0,236	0,413	0,138	0,487	0,301	0,507	0,449	0,462	0,346	0,203	0,026	0,585	0,231	0,287	0,237
A4	0,445	0,334	0,156	0,449	0,412	0,241	0,297	0,437	0,506	0,533	0,430	0,492	0,577	0,492	0,622
A5	0,308	0,477	0,672	0,543	0,491	0,457	0,407	0,403	0,460	0,406	0,655	0,426	0,462	0,195	0,413
A6	0,218	0,358	0,245	0,356	0,285	0,572	0,492	0,422	0,343	0,304	0,100	0,240	0,115	0,574	0,332

Weighted Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Benefical value	Min	Max	Min	Max	Max	Min	Max	Min	Max	Min	Min	Min	Max	Min	Min
Criteria weights	12,6%	6,4%	3,7%	6,0%	4,7%	6,8%	2,9%	12,1%	4,3%	7,3%	11,0%	6,3%	4,5%	6,3%	5,2%
A1	0,072	0,029	0,015	0,013	0,026	0,013	0,010	0,043	0,017	0,042	0,064	0,020	0,010	0,019	0,023
A2	0,067	0,026	0,020	0,018	0,015	0,023	0,012	0,043	0,016	0,020	0,022	0,017	0,026	0,029	0,015
A3	0,030	0,027	0,005	0,029	0,014	0,034	0,013	0,056	0,015	0,015	0,003	0,037	0,010	0,018	0,012
A4	0,056	0,022	0,006	0,027	0,019	0,016	0,008	0,053	0,022	0,039	0,047	0,031	0,026	0,031	0,033
A5	0,039	0,031	0,025	0,032	0,023	0,031	0,012	0,049	0,020	0,029	0,072	0,027	0,021	0,012	0,022
A6	0,027	0,023	0,009	0,021	0,013	0,039	0,014	0,051	0,015	0,022	0,011	0,015	0,005	0,036	0,017
A+ (PIS)	0,027	0,031	0,005	0,032	0,026	0,013	0,014	0,043	0,022	0,015	0,003	0,015	0,026	0,012	0,012
A- (NIS)	0,072	0,022	0,025	0,013	0,013	0,039	0,008	0,056	0,015	0,042	0,072	0,037	0,005	0,036	0,033

Ranking

	Si+	Si-	Pi	RANK
A1	0,086	0,043	0,336	6
A2	0,054	0,068	0,560	3
A3	0,040	0,094	0,702	1
A4	0,068	0,050	0,423	4
A5	0,078	0,055	0,412	5
A6	0,048	0,085	0,639	2

1 =most optimal alternative
6 =worst alternative

Table 6.2.11 TOPSIS Decision Analysis - Decision Support Tool

6.2.3 Limitations of Decision Support Tool

The developed decision support tool is very much a concept tool, and has several limitations. The following limitations are identified:

1. The tool is currently limited to comparing 6 alternatives based on exactly 15 decision criteria, 5 in each sustainability category, while incorporating the preferences of 1 up until 5 stakeholders. Real-world decision-making problems are likely to have either less or more decision criteria, potentially unequally distributed among the three categories. It is also likely to have either more or less renovation alternatives, and more than 5 stakeholders whose preferences requires balancing. Allowing for this flexibility would highly improve the usability of the tool.

2. The tool uses the TOPSIS and pairwise comparison method, known limitations of those methods also apply to this tool. For example, the pairwise comparison requires a level of consistency, which depends on the subjective judgements of the stakeholders. Using criteria weights with a higher than desirable consistency ratio could lead to an unreliable ranking of alternatives. Just like a significant deviation of performance values in a single criterion can lead to out of proportion ranking results in the TOPSIS method.

3. A human error can be easily made when determining if a high or low performance value is beneficial. This simple mistake has a very significant impact on the ranking of the alternatives, since the TOPSIS method is based on a positive and negative ideal solution.

4. The TOPSIS method is developed to process mainly quantitative data. If the users of the framework want to incorporate many qualitative criteria, a fuzzy TOPSIS would be a better match for the decision analysis calculation, something that the current tool does not allow for.

6.2.4 Suggested Improvements – Future Development

To improve the decision support tool, several optimizations can be made. The interface could be made more user-friendly and intuitive. Incorporating more visual representations of the performance of the alternatives will help the users in better understanding the results of the tool. Another optimization suggestion is to add a filter that automatically eliminates renovation alternatives from the comparison when their performance values exceed set benchmarks, streamlining the current manual elimination process. In addition to that, allowing the users to scale the number of decision criteria and renovation alternatives will make the tool more flexible and widely applicable. Enabling the inclusion of more stakeholders and their preferences also contributes to this flexibility and applicability. Implementing these improvements will enhance the functionality and usability of the decision support tool, making it more effective for users who aim to renovate their buildings to enable low-temperature heating.

VALIDATION

7. VALIDATION

Validation of LTH-DS Framework & Tool

7.1 Objective

The decision support framework and tool as presented in the previous chapter is based on literature research. The framework aims to guide stakeholders in selecting suitable renovation alternatives to enable LTH. It is important to validate the developed products to establish credibility and reliability. Both stakeholders (target audience) as other researchers need to be able to trust that the framework is based on sound principles and can consistently deliver accurate and useful results. Another important reason for validation is ensuring the practical relevance and usability of the framework. A framework that is theoretically sound but impractical to use is less valuable. Testing the framework on how well it can represent a real-world scenario ensures its relevance. Validation also provides essential feedback which can help refine and improve the framework and tool. In short, the framework needs validation on its decision-support function, how well it represents a real-world scenario and its usability.

7.2 Case Study

7.2.1 Case study requirements

A case study is required to perform the validation, to gain insight into the performance of the framework in the real world. When searching for a case study the following characteristics are deemed important:

1. The case study has to represent a significant part of the Dutch building stock, so that the framework and tool can be applied to a large number of buildings for future use.
2. The case study should have a worse enough energy performance that switching to LTH requires multiple renovation measures, so that multiple renovation alternatives can be compared.

An analysis of the current Dutch building stock, which can be found in Appendix A, shows that terraced houses are the most common building type. However, selecting a different building type would contribute to the expansion of LTH-renovation research, since terraced housing already has been researched to some extend in the context of LTH-renovations. Based on the findings of Appendix A, it is safe to state that (in general) buildings built before 1991 have a worse enough energy performance to require multiple renovation measures when switching to LTH. Multiple stakeholder involvement is most likely to occur in multi-family buildings. Those multi-family buildings are also more likely for LTDH to become feasible due to the urban density (see chapter 2.1.3). Besides that, renovating a multi-family complex prepares multiple homes at once for the energy transition, contributing to the acceleration of the energy transition.

Due to these reasons, the case study is narrowed down to a multi-family building like *gallerijwoning, portiekwoning* or apartment building built before 1991. Additional case study requirements are defined to validate the framework and tool on its decision-support function:

1. Relevant building data needs to be available to calculate a benchmark performance as well as calculating the performance of the renovation alternatives. Appendix B provides an overview of data requirements.
2. The case study has to involve multiple stakeholders, so that the tool can be tested on its functionality of balancing stakeholders' preferences. The stakeholders need to participate in a workshop to test if the framework represents the real-world decision-making process sufficiently as well as providing decision-support for selecting a renovation scenario.

7.2.2 Case study description

The case study was acquired by reaching out to an energy transition company that focusses on residential energy renovations. Stakeholders involved in this case study or similar projects were willing to participate in the workshop for the validation. This company provided the information as per appendix B, as well as additional documents on their decision-making process. This included information on the technical inspection documents (building photo's, floorplans, installations, VABI-data), social inquires (occupants complaints/whishes) and financial quotes of the renovation measures. This data was summarized by them in the *projectplan* document, containing a description of the existing building context, a scenario analysis and a plan of approach for the preferred scenario. The building context part provides information on location, technical properties, energy performance, maintenance plan, fire safety, asbestos, flora & fauna and a social aspect description. The scenario analysis part elaborates on the renovation measures of 4 different scenario's, the quantification of scenario's performance, and the advice on and argumentation for selecting a certain scenario, including trade-offs. Based on that a scenario preference is identified, as well as a second best option in case of technical feasibility issues in the preferred one. The plan of approach contains a risk analysis, describes technical, economic and social recommendations for implementation and provides a planning. The information from the *projectplan* document formed the basis of the case study application.

7.2.2.1 Building context

The complex is built in 1979-1980 and is located near the coastal area of the Dutch province Noord-Holland, and is surrounded by a wooded area. The complex consists of 99 one-bedroom apartments and 9 two-bedroom apartments. The apartments are accessible via stairwells and elevators located at various points within the building sections, and can be reached through a radiator heated indoor gallery with single glazing that borders the outside, as well as internal corridors. The complex ranges from two to four stories. The residential complex features a recreation room, a guest apartment for residents' visitors, and a bicycle storage room. The complex residents are seniors who can request care services at home. A resident consultant is available on-site as a contact point for the residents. The complex is owned by a social housing association and all apartments are rented out in accordance with social rental prices. The technical room is located at ground level, situated northwest against the building.

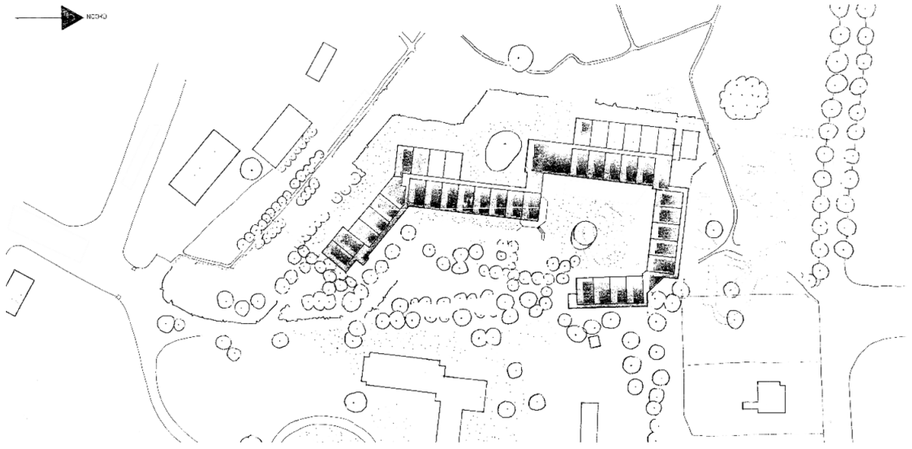


Figure 7.2.1 Building complex situation plan

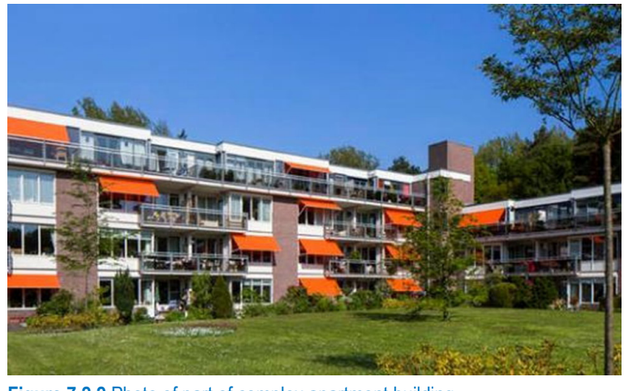
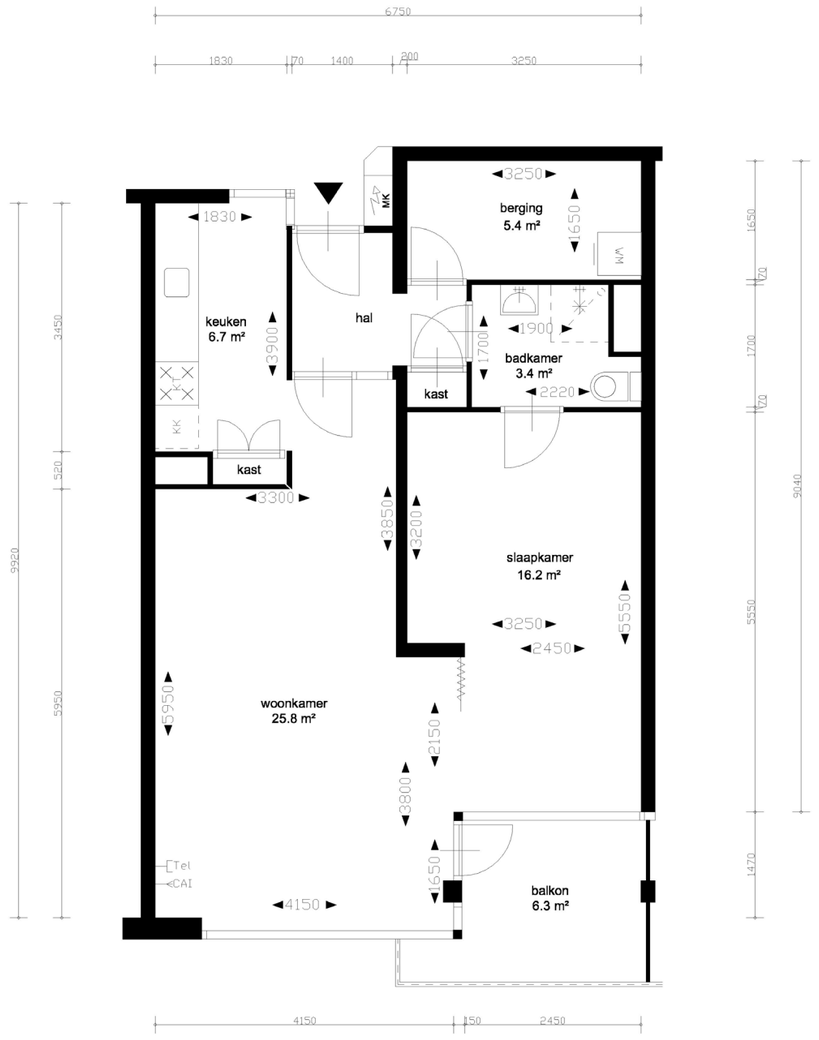


Figure 7.2.2 Photo of part of complex apartment building

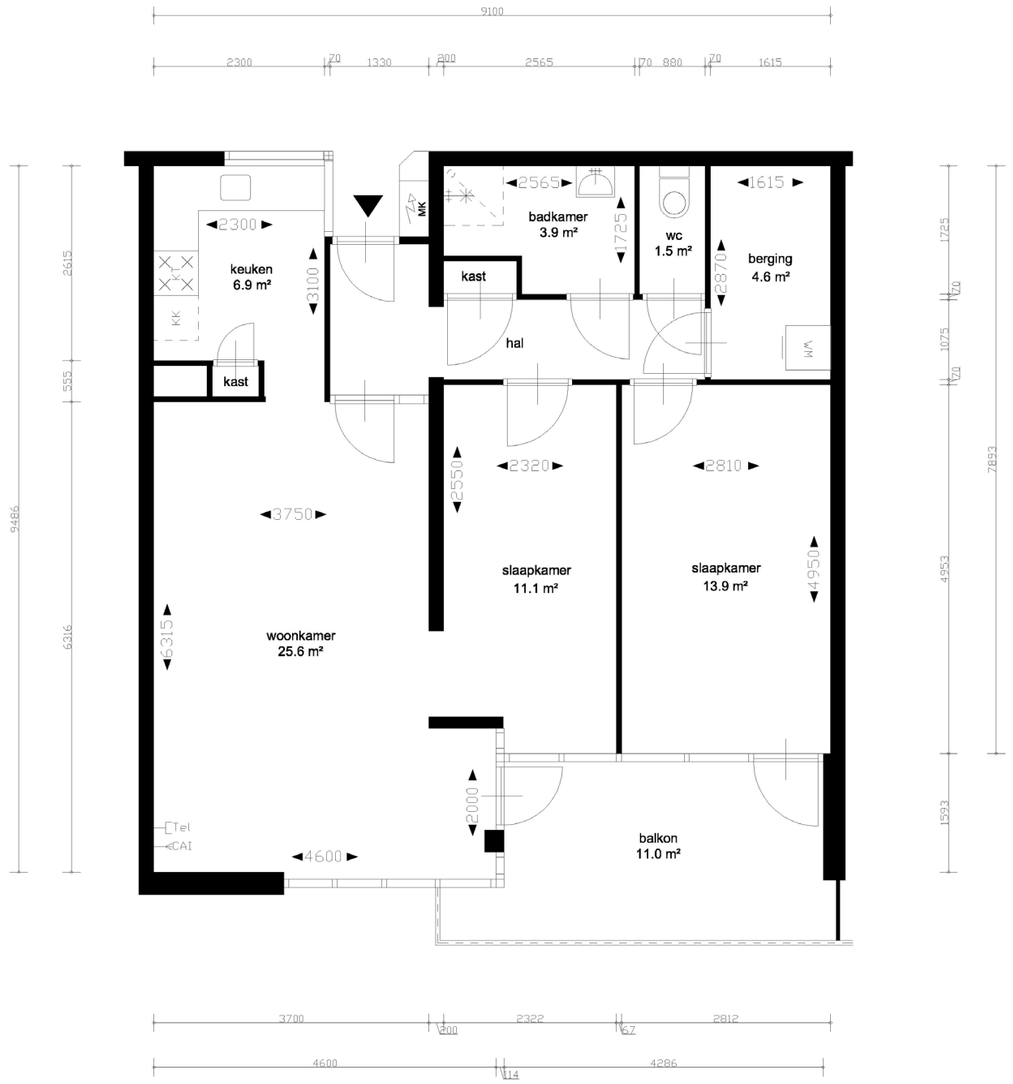
7.2.2.2 Floorplans

The 99 one-bedroom apartments all have an identical floorplan, except for a difference in balcony size. The floorplan with the balcony only in the corner instead of over the full width of the apartment is shown in figure 7.2.3. The floorplan of the 9 two-bedroom apartments are all identical and is shown in figure 7.2.4.



Woonoppervlakte = 62.9 m²

Figure 7.2.3 Floorplan one-bedroom apartment



Woonoppervlakte = 76.34 m²

Figure 7.2.4 Floorplan two-bedroom apartment

7.2.2.3 Technical properties

The following description of the technical properties of the building is based on the original situation before the building was energetically renovated in 2021.

Building envelope

The rear and side facades of the apartment consist of an inner cavity wall with a 6 cm cavity filled with 4 cm of mineral wool. The rear facades of the apartments (balcony side) consist of wooden window frames with parapet panels and glazing. In 2007, the glazing was replaced with HR++ glazing. The panels have a wooden plate on the inside, wooden cladding on the outside. In between is about 6 cm of rock wool insulation, with a cavity of about 1.5 cm. The apartment complex has flat concrete roofs everywhere, with 4 cm PUR-like insulation, on which a mixture of cement and EPS granules has been applied for slope. The ground floors consist of Dato system floors. No insulation is shown on the drawings. Under the ground floor apartments is a crawl space with a minimum height of 55 cm according to the construction drawings, accessible via the traffic areas.

Building installations

Duco vents are present in the window frames. On the ground floor on the north side, outside the thermal envelope, is the boiler room. The complex is heated by a collective system (*blokverwarming*). Heat is provided by HR-100 boilers from 1997. Domestic hot water is prepared by an indirectly fired system with HR107 boilers. In 2019, one of these boilers was replaced by a Remeha Quinta 60 kW. The radiators in the apartments are equipped with Techem heat meters (evaporation) for individual billing. In 2009 a central, mechanical exhaust, time-driven ventilation system was installed. Valves for mechanical exhaust are located in the kitchen, bathroom, storage room, and toilet.

Energy performance

The company who provided the case study did an Energy-Index calculation in 2020 for the pre-renovated building. For the EI-calculations six apartment positions were simulated: corner-roof, corner-intermediate, corner-ground, intermediate-roof, intermediate-intermediate, intermediate-ground. They found an average simulated EI value of 1,70, resulting in energy label C.

Social characteristics

The complex is a social housing complex. As explained in Chapter 5.1, at least 70% of the tenants need to agree with the renovation plans in order for the housing association to be allowed to carry it out. Obtaining this support (*draagvlak*) can be quite a challenge. Incorporating renovation elements that solve complaints or contribute to the residents' wishes can be beneficial to obtain this support, even when those measures have only a very small impact on improving the energy performance. The residents' complaints and wishes are provided in table 7.2.1. There is no resistance for the renovation plan expected as long as the housing costs decrease and the indoor comfort increases.

Residents' wishes	Residents' complaints
Swap TL-lights for LED lights in corridor	Cracks in front doors, draft from balcony door (airtightness)
Add motion sensors for lighting in communal spaces	Sewage smell when mechanical ventilation system is activated
Replace single glazing corridors with double glazing	Apartments at the north side are underheated during winter (lack of capacity)
Ability to switch off heating in communal spaces during hot summer days	Wall panels are insufficiently insulated, cold radiation from walls
Solar panels	The boiler does not switch on when the weather changes from warm to colder weather

Table 7.2.1 Residents' wishes and complaints, taken from Projectplan

7.2.2.4 Renovation Scenarios

The energy renovation company developed and compared four renovation scenario's that were taken into consideration for the decision. Table 7.2.2 shows the *scenario table* from the *projectplan*, which contains a description of the renovation scenario's with performance values. Scenario 0 is the original scenario, it forms the base for comparison. Scenario 1 consist of cavity and panel insulation, improving the airtightness and replacing the collective boilers. Scenario 2 consist of the same measures as scenario 1, but also applies roof insulation and places 4 PV panels per apartment unit. The renovation measures from Scenario 3 consist of insulating cavity, panels and roof and the placement of collective heat pumps (air-water) and 4 PV panels per apartment unit. Scenario 4 consists of the same measures as Scenario 3, but adds PVT panels with a solar boiler system. It is relevant to mention that Scenario 1 and Scenario 2 continue to rely on a HTH system, and only Scenario 3 and 4 switch to a LTH system by heat pump. The advise from the *projectplan* suggested Scenario 4 to be the best renovation solution.

Scenario's		Scenario 0		Scenario 1		Scenario 2		Scenario 3		Scenario 4	
Maatregelen		Afmelden na validatie		Het isoleren van spouwmuren, panelen, kierdichting en ketel vervangen		Het isoleren van spouwmuren, panelen, kierdichting, dakisolatie aanbrengen, ketel vervangen en plaatsen van 4 pv panelen		Het isoleren van spouwmuren, panelen, kierdichting, dakisolatie aanbrengen, warmtepomp lucht water en plaatsen van 4 pv panelen		Het isoleren van spouwmuren, panelen, kierdichting, dakisolatie aanbrengen, warmtepomp lucht water plus pvt met zonneboiler systeemen plaatsen van 4 pv panelen	
Type:	Omschrijving type:	Label	EI	Label	EI	Label	EI	Label	EI	Label	EI
A	Hoekwoning, onder dak	D	1,81	C	1,43	A	0,98	A	0,81	A++	0,6
B	Hoekwoning, tussenverdieping	C	1,71	B	1,29	A	0,99	A	0,84	A++	0,6
C	Hoekwoning, onderste woonlaag	C	1,78	B	1,38	A	1,12	A	0,9	A+	0,68
D	Tussenwoning, onder dak	D	1,87	C	1,47	A	0,98	A	0,82	A++	0,59
E	Tussenwoning, tussenverdieping	C	1,63	B	1,27	A	0,93	A	0,82	A++	0,56
F	Tussenwoning, onderste woonlaag	C	1,59	B	1,25	A	0,96	A	0,81	A++	0,58
Label	Gemiddelde EI	C	1,70	B	1,33	A	0,97	A	0,82	A++	0,58
Het Projectplan:											
Totaal investering incl. btw, excl. subsidie		**€ 135.388**		**€ 3.047.864**		**€ 3.842.163**		**€ 4.104.648**		**€ 4.413.787**	
Aantal woningen		108		108		108		108		108	
Aantal labelstappen		9		82		225		225		436	
Aantal labelstappen per woning		0,1		0,8		2,1		2,1		4,0	
Benodigde budgetten:											
Totaal investering incl. btw, excl. subsidie		€ 135.388		€ 3.047.864		€ 3.842.163		€ 4.104.648		€ 4.413.787	
Planmatig onderhoud (PO) incl. asbest sanering		€ -		€ 1.192.710		€ 1.192.710		€ 1.192.710		€ 1.192.710	
Aanvullende duurzaamheidsingrepen (AD)		€ -		€ 650.703		€ 650.703		€ 650.703		€ 650.703	
Energetische maatregelen		€ 135.388		€ 1.204.450		€ 1.998.750		€ 2.261.235		€ 2.570.374	
Kengetallen											
Totaal investering per woning		€ 1.254		€ 28.221		€ 35.576		€ 38.006		€ 40.868	
PO, asbest en BI per woning		€ -		€ 17.069		€ 17.069		€ 17.069		€ 17.069	
Energetisch per woning		€ 1.254		€ 11.152		€ 18.507		€ 20.937		€ 23.800	
Energetisch per labelstap (benchmark 7.000)						**€ 8.883**		**€ 10.050**		**€ 5.895**	
Subsidie mogelijkheden											
Energetische maatregelen				€ 1.204.450		€ 1.998.750		€ 2.261.235		€ 2.570.374	
Subsidie				€ -		€ -		€ 84.007		€ 324.000	
Totaal energetisch minus subsidie				€ 1.204.450		€ 1.998.750		€ 2.177.228		€ 2.246.374	
Energetisch minus subsidie per labelstap				€ 14.688		€ 8.883		€ 9.677		€ 5.152	
Risico's:	*0 = geen, 1 = zeer klein, 5 = zeer groot*										
Omgevingsvergunning		0		0		0		0		0	
Wet Natuurbescherming		0		3		3		3		3	
Draagvlak		0		3		2		3		1	
Asbest		0		2		2		2		2	
Gevolgen bewoners:	*0 = geen, 1 = minimaal, 5 = veel*										
Overlast door werkzaamheden		0		1		1		1		1	
Toelichting werkzaamheden in de woning		n.v.t.		Kierdichting zal vanuit binnen gedaan worden		Kierdichting zal vanuit binnen gedaan worden		Kierdichting zal vanuit binnen gedaan worden		Kierdichting zal vanuit binnen gedaan worden	
Comfort verbetering	*0 = hoog, 1= goed, 5 = geen verbetering*	5		2		2		2		2	
Profijt woonlasten		5		3		1		1		1	
Toelichting woonlasten		n.v.t.		Mogelijk weinig effect omdat de ketel een lager rendement heeft dan nieuwe opties niet worden gedaan.		Gehele schil geisoleerd. Lasten minder. Eigen opwekking pv-panelen		Gehele schil geisoleerd. Lasten minder door warmtepomp. Eigen opwekking pv-panelen		Gehele schil geisoleerd. Lasten minder door PVT en warmtepomp+ zonneboiler Eigen pv-panelen.	

Table 7.2.2 Scenariotabel, taken from Projectplan

7.3 Validation Method

This study proposes a workshop approach to validate the framework with stakeholder participation. According to Storvang et al. (2017), workshops are effective in exploring a shared topic through interactive, participatory environments and can validate data from other sources, such as individual interviews. This study adopts the general approach for organising a participatory workshop as presented by Storvang et al. (2017), which includes four phases: diagnosis, planning, facilitation, and analysis (figure 7.3.1). Table 7.3.1 provides a description of each phase.

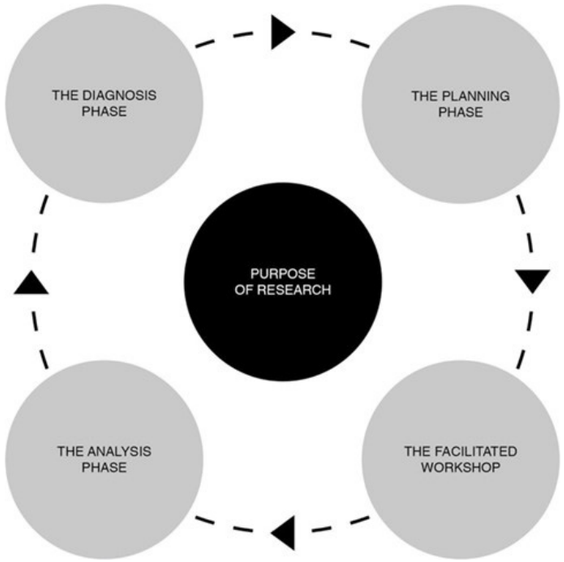


Figure 7.3.1 A framework to diagnose, plan, facilitate and analyze workshops. Taken from *Collaborative Research Design* (p.161), by Storvang et al., 2017.

7.3.1 Diagnosis

7.3.1.1 Purpose of the workshop

Validating the decision-support framework is an essential part of its development, specifically determining which aspects require validation. According to Gass (1983) and Borenstein (1998), the process of validating a Decision Support System (DSS) involves verifying whether the DSS accurately reflects the real world in the particular problem area it is designed for. Gass (1983) described another validation aspect involving comparing real-world data with model-generated data. In that respect, Lu et al., 2021 developed a decision-making framework for existing buildings based on cost-benefit analysis and energy simulation, which was validated for its application but recommended to be validated further for its practical use. It can be difficult to validate decision models that are novel in nature. For that, Gass (1983) proposed that decision models without any precedence can be validated by expert evaluation of the credibility of the process.

Consequently, the main purpose of the workshop is to validate the usefulness of the framework in supporting the selection of renovation solutions that prepare the dwelling for LTH. The study argues that usefulness can be defined as simple as whether the theoretical framework can be applied in practice. As a result, the framework is considered validated when the stakeholders consider it to be usable in supporting the selection of renovations to make their dwelling ready for LTH.

Phase	Description
Diagnosis	Determine the purpose of the workshop and identify the relevant participants.
Planning	Planning the content, exercises or boundary objects relevant to achieving the purpose of the workshop.
Facilitation	Facilitating the workshop to gather information through a collaborative process among stakeholders and facilitators/researchers.
Analysis	The final phase corresponds to analysing the collected data to identify patterns relevant to achieving the workshop's purpose.

Table 7.3.1 Storvangs' workshop phases

7.3.1.2 Stakeholder identification

Through literature studies, categories of stakeholders are identified that are generally involved with local heat transition, including energy renovation projects. Some are decision-makers, some are influencers, while others are authorizers or implementers. Chapter 5.1, table 5.1.1 illustrates common stakeholders in energy renovations along with their role description and expected influence on the decision-making process.

For the purpose of the workshop, it is essential to have individuals who have played a significant role in the decision-making process of renovating the chosen case study. This includes stakeholders who have influenced different aspects, such as:

- Social factors, such as representing tenants' interests (e.g., reducing housing costs, limiting rent increases, and enhancing thermal comfort).
- Economic factors, such as budget management (e.g., determining the investment budget size, desired payback period, future maintenance costs, and available subsidies).
- Environmental and sustainability considerations (e.g., improving energy efficiency labels, reducing heat demand, saving gas, cutting CO_2 emissions, and increasing the share of renewable energy).

There were 4 expert stakeholders present during the workshop. Chapter 7.3.4 Analysis, stakeholders' role elaborates on the specific roles and influence on the decision-making process.

7.3.2 Planning

To achieve the purpose of the workshop, the workshops' content is planned, as well as identification of workshops' preparations. The purpose of the workshop is to validate the framework on its usability. The workshop consists of three main components:

1. **Presentation.** A demonstration of the framework and tool by applying it to a case study. This involves a walkthrough of the frameworks' steps as well as explaining the method of the tool, showing how it works when applied to a real-world scenario.
2. **Exercise.** The participants conduct a pairwise comparison to establish criteria weights for various decision criteria. These weights are then used in a TOPSIS decision matrix to rank the renovation alternatives based on their performance and obtained preferences.
3. **Semi-structured interviews.** A semi-structured group interview is conducted with expert stakeholders, supported by a short questionnaire. A mix of open and ranking questions are presented to evaluate the frameworks' decision support function in selecting a LTH renovation scenario. Participants are also asked about suggestions for improvement of the framework.

The validation of the usability of the framework is approached in two ways. The first approach is a comparative analysis: the case study consists of real-world data and results, which are compared to data and results produced by the framework while assuming similar conditions to assess the accuracy and relevance. The second approach is stakeholder feedback: stakeholders utilized the decision support tool (pairwise comparison) to obtain criteria weights reflecting their preferences of the decision criteria, as well as providing feedback on its usability. The results from the pairwise comparison are discussed with the stakeholders to understand how effectively the tool represents and balances their preferences.

To ensure a smooth workshop, preparations are required. Some preparations can be considered boundary objects. Boundary objects are an essential part of the facilitating workshop as they help in the dialogue between the different stakeholders. As per Storvang et al. (2017), boundary objects could be drawings, models, prototypes, computer animations or any artefact that can initiate dialogue among the stakeholders. Additionally, boundary objects are designed to cater for the purpose of the workshop can help the stakeholders to utilise their tacit knowledge, which otherwise is difficult to tap. The following preparations are taken:

1. **Informed consent.** Working with people as test subjects to obtain results requires permission from the Human Resources Ethics Committee (HREC) of the TU Delft. Permission was granted. An informed consent document was prepared and signed by all participants of the workshop beforehand. For safety reasons all collected data is stored at an secured TU Delft drive which is only accessible to the involved researchers (P. Wahi and V.I. Koster).
2. **Venue.** The venue needs to be a neutral place where the facilitation can happen. In this case, the venue was an office where the stakeholders of the case study project regularly met.
3. **Dutch language.** Due to the natural work environment of the participants, the workshop is prepared and given in Dutch.
4. **Interview protocol.** Qualitative & quantitative questions are developed to obtains results for validation of the frameworks' function. Table 7.3.2 illustrates the validation aspects and intent, leading to the validation questions and boundaries objects.
5. **Decision support tool**. A decision support tool was developed in advance and tailored to the case study to facilitate the exercise part of the workshop. The main focus for the tool was on being able to obtain criteria weights based on balanced preferences of the participants, as well as an automatic ranking based on those criteria weights and performance values. The tool is elaborated upon in Chapter 6.2.
6. **Case study application preparations.** To illustrate the framework and tool applied to the case study, preparations need to be made like designing additional renovation scenario's, quantifying alternatives performance by benchmarking the original energy and thermal performance, simulating the new performance values, and calculating costs. This case study application is elaborated in Chapter 7.3.3.
7. **Presentation.** A presentation was made to explain the framework and tool applied to the case study, as well as presenting the questions and results of the tool. The (Dutch) presentation slides can be found in appendix C.
8. **Paper backups.** To guarantee a smooth workshop flow, essential workshop preparations were printed out, like presentation slides, paper questionnaires and paper pairwise comparison sheets.

The participants of the workshop had a limited (and unclear) time availability for the workshop. Therefore a workshop time planning was made, shown in table 7.3.3. The workshop is prepared in a way that allows for some flexibility. However, the minimum required time was considered 60 minutes, the maximum required time 120 minutes.

	Validation Asepct	Intent	Questions	Boundary objects
A1	**Role of stakeholders in the decision-makign process**	Capture the role, when are they involved, what is required for making decisions	1. Can you describe your role in the process of selecting renovations? 2. When are you involved in the decision-making process? 3. What key information do you need to make informed decision about choosing a scenarios ?	Presentation introducing the general framework. A3 with a typical framework where the stakeholder can mark
A2	**Usability of the framework**			
A2.1	Representation of real-world problem	Capturing if the framework could represent the real-world (case study) and provide acceptable insights.	4. Does the framework represent the decision-making process you followed for the case study to a reasonable accuracy? 5. How thorough did you find the application of the case study to the framework?	Application of the case study Questionnaire with ranking statements
A2.2	Incorporation of stakeholder's preference	Capturing if the framework could support the incorporation of stakeholder's preferences	6. How do you typically consider stakeholder preferences during the renovation process? 7. How effectively does the tool allow you to express your preferences for renovations? 8. To what extent do you agree or disagree with the solutions proposed after incorporating the preferences?	Excel tool for criteria weighting and ranking scenario's Questionnaire with ranking statement
A2.3	Effectiveness in supporting decisions	Capturing if the framework is effective for supporting decisions in the process	9. How effective do you find the framework in facilitating the decision-making process for renovations?	
A3	**Further development of the framework**	Capturing the shortcomings of the framework and ideas for improvement.	10. Can you use this framework in your next project for supporting decisions? Why and Why not? 11. What changes do you suggest so that you would use it for your next project?	

Table 7.3.2 Validation aspects, intent, questions and boundary objects.

Activity	Time	Description
Introduction	5 min	A round of introduction and workshop objectives
A1: role of stakeholders	15 mins	Ask about the role Present simplified decision support framework based on MCDM Ask them to mark when and where they are involved in the process Ask about the key information they need
A 2.1: Representation of real-world problem	20 mins	Present application of the case Ask about representation and application of the framework on the case
A 2.2 Stakeholder preference	20 mins	Ask how they incorporate preferences Present the pairwise method. Ask them to use the Excel tool to give their preference. Ask them about the process (while collating and finding new solutions) Ask them about the new solution after preferences.
A 2.3 Effectiveness in supporting decision	10 mins	Ask about the effectiveness of the framework in supporting decisions.
A3 Further development	20 mins	Ask about what worked, and what did not work for them Ask about how to improve.
Reflection and closing	10 mins	Reflection on the content and organisation Final remarks and closing
	100 mins	

Table 7.3.3 Time planning workshop

7.3.3 Facilitation - Case Study Application/ Workshop preparations

The LTH decision support framework as presented in chapter 6.1 is simplified and translated to Dutch, to present the objective of the framework in a concise manner to the participants of the workshop. This simplified framework is shown in figure 7.3.2. The following subchapters (7.3.3.1-6) elaborate on the case study application preparations taken for the workshop. Framework step 3 and step 6 (&7) requires additional input from the participants during the workshop to complete, while the other steps are determined in advance based on the provided case study documentations.

7.3.3.1 Identification & Analysis

In preparation of benchmarking the heating demand and thermal discomfort of the complex, all available case study documents were reviewed. The data required to calculate both the heating demand and thermal discomfort was extracted. The provided documents contained VABI-data for the heating demand, which is used as reference and to calibrate the LTH-grasshopper model. This calibration ensures that when new renovation alternatives are simulated, the calculated heating demand are within reasonable expectance of what existing in-depth dynamic simulation software would output, while saving on time-consuming modelling. The LTH model also quantifies thermal (dis)comfort, something that existing energy simulation software lacks, and is essential for the LT-ready filter and comparison of performance on thermal comfort of renovation alternatives for the decision analysis.

The LTH-grasshopper tool uses a standard setpoint temperature of 20 °C. However, since the case study is an apartment building for elderly people, the LTH-grasshopper tool is adapted to a setpoint temperature of 21 °C. Table 7.3.4 shows the data input for the LTH-grasshopper simulation tool, extracted from the provided documents.

The case study provided BENG2 data (kWh/m^2 per year) for every 108 apartments. The 108 apartments are divided into six unique apartment positions (figure 6.1.2): 1. intermediate-intermediate (34), 2. corner-intermediate (4), 3. intermediate-ground (27), 4. intermediate roof (31), 5. corner-ground (5) and 6. corner-roof (7). The position of the apartment influences the compactness ratio, which is calculated by dividing the exterior surface are of the apartment (heat loss area A_{ls}) with the floor surface

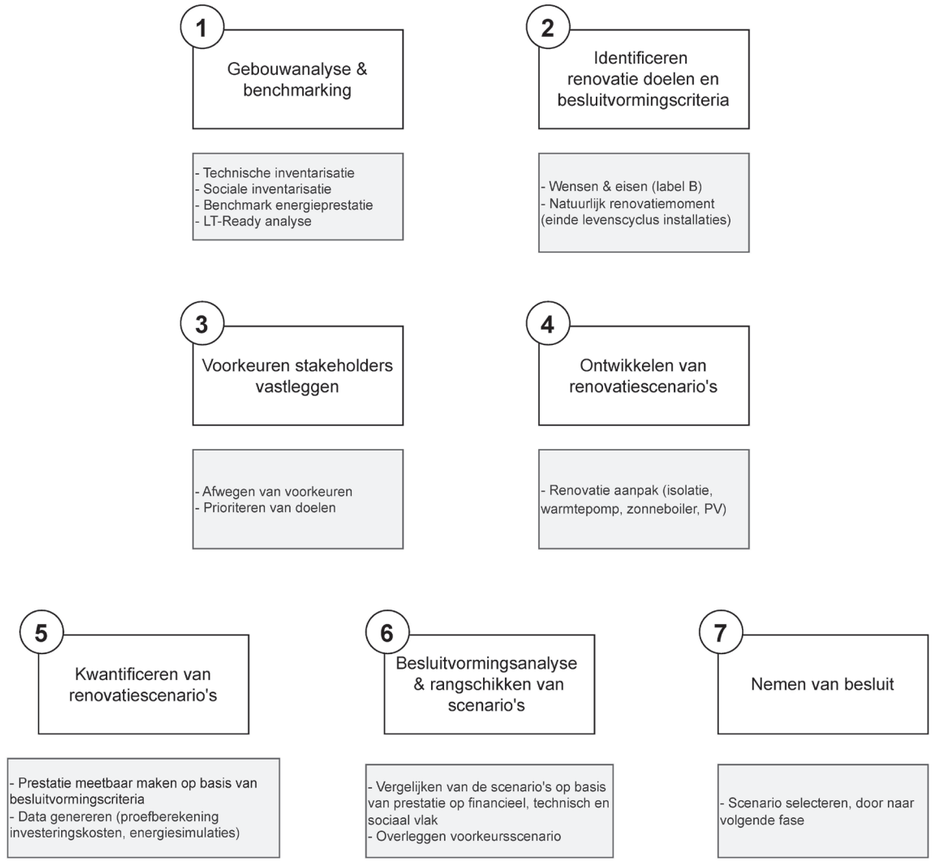


Figure 7.3.2 Simplified decision support framework for LTH renovations

area of the apartment (A_g). To ensure reasonable accuracy of simulation results from the LTH-grasshopper tool, the tool was calibrated to perform in a similar manner as the original energy performance data that was made available. To limit the amount of simulations necessary, some simplifications are made. Firstly, the 9 two-bedroom apartments are excluded from simulations. Secondly, it is assumed that the floorplans of all 99 one-bedroom apartments are identical, excluding the difference in balcony size and thereby variances in shading with a potential influence on the heating demand. Thirdly, only the three most common orientations are included in the simulations, which are the apartment orientations with the balconies facing East, North-East and South-East (figure 7.2.1). Fourthly, the unequal distribution in apartment positions (higher number of intermediate units compared to corner units) is assumed to be equally distributed. The averaged apartment values are therefore likely to be worse performing than if the distribution variance was incorporated. Fifthly, the floorplan in Rhino is simplified to be made compatible with the grasshopper script. The model neglects interior wall thickness, leading to a slightly higher surface area of the apartment (67,5 m^2) compared to the provided floorplan (62,9 m^2).

These simplification reduces the required simulations from 108 samples to 18 samples (assumption of 3 unique orientations and 6 unique apartment positions, 3*6=18). Table 7.3.5 shows the provided data on heating demand, energy-index (EI), energy label and surface area from the case study for every unique apartment position, based on a HT supply. Next to the original case study data is the simulated data from the LTH tool for every unique apartment position, also based on HT supply. Table 7.3.6 shows the performance for an average apartment.

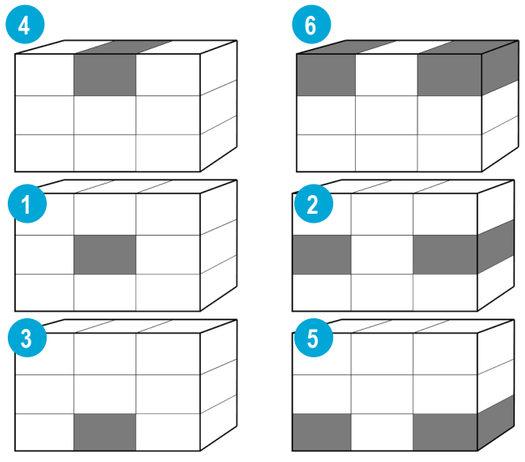


Figure 6.1.2 Six unique positions for multi-family buildings

	Heating demand (kWh/m^2)	EI	Label	Surface area
Case study average 108 units	212,53	1,68	C	67,34
Case study average 6 positions	227,49	1,76	C	68,63
LTH-grasshopper average 6 positions	206,88	1,66	C	67,50

Table 7.3.6 Benchmark: case study energy performance data compared to LTH-tool energy performance data for average apartment

Sample Number	Construction Year	Orientation	Compactness Ratio	Position	Window to Wall Ratio	Rc Ground Floor	Rc Wall	Rc Roof	U-value Window	U-value Door	Infiltration	Ventilation type	Temperature setpoint
1	1976-1991	270	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
2	1976-1991	270	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
3	1976-1991	270	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
4	1976-1991	270	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
5	1976-1991	270	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
6	1976-1991	270	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
7	1976-1991	280	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
8	1976-1991	280	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
9	1976-1991	280	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
10	1976-1991	280	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
11	1976-1991	280	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
12	1976-1991	280	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
13	1976-1991	350	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
14	1976-1991	350	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
15	1976-1991	350	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
16	1976-1991	350	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
17	1976-1991	350	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21
18	1976-1991	350	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21

Table 7.3.4 Data input for benchmark LTH-grasshopper tool. [ventilation type 3 = C1, mechanical exhaust]

After benchmarking the complex, it is important to do an LT-ready analysis to determine if renovation measures are necessary. The LT-ready definition can be found in Chapter 2.3.4. The LT-ready analysis consists of the following steps utilizing the LTH-grasshopper tool:

1. Benchmark original HT situation for heating demand (kWh/m^2) and thermal discomfort (hours too cold) for average apartment.
2. Simulate under same conditions, except lowering the HT setpoint to LT setpoint, to calculate LT heating demand and LT thermal discomfort for the pre-renovation situation.
3. Determine if original complex is LT-Ready or not. If heating demand pre-renovated HT situation ≥ heating demand pre-renovated LT situation AND thermal discomfort pre-renovated HT situation ≥ thermal discomfort pre-renovated LT situation, no renovation measures are required. The temperature can be lowered to LTH without additional measures. If one or both pre-renovated LT situation values are higher than the pre-renovated HT situation, renovation measures are required and the framework can be continued.

Building analysis

A natural renovation moment is mentioned for replacing the collective boilers, since they've reached the end of their lifespan. The *projectplan* also mentions that the façade panels are in bad condition.

7.3.3.2 Renovation objectives & criteria

In order to tailor the decision support tool to the case study, decision parameters are extracted from the projectplan and compared to the identified decision parameters in literature (Chapter 4.1). The identified decision parameters from the projectplan were complemented with the decision parameters from literature, which are marked with an *. Table 7.3.7 and figure 7.3.3 illustrate the tailored decision parameters.

The *projectplan* states one clear main objective in their 'scenario analyse' chapter, which is to energetically improve the building complex of 108 apartment units from energy label C (93x) and D (15x) to at least label B. This is represented in table 7.3.7 by O1 and C2. This energy label B should be achieved on average, the objective is not to achieve label B for every individual dwelling.

When reviewing the *projectplan*, additional decision objectives and criteria can be found, although not mentioned as explicitly as the first objective.

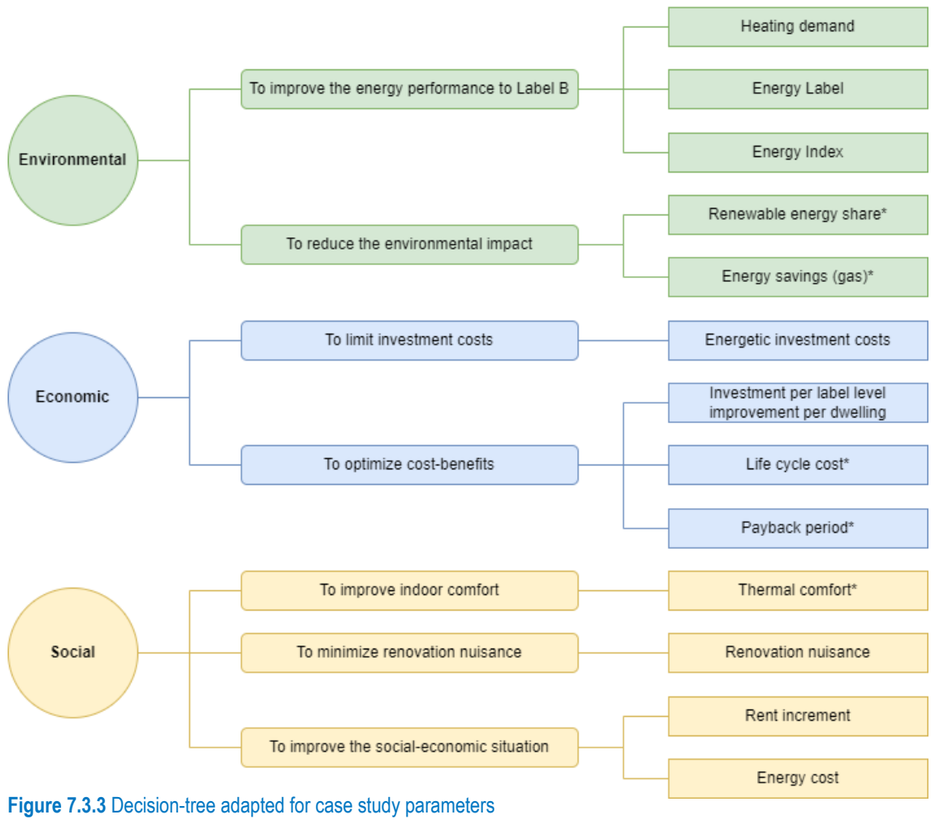


Figure 7.3.3 Decision-tree adapted for case study parameters

Categorie (duurzaam)		Doelen case study		Kwantificering	Benchmark	Is de optimale waarde de min of max waarde?
S1	Milieu	O1	Appartementencomplex energetisch verbeteren naar energielabel B	kWh/m^2 per jaar gemiddeld appartement	< originele situatie	Min
				A++=1, A+=2, ..., G=9	Label B of hoger	Min
				[-]	≤ 1,40	Min
		O2	Milieuimpact minimaliseren	%	> 0	Max
				m^3 per jaar gemiddeld appartement	> 0	Max
S2	Economie	O3	Minimaliseren investeringskosten	€	?	Min
				€	<€7.000	Min
		O4	Optimaliseren kosten-baten	€	>€0	Max
				jaar	<20 jaar?	Min
S3	Sociaal	O5	Verbeteren comfort	uren (onderverwarmd) per gemiddeld appartement	< originele situatie	Min
				minimaal=1, ..., veel=5	?	Min
		O6	Minimaliseren overlast voor huurders	€/maand per gemiddeld appartement	?	Max
		O7	Optimaliseren woonlasten voor huurders	€/maand	<€26,50	Min

Besluitvormingscriteria case study	
C1	Warmtebehoefte
C2	Energielabel
C3	Energie-Index
C4	Aandeel hernieuwbare energie*
C5	Energiebesparing (gas)*
C6	Energetische investeringskosten
C7	Investering per labelstap per woning
C8	Life cycle costs (LCC 30 jaar)*
C9	Terugverdientijd (simpel)*
C10	Thermisch comfort*
C11	Overlast door werkzaamheden
C12	Energiekosten besparing
C13	Huurverhoging

Table 7.3.7 Decision parameters tailored to case study

Apartment position	Case study data BENG2 (kWh/m^2)	LTH-grasshopper simulation Heating demand (kWh/m^2)	Case study data Energy -Index	LTH-grasshopper simulation Energy -Index	Case study data Energy Label	LTH-grasshopper simulation Energy Label	Case study data Surface area	LTH-grasshopper simulation Surface area
Corner-Roof	258,71	306,18	1,80	1,97	C	D	72,60	67,50
Corner-Ground	262,80	214,51	1,93	1,59	D	C	71,06	67,50
Corner-Intermediate	223,50	191,86	1,87	1,74	D	C	67,85	67,50
Intermediate-Roof	230,84	244,04	1,68	1,80	C	C	65,24	67,50
Intermediate-Ground	207,30	157,46	1,62	1,39	C	B	67,92	67,50
Intermediate-Intermediate	181,79	127,22	1,64	1,46	C	C	67,09	67,50

Table 7.3.5 Benchmark: case study energy performance data compared to LTH-tool energy performance data for 6 apartment positions

Environmental Objectives

The project plan mentions the aim of achieving the highest energy performance improvement per euro invested, which could be accomplished with a life-cycle cost (LCC) analysis. There is a strong focus on achieving a significant reduction in energy and gas usage. Additionally, there is a natural renovation moment for replacing the collective boilers, with a preference for replacing them with heat pumps and solar boilers.

Economic Objectives

The objective is to achieve the lowest possible investment costs with the highest possible energy reduction. Subsidy options, which reduce the cost of energy improvements per label step per dwelling, are also considered. The total available investment budget depends on planned maintenance (MJOP). An increase in the value of the complex is seen as beneficial, as it allows for higher rent prices after tenant turnover.

Social Objectives

One key objective is to gain tenant support, referred to as ‘draagvlak’. This tenant support is likely to be achieved when PV panels are implemented. Financial consequences for tenants are also a factor: the aim is to lower energy costs for tenants and prevent an increase in housing costs (assuming equal energy behaviour). The aim is to balance any rent increases with energy bill savings. A rent increase of €26.50 is considered significant but reasonable given the benefits.

Decision objective O1, O4, O5, O6 and O7 are directly mentioned in the projectplan. However, the projectplan lacks clarity on how O5 is quantified. To ensure LT-readiness, C1 and C10 are essential decision criteria, and are therefore added to the list of decision criteria, connecting O5 to C10, solving the problem of unquantified objectives.

Decision criteria C2, C3, C6, C7 and C11 are directly extracted from their scenario table (see table 7.2.2). Decision criteria C12 and C13 are extracted from the appendix of the projectplan. C4 and C5 are generally mentioned in the project plan. Besides the LT-essential criteria C1 and C10, additional decision criteria C8, and C9 is added from literature. Even though these criteria aren’t explicitly mentioned, there are a logical extension of the projects objectives.

7.3.3.3 Capturing stakeholders’ preferences

In preparation for the workshop, the decision support tool as presented in Chapter 6.2 is adapted to the case study decision parameters and the correct amount of decision criteria. The pairwise comparison matrixes in the tool are scaled to the correct amount of criteria, as shown in figure 7.3.4. Appendix D shows the pairwise comparison sheets the participants were given to obtain criteria weights.

7.3.3.4 Developing renovation scenarios

The company that provided the case study developed four renovation alternatives, of which only 3 and 4 are LT-renovation scenarios. The only difference between A3 an A4 is the addition of a solar boiler. This clearly shows that the renovation objective is to improve the energy label, instead of enabling LTH, influencing the approach towards renovation scenario development. Since the developed framework aims to enable LTH through renovations, 9 additional renovation scenarios are developed for comparison based on the identified renovation measures from chapter 2.2. Table 7.3.8 shows the selected renovation measures per scenario, A1-A4 being the scenarios considered in the case study, A5-A13 the newly developed scenarios. Appendix H contains visualizations of the renovation measures with their LT-performance.

The renovation scenarios are developed based on a priority approach, the priority being the renovation measure that has the highest impact on reducing the heating demand. For low-temperature heating, the following priority is considered:

1. Temperature setpoint
2. Infiltration
3. Roof insulation
4. Compactness ratio
5. Ventilation system
6. Window glazing
7. Wall insulation
8. Ground insulation
9. Door insulation
10. Orientation
11. Window to wall ratio

When developing A5-A9, the choice was made to keep the building installations like HP/PVT/solar boiler and solar panels with LED lighting the same as scenario A4, so that criteria quantification for costs only had to be adjusted for measures where a costs indication was available from the RVO kostenkentallen site (Netherlands Enterprice Agency, n.d.).

Every scenario is simulated for its heating demand and thermal discomfort, to check if the newly generated renovation alternatives are LT-ready. The summarized results can be found in table 7.3.9. Appendix E provides the complete data

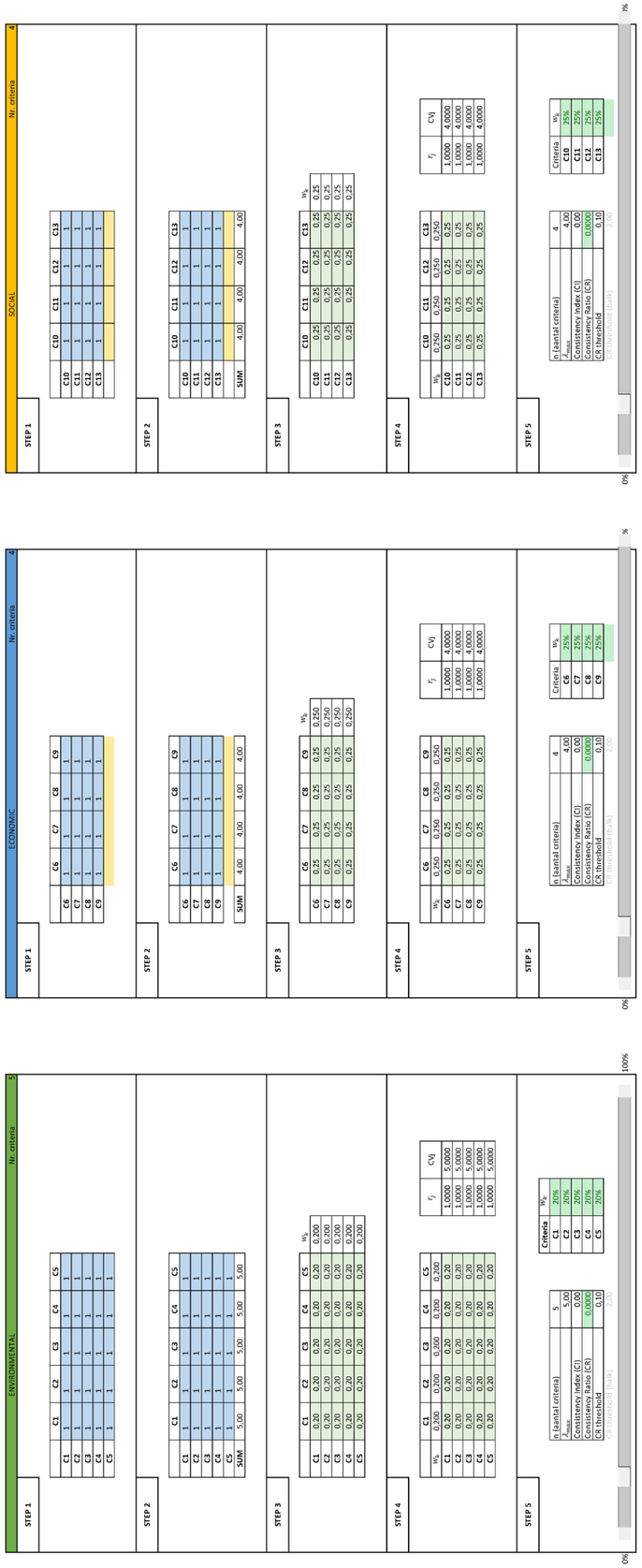


Figure 7.3.4 Calculation matrices in decision support tool tailored to case study

set. Scenario A12 is eliminated from the decision analysis since it is not LT-ready. Even though A3 and A4 are also not LT-ready, they are included in the decision analysis since they are a part of the original case study scenarios. Eliminating those scenarios could potentially confuse the stakeholders participants in understanding the framework function, since it contained their chosen scenario. It makes sense that A3 and A4 were considered as good renovation options to the company, since they based their comparison on energy performance and not thermal comfort. It was explained to the participants that based on the LTH-grasshopper simulations and the LT-ready definition, none of their original renovation alternatives are sufficient, but that they were included for their reference and understanding of the framework. Scenario A10, A11 and A13 are also eliminated from the decision analysis to limit the amount of alternatives to quantify and compare in the final decision analysis. The reason for eliminating those scenarios was a slightly worse thermal comfort performance for certain apartment positions (table 7.3.9 only shows average of 6 positions). It is important to note that only A9 is fully LT-ready for all apartment positions.

7.3.3.5 Quantification of performance renovation scenarios

Based on the provided data from the case study, the renovation alternatives were quantified for the decision criteria. Table 7.3.10 illustrates the quantified renovation alternatives based on the decision criteria. C1 (heating demand) and C10 (thermal comfort) are calculated through LTH-grasshopper simulation. Additional tools were developed to automatically calculate C3 (energy-index), C6 (investment costs) and C8 (LCC) for every alternative. Based on the EI-value C2 (energy label) is determined. C4 (renewable energy) was extracted from the provided case study documentation, and assumed that for A5-9 the C4 value is the same as for A4, since no changes were made to the renewable energy measures. C5 (gas savings) and C9 (payback period) is calculated based on the method presented in chapter 2.2.2. C11 (nuisance due to construction work) is estimated on a 1-5 scale as presented in table 7.2.2 (scenario table). C12 (energy cost savings) and C13 (rent increment) was extracted from the projectplan, and for A5-A9 the same value as for A4 is assumed.

	Gebouwschil			Gebouwinstallaties			
	Isolatie (dak, gevel, vloer)	Open geveldelen (ramen, deuren)	Kierdichting	Warmteopwekker (HR 107, warmtepomp, PVT, zonneboiler)	Warmte-afgiftesysteem (radiatoren extra paneel)	Ventilatiesysteem (Mechanische afvoer, balansventilatie, WTW, CO2-gestuurd)	Elektriciteit (zonnepanelen, LED verlichting)
A1	Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,5	HR 107	Bestaande radiatoren	Mechanische afvoer	LED verlichting
A2	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	HR 107	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A3	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A4	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A5	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,6)	Ramen woning (U 1,0)	0,4	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Balansventilatie Warmteterugwinning CO2-gestuurd	Zonnepanelen LED verlichting
A6	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,0)	1	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A7	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen woning (U 1,0)	0,7	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A8	Buitenkant gevel (Rc 6,3)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2-gestuurd	Zonnepanelen LED verlichting
A9	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,6)	Ramen woning (U 1,0)	0,4	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A10	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,0)	1	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2-gestuurd	Zonnepanelen LED verlichting
A11	Dak (5,84) Spouwisolatie (Rc 1,69)	Ramen woning (U 1,0)	0,7	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2-gestuurd	Zonnepanelen LED verlichting
A12	Buitenkant gevel (Rc 6,3)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A13	Dak (Rc 3,5) Spouwisolatie (1,7) Vloer (Rc 3,5)	Ramen woning (U 1,7) Deur (U 1,4)	0,4	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Balansventilatie Warmteterugwinning CO2-gestuurd	Zonnepanelen LED verlichting

Table 7.3.8 Developed renovation scenarios for framework and tool

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Warmtebehoefte	Energielabel	Energie-Index	Aandeel hernieuwbare energie	Energiebesparing (gas)	Energetische investeringskosten	Investering per labelstap per woning	Life cycle costs (LCC 30 jaar)	Terugverdientijd (simpel)	Thermisch comfort	Overlast door werkzaamheden	Energiekosten besparing	Huurverhoging
	kWh/m^2 per jaar gemiddeld appartement	A+++, A++, A+, A, B, C, D, E, F, G	[-]	%	m^3 per jaar gemiddeld appartement	€	€	€	jaar	uren (onderverwarmd) per gemiddeld appartement	minimaal 1, ..., veel 5	€/maand per gemiddeld appartement	€/maand
A0	206,88	C	1,66	0	0	0		0	0	326	0	0	0
A1	174,34	C	1,46	0,0%	250	€ 1.260.513,65	€ 27.402	€ 142.593,19	32	263	1	€ 5,13	€ 7
A2	153,76	A	1,18	15,0%	407	€ 1.806.737,31	€ 11.732	€ 137.953,67	28	230	1	€ 20,83	€ 9
A3	122,80	A	1,01	25,0%	645	€ 1.944.888,39	€ 9.923	€ 137.097,11	19	919	1	€ 20,83	€ 19
A4	122,80	A++	0,49	38,2%	645	€ 2.254.026,66	€ 5.471	€ 139.959,50	22	919	1	€ 26,53	€ 22
A5	59,92	A++	0,21	38,2%	1127	€ 3.133.626,00	€ 7.606	€ 123.490,32	18	225	4	€ 26,53	€ 22
A6	124,50	A++	0,49	38,2%	632	€ 2.933.433,91	€ 7.120	€ 144.240,16	30	271	3	€ 26,53	€ 22
A7	118,45	A++	0,47	38,2%	678	€ 2.581.736,28	€ 6.266	€ 137.950,56	24	210	2	€ 26,53	€ 22
A8	114,43	A++	0,35	38,2%	709	€ 4.014.916,55	€ 9.745	€ 159.006,80	36	285	4	€ 26,53	€ 22
A9	94,63	A++	0,37	38,2%	861	€ 2.782.502,88	€ 6.754	€ 127.849,30	21	63	3	€ 26,53	€ 22

Table 7.3.9 LTH-grasshopper simulation results

Table 7.3.10 Quantified renovation alternatives

7.3.3.6 Decision Analysis

The projectplan provides a written elaboration as decision analysis, where scenario A4 is suggested as the optimal scenario, with scenario A2 as a second best option. Explicitly mentioned arguments for the preference of A4 are the relative lowest investment costs compared to the highest improvement of energy label, the largest energy and gas consumption reduction, the possibility to take advantage of the natural renovation moment to replace the existing boilers with heat pumps and solar boilers, and the tenants wishes for sustainability improvements like done with PV panels.

The TOPSIS calculation tab in the decision support tool was adapted to the 13 identified decision criteria (see table 7.3.11 & 7.3.12). When assuming equal importance of the decision criteria (=equal weights), the following ranking of the alternatives is provided by the tool (see figure 7.3.3). The developed decision support tool provides the same suggestion of A4 as the most optimal renovation alternative considering the selected decision criteria. This is a positive indication that the decision support tool can potentially represent a real-world decision-making process accurately.

When extending the comparison with A5-A9, is becomes clear that A9 would be the most optimal solution based on the performance of the decision criteria, with A7 as a second best. The previously preferred A4 is now ranked 5th position.

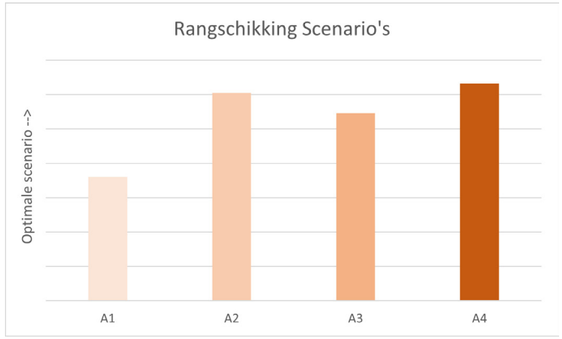


Figure 7.3.5 TOPSIS ranking for renovation alternative A1-A4 equal weights

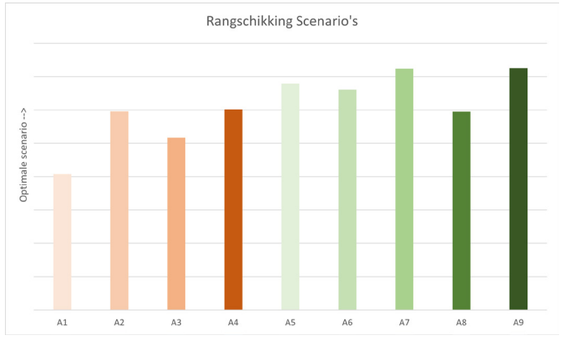


Figure 7.3.6 TOPSIS ranking for renovation alternative A1-A9 equal weights

Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	174,34	5,00	1,46	0,00	249,59	1260513,65	27402,47	142593,19	32,25	263,28	1,00	5,13	7,00
A2	153,76	3,00	1,18	0,15	407,44	1806737,31	11732,06	137953,67	28,32	229,72	1,00	20,83	9,00
A3	122,80	3,00	1,01	0,25	644,92	1944888,39	9922,90	137097,11	19,26	919,39	1,00	20,83	19,00
A4	122,80	1,00	0,49	0,38	644,92	2254026,66	5470,94	139959,50	22,32	919,39	1,00	26,53	22,00

Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	0,601	0,754	0,667	0,000	0,242	0,340	0,859	0,511	0,619	0,196	0,500	0,128	0,224
A2	0,530	0,452	0,539	0,312	0,396	0,488	0,368	0,495	0,544	0,171	0,500	0,521	0,288
A3	0,423	0,452	0,462	0,520	0,626	0,525	0,311	0,492	0,370	0,683	0,500	0,521	0,608
A4	0,423	0,151	0,224	0,795	0,626	0,609	0,172	0,502	0,429	0,683	0,500	0,664	0,705

Weighted Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Benefical value	Min	Min	Min	Max	Max	Min	Min	Max	Min	Min	Min	Max	Min
Criteria weights	6,7%	6,7%	6,7%	6,7%	6,7%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%
A1	0,040	0,050	0,044	0,000	0,016	0,028	0,072	0,043	0,052	0,016	0,042	0,011	0,019
A2	0,035	0,030	0,036	0,021	0,026	0,041	0,031	0,041	0,045	0,014	0,042	0,043	0,024
A3	0,028	0,030	0,031	0,035	0,042	0,044	0,026	0,041	0,031	0,057	0,042	0,043	0,051
A4	0,028	0,010	0,015	0,053	0,042	0,051	0,014	0,042	0,036	0,057	0,042	0,055	0,059
A+ (PIS)	0,028	0,010	0,015	0,053	0,042	0,028	0,014	0,043	0,031	0,014	0,042	0,055	0,019
A- (NIS)	0,040	0,050	0,044	0,000	0,016	0,051	0,072	0,041	0,052	0,057	0,042	0,011	0,059

Si+	Si-
0,109	0,061
0,054	0,083
0,066	0,079
0,063	0,108

Ranking

	Si+	Si-	Pi	RANK
A1	0,109	0,061	0,361	4
A2	0,054	0,083	0,605	2
A3	0,066	0,079	0,546	3
A4	0,063	0,108	0,632	1

1 =most optimal alternative
4 =worst alternative

Table 7.3.11 TOPSIS decision analysis for case study A1-A4 equal weights [highlighted scenario was choosen in case study by company]

Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	174,34	5,00	1,46	0,00	249,59	1260513,65	27402,47	142593,19	32,25	263,28	1,00	5,13	7,00
A2	153,76	3,00	1,18	0,15	407,44	1806737,31	11732,06	137953,67	28,32	229,72	1,00	20,83	9,00
A3	122,80	3,00	1,01	0,25	644,92	1944888,39	9922,90	137097,11	19,26	919,39	1,00	20,83	19,00
A4	122,80	1,00	0,49	0,38	644,92	2254026,66	5470,94	139959,50	22,32	919,39	1,00	26,53	22,00
A5	59,92	1,00	0,21	0,38	1127,24	3133626,00	7605,89	123490,32	17,75	225,11	4,00	26,53	22,00
A6	124,50	1,00	0,49	0,38	631,88	2933433,91	7119,99	144240,16	29,64	271,00	3,00	26,53	22,00
A7	118,45	1,00	0,47	0,38	678,29	2581736,28	6266,35	137950,56	24,31	209,72	2,00	26,53	22,00
A8	114,43	1,00	0,35	0,38	709,12	4014916,55	9744,94	159006,80	36,15	285,17	4,00	26,53	22,00
A9	94,63	1,00	0,37	0,38	861,00	2782502,88	6753,65	127849,30	20,64	63,44	3,00	26,53	22,00

Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	0,467	0,714	0,620	0,000	0,119	0,159	0,758	0,341	0,409	0,183	0,131	0,072	0,120
A2	0,412	0,429	0,501	0,153	0,193	0,228	0,325	0,330	0,359	0,160	0,131	0,291	0,154
A3	0,329	0,429	0,429	0,255	0,306	0,246	0,275	0,328	0,244	0,640	0,131	0,291	0,326
A4	0,329	0,143	0,208	0,390	0,306	0,285	0,151	0,335	0,283	0,640	0,131	0,371	0,378
A5	0,161	0,143	0,089	0,390	0,535	0,396	0,211	0,296	0,225	0,157	0,525	0,371	0,378
A6	0,333	0,143	0,208	0,390	0,300	0,371	0,197	0,345	0,376	0,189	0,394	0,371	0,378
A7	0,317	0,143	0,200	0,390	0,322	0,326	0,173	0,330	0,308	0,146	0,263	0,371	0,378
A8	0,307	0,143	0,149	0,390	0,337	0,507	0,270	0,381	0,458	0,198	0,525	0,371	0,378
A9	0,253	0,143	0,157	0,390	0,409	0,351	0,187	0,306	0,261	0,044	0,394	0,371	0,378

Weighted Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Benefical value	Min	Min	Min	Max	Max	Min	Min	Max	Min	Min	Min	Max	Min
Criteria weights	6,7%	6,7%	6,7%	6,7%	6,7%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%	8,3%
A1	0,031	0,048	0,041	0,000	0,008	0,013	0,063	0,028	0,034	0,015	0,011	0,006	0,010
A2	0,027	0,029	0,033	0,010	0,013	0,019	0,027	0,028	0,030	0,013	0,011	0,024	0,013
A3	0,022	0,029	0,029	0,017	0,020	0,020	0,023	0,027	0,020	0,053	0,011	0,024	0,027
A4	0,022	0,010	0,014	0,026	0,020	0,024	0,013	0,028	0,024	0,053	0,011	0,031	0,031
A5	0,011	0,010	0,006	0,026	0,036	0,033	0,018	0,025	0,019	0,013	0,044	0,031	0,031
A6	0,022	0,010	0,014	0,026	0,020	0,031	0,016	0,029	0,031	0,016	0,033	0,031	0,031
A7	0,021	0,010	0,013	0,026	0,021	0,027	0,014	0,028	0,026	0,012	0,022	0,031	0,031
A8	0,020	0,010	0,010	0,026	0,022	0,042	0,022	0,032	0,038	0,017	0,044	0,031	0,031
A9	0,017	0,010	0,010	0,026	0,027	0,029	0,016	0,026	0,022	0,004	0,033	0,031	0,031

Si+	Si-
0,090	0,062
0,052	0,076
0,066	0,070
0,059	0,089
0,046	0,097
0,045	0,087
0,036	0,094
0,057	0,084
0,037	0,098

A+ (PIS)	0,011	0,010	0,006	0,026	0,036	0,013	0,013	0,032	0,019	0,004	0,011	0,031	0,010
A- (NIS)	0,031	0,048	0,041	0,000	0,008	0,042	0,063	0,025	0,038	0,053	0,044	0,006	0,031

Ranking

	Si+	Si-	Pi	RANK
A1	0,090	0,062	0,408	9
A2	0,052	0,076	0,596	6
A3	0,066	0,070	0,517	8
A4	0,059	0,089	0,601	5
A5	0,046	0,097	0,679	3
A6	0,045	0,087	0,661	4
A7	0,036	0,094	0,723	2
A8	0,057	0,084	0,595	7
A9	0,037	0,098	0,725	1

1 =most optimal alternative
9 =worst alternative

Table 7.3.12 TOPSIS decision analysis for case study A1-A9 equal weights [highlighted scenario was choosen in case study by company]

7.3.4 Analysis - Workshop results

7.3.4.1 Workshop participants: stakeholders' role

At the start of the workshop the simplified decision support framework was presented. After this, the participants were asked to describe their role and influence on the decision-making process. Table 7.3.13 presents the stakeholder identification of the present participants. During the workshop participants expressed that their influence on the decision-making process changes throughout the project phases. Some might start as informants, switch to decision-makers or authorizers or the other way around. The distinction between informant and decision-maker is blurry.

7.3.4.2 Stakeholder involvement in framework phases

The participants were asked to reflect on the decision support framework and elaborate at which steps they recognized their roles in the presented framework phases. Figure 7.3.7 shows the stakeholder involvement per framework step, which is based on the obtained written and oral data from the workshop. The stakeholders validated both verbally and through the ranked questionnaire that the presented decision support framework is an reasonably accurate representation of their decision-making process. A suggested adaption to improve accuracy of the process representation in the framework is to switch step 1 and 2. This is due to step 2 being their starting point for the overarching program, while step 1 is project specific. The first 6 steps of the process is done by the project team, which includes the project leaders and program managers. The last step, the final decision, is taken by the steering group (involving different stakeholders), who are informed by the program managers, who are on their turn informed by the project leaders. Step 2 identification of decision parameters is based on a yearly meeting where the organizations' policy is determined. If required during project development, project specific decision criteria are added.

7.3.4.3 Pairwise comparison results

The stakeholders are asked to do individual pairwise comparisons for all three categories (environmental, economic, social). Figure 7.3.8 illustrates the results of this comparison for stakeholder 1. Appendix F shows the individual results of all stakeholders. Table 7.3.14 shows the balanced criteria weights of all stakeholders. Not all stakeholders were able to give consistent answers, since the consistency threshold of 10% was surpassed (red marked criteria weights) by 3 out of 4 stakeholders for 2 categories. However, all criteria weights would be deemed consistent if a consistency threshold of 25% was adapted. At a consistency threshold of 13%, 2 out of 4 stakeholders give consist answers. It is recommended to revise the answers given in the pairwise comparison if the

Stakeholder	Organisation	Role	Description
1	Energy transition company	Project leader	Prepare the decision together with the project team. Developing multiple renovation options. Gathering information and doing research into possibilities to substantiate choices. Contact person for stakeholders like resident consultant, asset manager, regional manager, technical manager.
2	Social housing corporation	Programme manager	Responsible for the sustainability program within the social housing corporation. Involved in decision-making process in multiple phases. At the PV1 (developing scenarios and advise/decide on optimal scenario) this stakeholder is an informant, and at PV3 (implementation of decision) this stakeholder is a decision-maker.
3	Energy transition company	Programme manager	Quality control over the developed plans from the project team, ensuring everthing is according to the existing agreements. Involved in the preparation of the decision-making. Present when the decision-makers are making the final decision.
4	Energy transition company	Project leader	Involved in project content and preparation like stakeholder 1. Present in the steering group where decision are made. In contact with stakeholder 2 and 3 to develop a quality guaranteed project.

Table 7.3.13 Stakeholder identification present participants

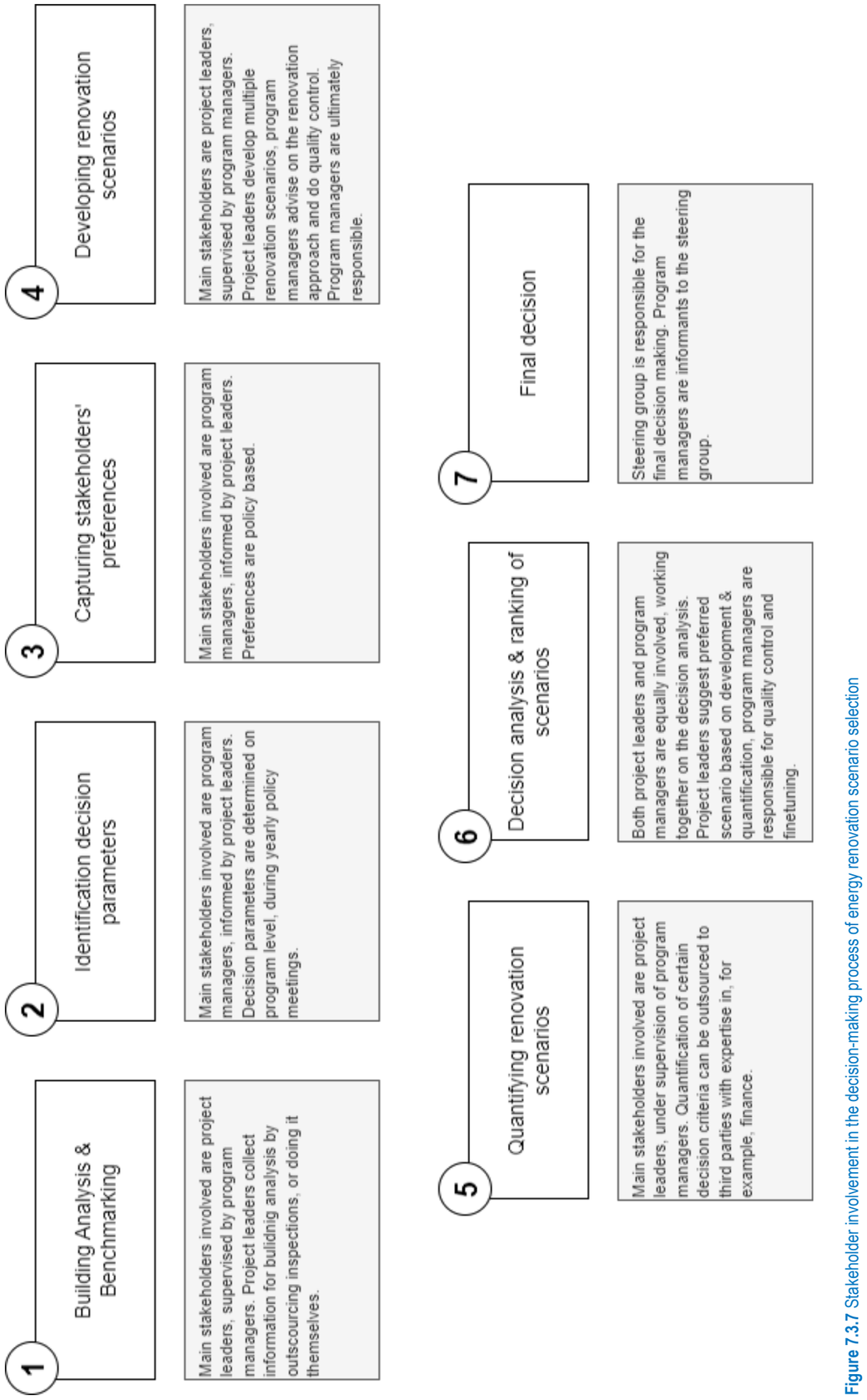


Figure 7.3.7 Stakeholder involvement in the decision-making process of energy renovation scenario selection

consistency ratio is higher than the threshold. Due to time constraints of the workshop, the inconsistency was accepted and not further discussed. It is important to keep in mind that this inconsistency does have an influence on the reliability of the ranking results of the weighted decision analysis.

7.3.4.4 Decision analysis TOPSIS with stakeholders preferences results

The balanced criteria weights are now incorporated into the decision analysis, and used to represent the preferences (priority) of certain decision criteria. Table 7.3.15 shows the decision analysis results for A1-A4, table 3.16 shows the decision analysis results for A1-A9. Figure 7.3.9 & 7.3.10 shows the graphical ranking of A1-A4, respectively A1-A9.

Figure 7.3.9 shows the ranking of A1-A4 with balanced criteria weights. When compared to figure 7.3.5 where A1-A4 is ranked with equal weights (thus purely on performance values), it becomes evident that incorporating stakeholders' preferences changes the most optimal renovation scenario from A4 to A2. In the project plan, A4 was suggested as the most optimal renovation alternative. There are two main explanations for this shift in renovation alternative preference:

1. **Policy has changed.** Participants have filled out the pairwise comparison based on new policy (2024), compared to the policy during the time of the case study (2018). An example is that the projectplan main objective was improving the energy label, which causes an expectation for a high criteria weight on decision criteria C2 (energy label). However, after pairwise comparison this preference is not reflected, instead C1 (heating demand) and C12 (energy cost savings) are marked highly important compared to the energy label performance. Some participants also incorporated their personal preferences instead of policy preferences, potentially adding to the shift from the original policy and thus expected preference reflection.
2. **Consistency ratio is high.** The consistency of the obtained criteria weights is questionable, therefore the ranking of the alternatives based on those balanced criteria weights is also questionable.

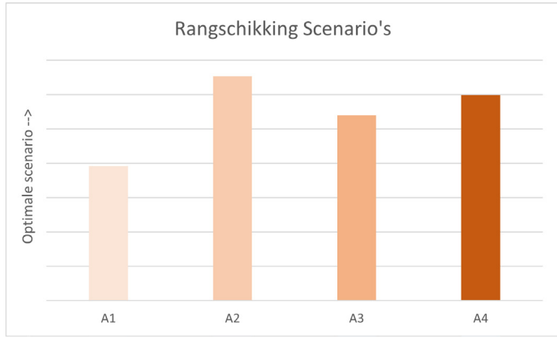


Figure 7.3.9 TOPSIS ranking for renovation alternatives A1-A4 balanced criteria weights

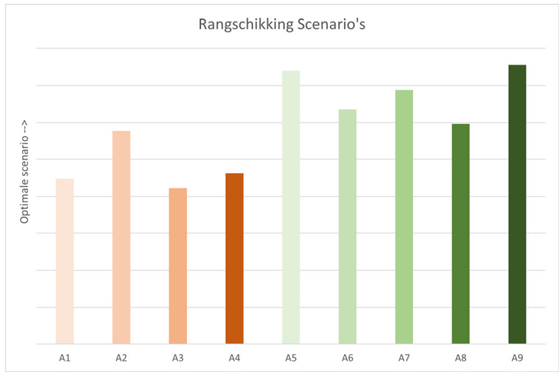


Figure 7.3.10 TOPSIS ranking for renovation alternatives A1-A9 balanced criteria weights

Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	174,34	5,00	1,46	0,00	249,59	1260513,65	27402,47	142593,19	32,25	263,28	1,00	5,13	7,00
A2	153,76	3,00	1,18	0,15	407,44	1806737,31	11732,06	137953,67	28,32	229,72	1,00	20,83	9,00
A3	122,80	3,00	1,01	0,25	644,92	1944888,39	9922,90	137097,11	19,26	919,39	1,00	20,83	19,00
A4	122,80	1,00	0,49	0,38	644,92	2254026,66	5470,94	139959,50	22,32	919,39	1,00	26,53	22,00

Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	0,601	0,754	0,667	0,000	0,242	0,340	0,859	0,511	0,619	0,196	0,500	0,128	0,224
A2	0,530	0,452	0,539	0,312	0,396	0,488	0,368	0,495	0,544	0,171	0,500	0,521	0,288
A3	0,423	0,452	0,462	0,520	0,626	0,525	0,311	0,492	0,370	0,683	0,500	0,521	0,608
A4	0,423	0,151	0,224	0,795	0,626	0,609	0,172	0,502	0,429	0,683	0,500	0,664	0,705

Weighted Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Benefical value	Min	Min	Min	Max	Max	Min	Min	Max	Min	Min	Min	Max	Min
Criteria weights	12,8%	3,0%	2,0%	4,9%	10,7%	10,9%	3,7%	12,9%	5,9%	11,7%	3,2%	14,3%	4,1%
A1	0,077	0,022	0,013	0,000	0,026	0,037	0,032	0,066	0,036	0,023	0,016	0,018	0,009
A2	0,068	0,013	0,011	0,015	0,042	0,053	0,014	0,064	0,032	0,020	0,016	0,075	0,012
A3	0,054	0,013	0,009	0,025	0,067	0,057	0,012	0,064	0,022	0,080	0,016	0,075	0,025
A4	0,054	0,004	0,004	0,039	0,067	0,067	0,006	0,065	0,025	0,080	0,016	0,095	0,029
A+ (PIS)	0,054	0,004	0,004	0,039	0,067	0,037	0,006	0,066	0,022	0,020	0,016	0,095	0,009
A- (NIS)	0,077	0,022	0,013	0,000	0,026	0,067	0,032	0,064	0,036	0,080	0,016	0,018	0,029

Si+	Si-
0,104	0,067
0,048	0,091
0,071	0,083
0,070	0,104

Ranking

	Si+	Si-	Pi	RANK
A1	0,104	0,067	0,391	4
A2	0,048	0,091	0,654	1
A3	0,071	0,083	0,540	3
A4	0,070	0,104	0,599	2

1 =most optimal alternative
4 =worst alternative

Table 7.3.15 TOPSIS decision analysis for case study A1-A4 balanced criteria weights

	Wegingsfactoren gecombineerd												
	Milieu					Economie				Sociaal			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Stakeholder 1	34%	18%	14%	10%	25%	46%	23%	16%	16%	42%	10%	41%	7%
Stakeholder 2	31%	3%	3%	22%	40%	29%	10%	56%	5%	26%	10%	58%	6%
Stakeholder 3	44%	7%	4%	12%	33%	15%	8%	39%	39%	37%	12%	32%	20%
Stakeholder 4	45%	7%	3%	15%	30%	41%	4%	45%	11%	35%	6%	41%	17%
Balanced Criteria Weigths	39%	9%	6%	15%	32%	33%	11%	39%	18%	35%	10%	43%	12%
Final Balanced Criteria Weights	12,8%	3,0%	2,0%	4,9%	10,7%	10,9%	3,7%	12,9%	5,9%	11,7%	3,2%	14,3%	4,1%

Table 7.3.14 Final balanced criteria weights combined stakeholders' preferences

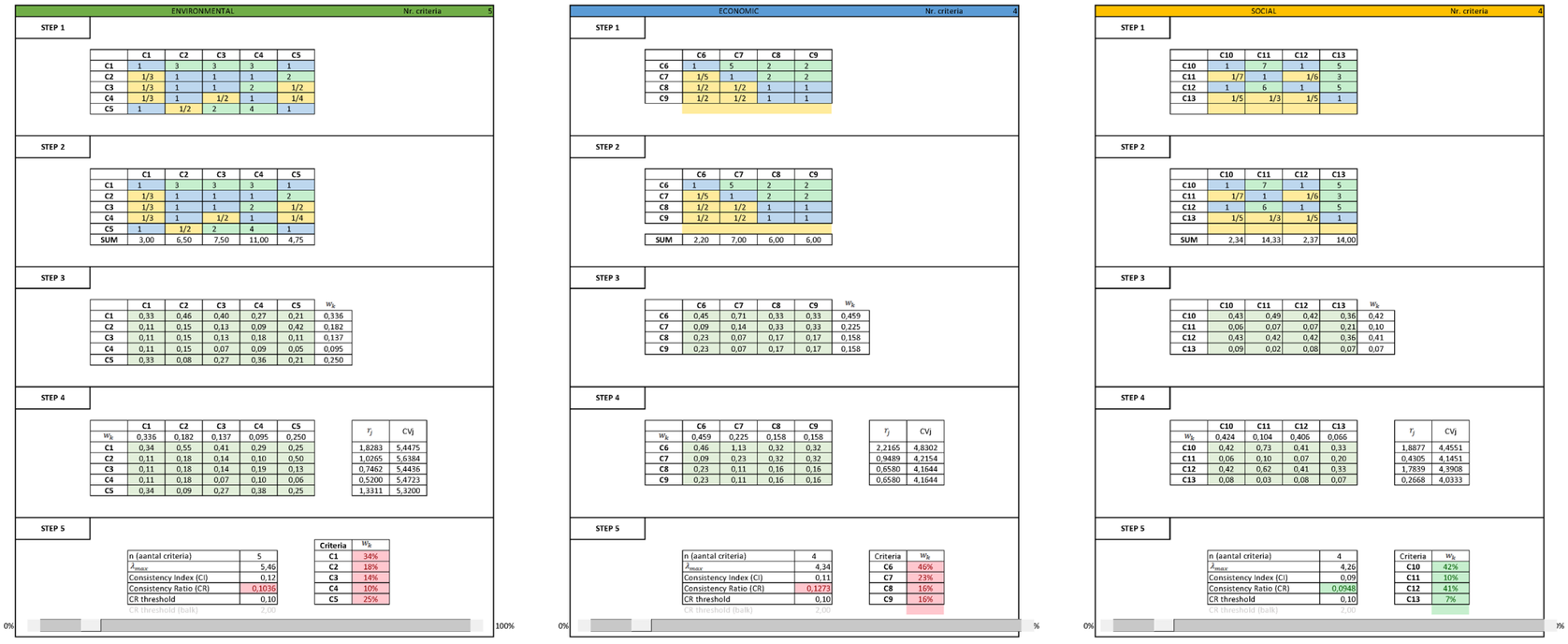


Figure 7.3.8 Pairwise comparison matrices of Stakeholder 1 – results criteria weights + consistency ratio

Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	174,34	5,00	1,46	0,00	249,59	1260513,65	27402,47	142593,19	32,25	263,28	1,00	5,13	7,00
A2	153,76	3,00	1,18	0,15	407,44	1806737,31	11732,06	137953,67	28,32	229,72	1,00	20,83	9,00
A3	122,80	3,00	1,01	0,25	644,92	1944888,39	9922,90	137097,11	19,26	919,39	1,00	20,83	19,00
A4	122,80	1,00	0,49	0,38	644,92	2254026,66	5470,94	139959,50	22,32	919,39	1,00	26,53	22,00
A5	59,92	1,00	0,21	0,38	1127,24	3133626,00	7605,89	123490,32	17,75	225,11	4,00	26,53	22,00
A6	124,50	1,00	0,49	0,38	631,88	2933433,91	7119,99	144240,16	29,64	271,00	3,00	26,53	22,00
A7	118,45	1,00	0,47	0,38	678,29	2581736,28	6266,35	137950,56	24,31	209,72	2,00	26,53	22,00
A8	114,43	1,00	0,35	0,38	709,12	4014916,55	9744,94	159006,80	36,15	285,17	4,00	26,53	22,00
A9	94,63	1,00	0,37	0,38	861,00	2782502,88	6753,65	127849,30	20,64	63,44	3,00	26,53	22,00

Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
A1	0,467	0,714	0,620	0,000	0,119	0,159	0,758	0,341	0,409	0,183	0,131	0,072	0,120
A2	0,412	0,429	0,501	0,153	0,193	0,228	0,325	0,330	0,359	0,160	0,131	0,291	0,154
A3	0,329	0,429	0,429	0,255	0,306	0,246	0,275	0,328	0,244	0,640	0,131	0,291	0,326
A4	0,329	0,143	0,208	0,390	0,306	0,285	0,151	0,335	0,283	0,640	0,131	0,371	0,378
A5	0,161	0,143	0,089	0,390	0,535	0,396	0,211	0,296	0,225	0,157	0,525	0,371	0,378
A6	0,333	0,143	0,208	0,390	0,300	0,371	0,197	0,345	0,376	0,189	0,394	0,371	0,378
A7	0,317	0,143	0,200	0,390	0,322	0,326	0,173	0,330	0,308	0,146	0,263	0,371	0,378
A8	0,307	0,143	0,149	0,390	0,337	0,507	0,270	0,381	0,458	0,198	0,525	0,371	0,378
A9	0,253	0,143	0,157	0,390	0,409	0,351	0,187	0,306	0,261	0,044	0,394	0,371	0,378

Weighted Normalized Decision Matrix

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Benefical value	Min	Min	Min	Max	Max	Min	Min	Max	Min	Min	Min	Max	Min
Criteria weights	12,8%	3,0%	2,0%	4,9%	10,7%	10,9%	3,7%	12,9%	5,9%	11,7%	3,2%	14,3%	4,1%
A1	0,060	0,021	0,012	0,000	0,013	0,017	0,028	0,044	0,024	0,021	0,004	0,010	0,005
A2	0,053	0,013	0,010	0,007	0,021	0,025	0,012	0,043	0,021	0,019	0,004	0,042	0,006
A3	0,042	0,013	0,008	0,012	0,033	0,027	0,010	0,042	0,014	0,075	0,004	0,042	0,013
A4	0,042	0,004	0,004	0,019	0,033	0,031	0,006	0,043	0,017	0,075	0,004	0,053	0,016
A5	0,021	0,004	0,002	0,019	0,057	0,043	0,008	0,038	0,013	0,018	0,017	0,053	0,016
A6	0,043	0,004	0,004	0,019	0,032	0,040	0,007	0,045	0,022	0,022	0,013	0,053	0,016
A7	0,041	0,004	0,004	0,019	0,034	0,036	0,006	0,043	0,018	0,017	0,008	0,053	0,016
A8	0,039	0,004	0,003	0,019	0,036	0,055	0,010	0,049	0,027	0,023	0,017	0,053	0,016
A9	0,033	0,004	0,003	0,019	0,044	0,038	0,007	0,040	0,015	0,005	0,013	0,053	0,016

Si+	Si-
0,084	0,068
0,056	0,077
0,080	0,059
0,079	0,068
0,035	0,100
0,047	0,082
0,040	0,088
0,055	0,082
0,032	0,100

A+ (PIS)	0,021	0,004	0,002	0,019	0,057	0,017	0,006	0,049	0,013	0,005	0,004	0,053	0,005
A- (NIS)	0,060	0,021	0,012	0,000	0,013	0,055	0,028	0,038	0,027	0,075	0,017	0,010	0,016

Ranking

	Si+	Si-	Pi	RANK
A1	0,084	0,068	0,447	8
A2	0,056	0,077	0,577	6
A3	0,080	0,059	0,422	9
A4	0,079	0,068	0,463	7
A5	0,035	0,100	0,740	2
A6	0,047	0,082	0,635	4
A7	0,040	0,088	0,688	3
A8	0,055	0,082	0,596	5
A9	0,032	0,100	0,755	1

1 =most optimal alternative
9 =worst alternative

Table 7.3.16 TOPSIS decision analysis for case study A1-A9 balanced criteria weights

Figure 7.3.10 illustrates the ranking of A1-A9 based on balanced criteria weights. Even though A2 was considered the most optimal alternative for balanced weights among A1-A4, it only ranks 6th when compared to the additional renovation alternatives. When comparing the equal weight rankings of A1-A9 (figure 6.3.6) to the balanced weights rankings of A1-A9, a shift in optimal alternative is noticeable. A9 remains to be the best alternative when considering both performance and preferences, but the second best option is now considered to be A5, with A7 as the 3rd optimal scenario. Page 101 and 102 provide visualizations on best performing scenario A9.

7.3.4.5 Sensitivity Analysis

The ranking of alternatives is based on the performance values and criteria weights. A sensitivity analysis can provide insights into which criteria are the most critical. Critical in this case relates to the influence/impact on the ranking order. It can also provide insight into what renovation alternatives are the most robust. Robustness in this case relates to performance of the alternative: if the top-rated alternative remains its ranking position even when given priority to a criterion, this indicates performance robustness.

To study the impact of changes in criteria weights on the final ranking, a local sensitivity analysis is conducted. According to Triantaphyllou & Sánchez (1997) there are two ways to determine the most critical (=most sensitive) criterion. The first approach focusses on whether the top-ranked alternative changes, while the second approach studies the change in the ranking of any alternative. In a local sensitivity analysis, priority is given to every criterion one-at-a-time (OAT) while keeping the other parameters fixed. For pairwise comparison, which originates from AHP, the following equation is always true:

$$\sum_{j=1}^{n} W_j = 1 \qquad (5.1)$$

When giving priority to one criterion, the other criteria should be decreased proportionally so that the total of the criteria weights (W_j) are always 100%. In this case 'fixed parameters' thus means decreasing the parameters proportionally. To study which criteria are the most critical and what alternatives are the most robust, the following steps are taken:

1. **Calculate the ranking of alternatives when all decision criteria are equally weighted.** This provides the base for the comparison for the new rankings after giving priority (see table 7.3.x). In the case study, there are 5 criteria in the category environmental, 4 criteria in economic and 4 in social. Equal weights in this case relates to the categories being equally weighted, so 33,33% per category. This results in equal weights of 6,67% per criterion in the environmental category, and 8,33% for every criterion in the economic and social category (6,67*5+8,33*4+8,33*4 = 100%).
2. **One-at-a-time prioritization.** To check the robustness of the ranking, a priority of +20% is given to a criterion. Since every category represents 33,33%, prioritizing a criterion from one category causes only the other criteria from that category to decrease proportionally. For example, when giving priority to the heating demand (C1) this results in a criterion weight of 6,67%+20% = 26,67%. Criteria C2, C3, C4 and C5 will be decreased proportionally resulting in a criterion weight of (33,33% - 26,67%)/4 = 1,67%, while the criteria of the economic and social categories remain 'equal' at 8,33%.
3. **Calculate priority rankings.** For all 13 criteria a new ranking is calculated. Appendix G provides a table with the relative closeness indices and new ranking after prioritizing a criterion, as well as a graphical representation of the ranking.

BASE CASE - Equal weights

	Pi	RANK
A1	0,408	9
A2	0,596	6
A3	0,517	8
A4	0,601	5
A5	0,679	3
A6	0,661	4
A7	0,723	2
A8	0,595	7
A9	0,725	1

Table 7.3.17 TOPSIS decision analysis ranking A1-A9 equal criteria weights

Figure 7.3.11 illustrates the changes in ranking order per alternative when a criterion is prioritized. The coloured dots on the right side of the figure represent the equal weights ranking. Figure 7.3.12 represents the occurrence of the top 3 highest ranked alternatives per criterion given priority. The yellow striped bar represents the equal weights ranking.

These two figures illustrate that when giving priority to the energy-index (C3), payback period (C9), thermal comfort (C10), or energy cost savings (C12), the highest ranked alternative remains A9. However, when prioritizing the heating demand (C1)

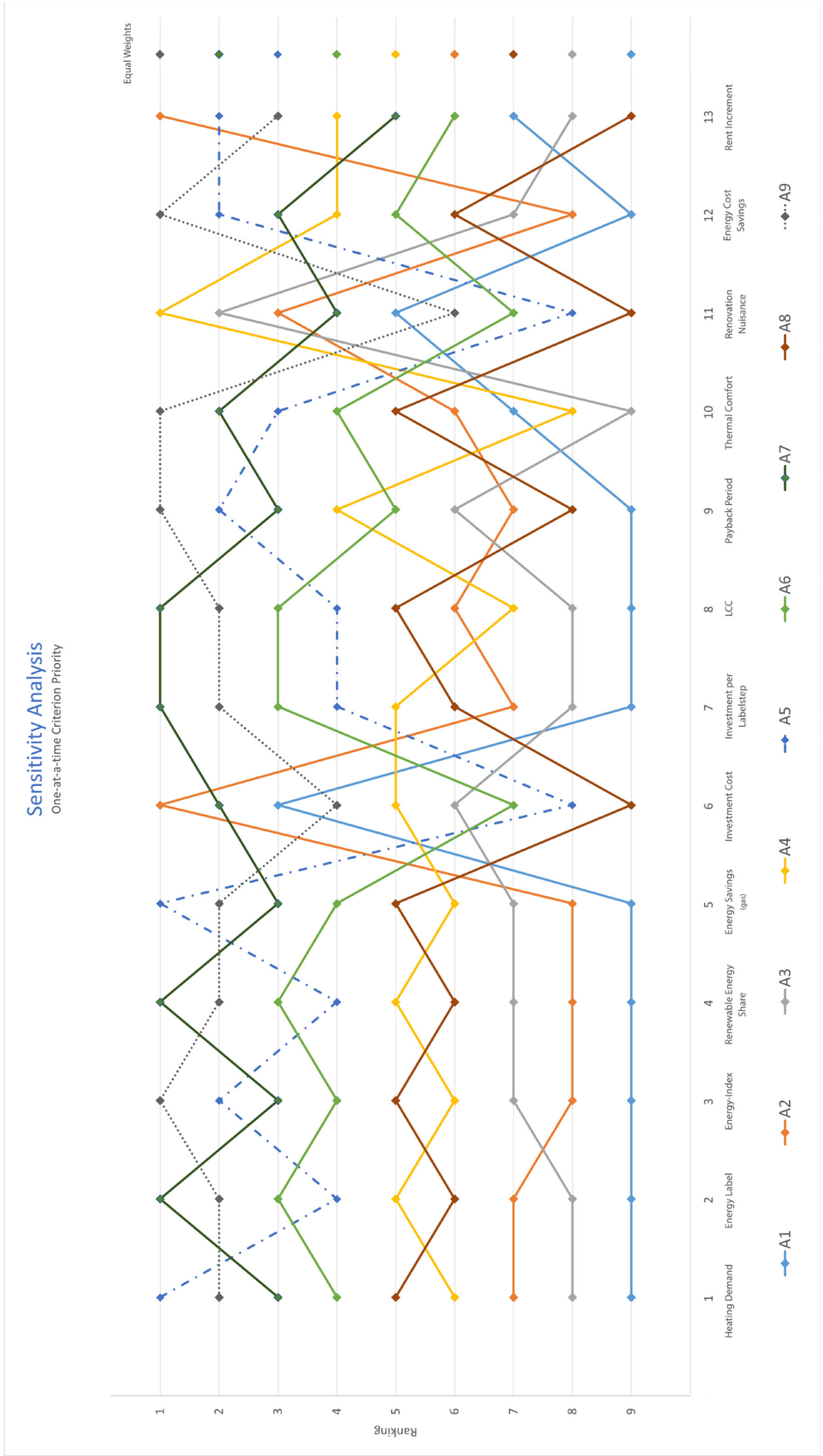


Figure 7.3.11 Sensitivity of Criterion when prioritized one-at-a-time illustrated through change in ranking order of Alternatives

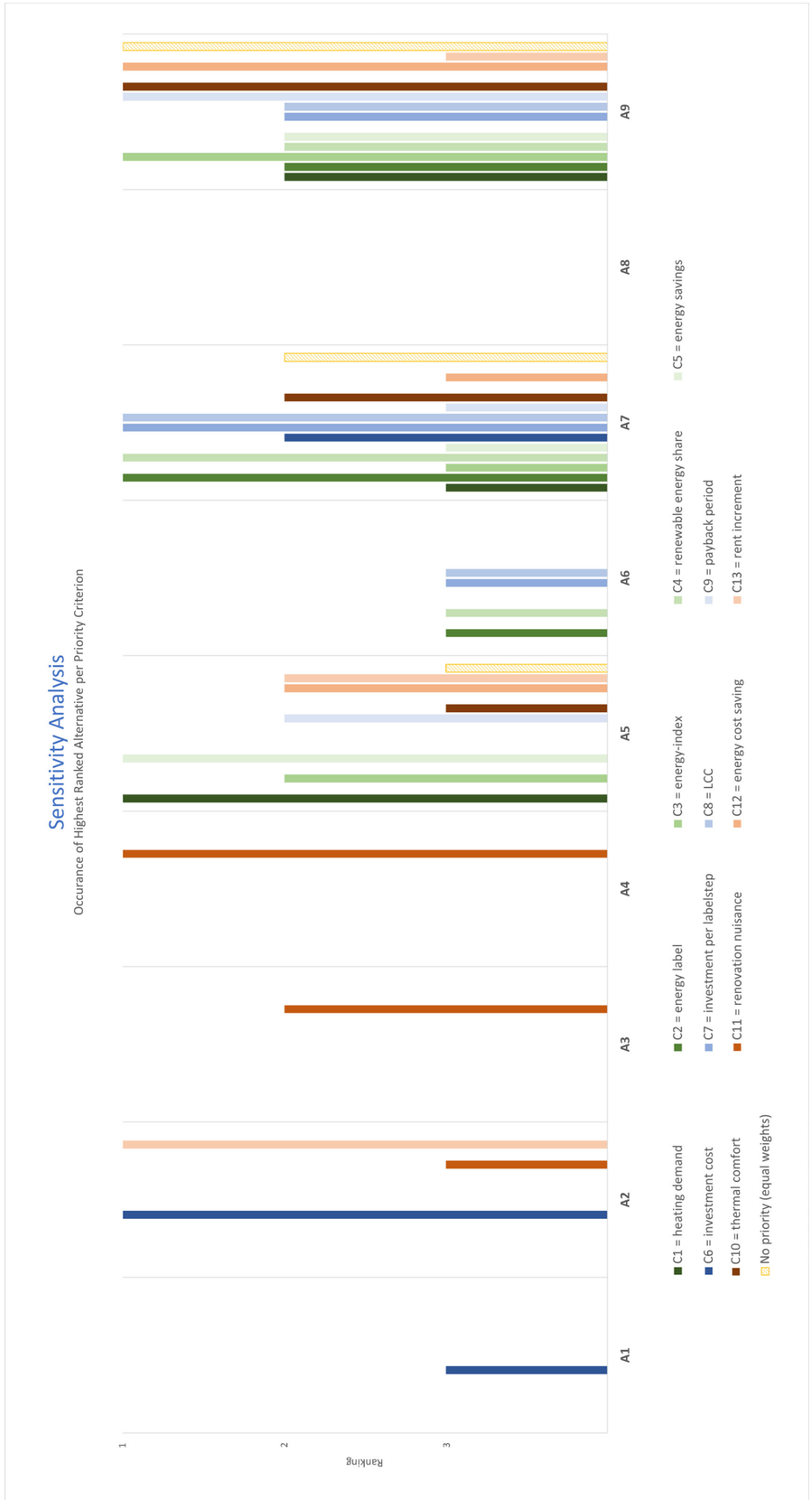


Figure 7.3.12 Occurance of top-three highest ranked alternative per priority criterion [green = environmental; blue = economic; orange = social]

or energy savings (C5), the highest ranked alternative changes from A9 to A5, placing A9 in the second position. Similarly, when giving priority to the energy label (C2), renewable energy share (C4), investment cost per label step (C7), or LCC (C8), the highest ranked alternative switches from A9 to A7, also placing A9 in the second position. When prioritizing the rent increment (C13), the new highest ranked alternative becomes A2, with A9 moving to the third position. Prioritizing the investment cost (C6) results in A2 becoming the highest ranked alternative and A9 falling to the fourth position. Finally, when prioritizing the renovation nuisance (C11), the highest ranked alternative shifts to A4, placing A9 in the sixth position.

In terms of sensitivity of the criteria, based on the suggested approaches of Triantaphyllou & Sánchez (1997), it can be concluded that C3, C9, C10 and C12 are non-critical. C1, C2, C4, C5, C7, and C8 show a change from 1st to 2nd rank, so those criteria can still be considered relatively non-critical. The most sensitive criteria are those which show a large shift: the decision criterion rent increment (C13) changes from 1st to 3rd, investment cost (C6) that changes from 1st to 5th, and renovation nuisance (C11) that changes from 1st to 6th. It makes sense that these criterion are the most critical criteria, since there is a high potential for trade-offs with the other criteria. It is somewhat concerning that two of the three most sensitive criteria have a low accuracy performance value. The performance of decision criterion of renovation nuisance is based on a descriptive 1-5 scale, estimating the expected nuisance. The performance value of rent increment for A5-A9 was extrapolated from the projectplans' estimation for A4. Due to the sensitivity of these criteria, it is important to review their performance values of those criteria to ensure a more reliable ranking.

Overall, scenario A9 is a top-performing alternative since it remains the highest ranked for 4 criteria (Energy-Index, payback period, thermal comfort, energy cost savings), ranks second for 6 criteria (heating demand, energy label, renewable energy share, investment per label step, LCC) and third for one criterion (rent increment). Its lowest ranking position is 6th, when giving priority to the renovation nuisance. Scenario A7 is also a high-performing alternative, achieving the highest ranking for 4 criteria (energy label, renewable energy share, investment per label step, LCC), second for 2 criteria (investment cost, thermal comfort) and third for 5 criteria (heating demand, energy-index, energy savings, payback period, energy cost savings). Its lowest ranking position is 5th when prioritizing the rent increment. Scenario A5 ranks highest when prioritizing heating demand and energy savings, indicating strong performance values in those areas. However, A5 also ranks lowest at 8th twice: when prioritizing investment cost and renovation nuisance. Scenario A2 is ranks highest for investment costs and rent increment, indicating high performance in those areas.

Generally speaking, the best performing alternatives for environmental criteria are A5, A7 and

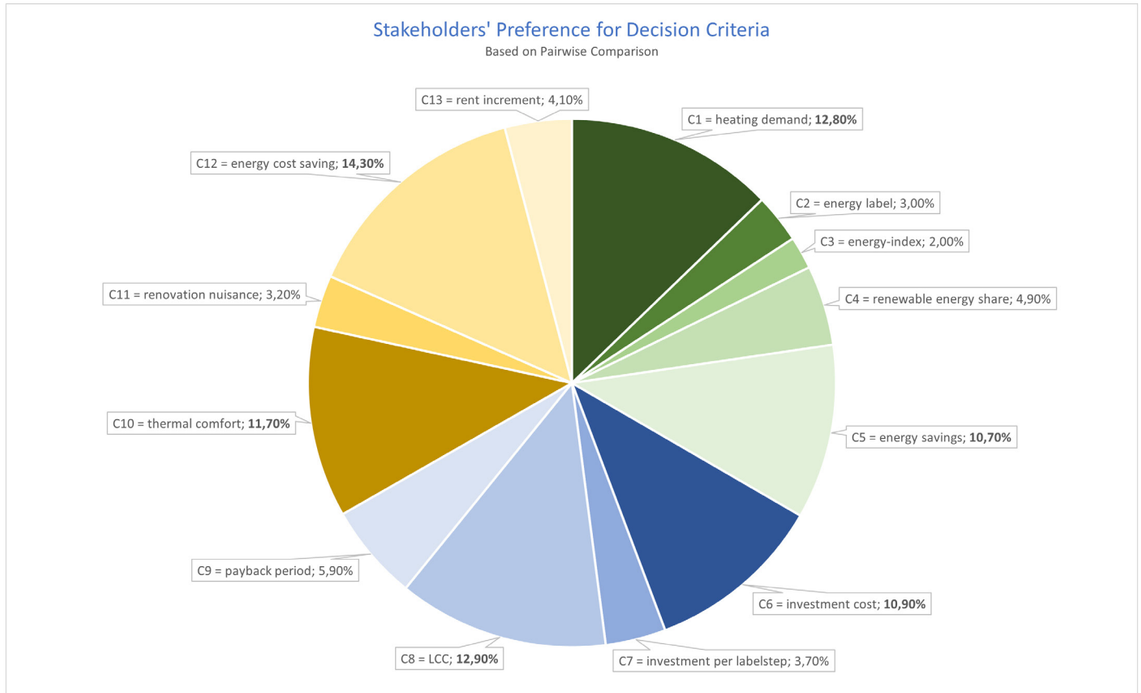


Figure 7.3.13 Stakeholders' preference for Decision Criteria [green = environmental; blue = economic; yellow = social]

A9. The best performing renovation scenarios for economic criteria are A7, A5 and A2, and the optimal alternatives for social criteria are A5, A2 and A4.

The participants of the workshop indicated a preference for energy cost saving (C12, 14.3%), heating demand (C1, 12.8%), LCC (C8, 12.9%), thermal comfort (C10, 11.7%), energy savings (C5, 10.7%) and investment cost (C6, 10.9%), see figure 7.3.13. Of their preferred criteria, only the investment cost is a critical criterion. In the final ranking based on the performance and balanced preferences of the stakeholders scenario A9 ranks 1st, followed closely by A5 and A7. Based on the results from the sensitivity analysis, it can be concluded that the ranking including the stakeholders' preferences is robust.

An additional sensitivity analysis is conducted to gain insight into the effect on the ranking of prioritizing and de-prioritizing the LT-ready criteria (C1 heating demand and C10 thermal comfort). The same approach as mentioned above is taken, only now equally prioritizing C1 and C10 and proportionally decreasing C2-C5 and C11-C13. A value of 1% is taken for the de-prioritization of C1 and C10, proportionally increasing C2-C5 and C11-C13. Table 7.3.18 shows the ranking of equal weights for comparison, and the new ranking for the prioritized and de-prioritized C1 and C10. Figure 7.3.14 provides the graphical representation of the ranking provided by the table. This sensitivity analysis shows that prioritizing both LT-ready criteria does not have an influence on what is considered the optimal alternative (still A9), and only switches 2nd and 3rd placed alternatives (A5 with A7). However, when de-prioritizing the LT-ready criteria, a larger shift in ranking is noticeable. It can be concluded that, as long as the LT-ready criteria are not extremely underrepresented in preference, it is likely that alternatives with a strong LT-ready performance are suggested as the optimal alternative through this way evaluating performance and preference.

	Equal weights		C1 = 26,7% C10 = 28,3%		C1 = 1% C10 = 1%	
	Pi	RANK	Pi	RANK	Pi	RANK
A1	0,408	9	0,555	7	0,371	9
A2	0,596	6	0,649	6	0,570	8
A3	0,517	8	0,263	9	0,611	6
A4	0,601	5	0,282	8	0,733	1
A5	0,679	3	0,811	2	0,641	5
A6	0,661	4	0,683	4	0,642	4
A7	0,723	2	0,743	3	0,705	2
A8	0,595	7	0,667	5	0,575	7
A9	0,725	1	0,857	1	0,679	3

Table 7.3.18 TOPSIS decision analysis ranking A1-A9 equal criteria weights compared to prioritized and minimized heating demand and thermal comfort decision criterion

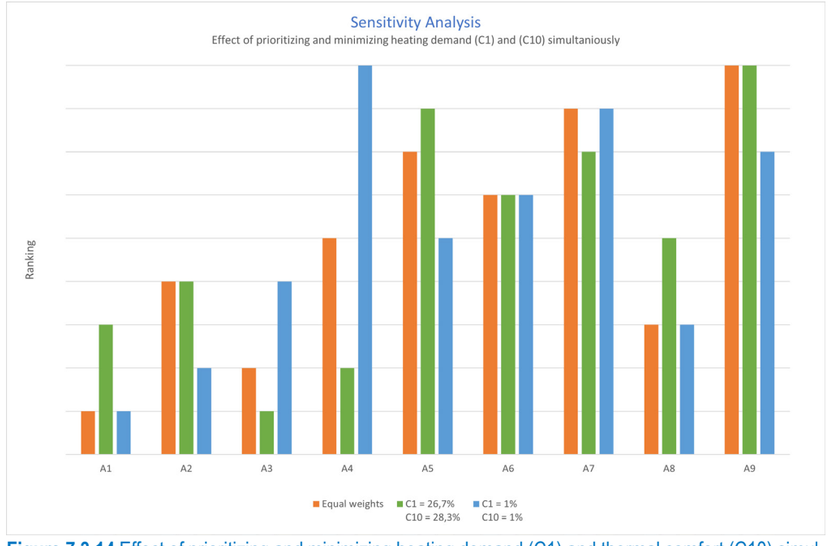


Figure 7.3.14 Effect of prioritizing and minimizing heating demand (C1) and thermal comfort (C10) simultaniously. [orange = equal; green = prioritized; blue = minimized]

7.3.4.6 Semi-structured interview results

During the workshop 3 question rounds were done. Some questions were ranking based questions supported by the questionnaire sheet, others were open questions.

Representation of real-world decision-making process

The participants of the workshop unanimously agreed both verbally and on paper in the ranking questionnaire that the framework is an accurate representation of their decision-making process on the case study. The framework is according to the stakeholders clear, concise and provides a structured overview representing the real-world process. The participants also expressed a (strong) agreement when asked if the presented framework application represented a thorough decision analysis, especially the analysis on the environmental aspects. It was mentioned that a more in-depth analysis of social aspects could be beneficial for a more accurate analysis. Furthermore, it was questioned if all decision aspects can be completely captured by a framework and/or tool due to the complexity of the real-world scenario. This comment related to the new developed renovation scenarios (A5-A9). Questions were raised about replacing the existing radiators, as well as introducing balanced ventilation systems. Although it was understood that those measures are a necessity to reach LT-readiness for this case, it does not represent feasible measures in the real-world scenario. The tenants need to be able to stay at home during renovations, an important limitation that was not mentioned in the provided case study documents and therefore not incorporated when developing new renovation scenarios. Questioned marks were also placed at the renovation measure of floor insulation. Although this might have a positive impact on reaching simulated LT-ready goals, in practice this measure has some footnotes. Tenants do not have given any complaints about cold feet, since the apartments are placed above the bicycle and storage area. Obtaining tenant support (draagvlak) for floor insulation is very unlikely since they would have to empty the bicycle and storage areas. It is difficult to capture those technical vs. social feasibilities in a framework and tool. On top of that, the stakeholders involved in the case study did not strive for LT-readiness, but for energy label improvement. Therefore, it makes sense that the new developed alternatives are to them an incorrect representation of the real-world scenario, and that their preference remains for scenario A4 or A2 instead of the newly presented A9, A5 or A7. When placing themselves in the perspective of LT-readiness, they do agree with the presented ranking. It would be interesting for future research to see if LT-readiness can be reached when limited to renovation measures that can be executed without tenant removal during renovations.

Decision support function

The participants unanimously agreed on the questionnaire that the decision support tool can accurately represent the stakeholders preferences, both from a policy and personal perspective. The method of pairwise comparison is according to the participants promising and supportive to the decision-making process, and could definitely help to make a better informed decision. It was mentioned that this is a quick and analytical way to get to an informed decision. In early stages of the project this can lead to concise and targeted discussions, speeding up the decision-making process. This is a novelty compared to their existing decision-making process, which is currently based on a mix of gut feelings selectively supported by quantified data on a few decision parameters. This framework and tool would provide an analytical backup to those gut feelings, which is according to the participants interesting and helpful. It was mentioned that it could also work as an reflective tool to evaluate policy from previous years.

Usability

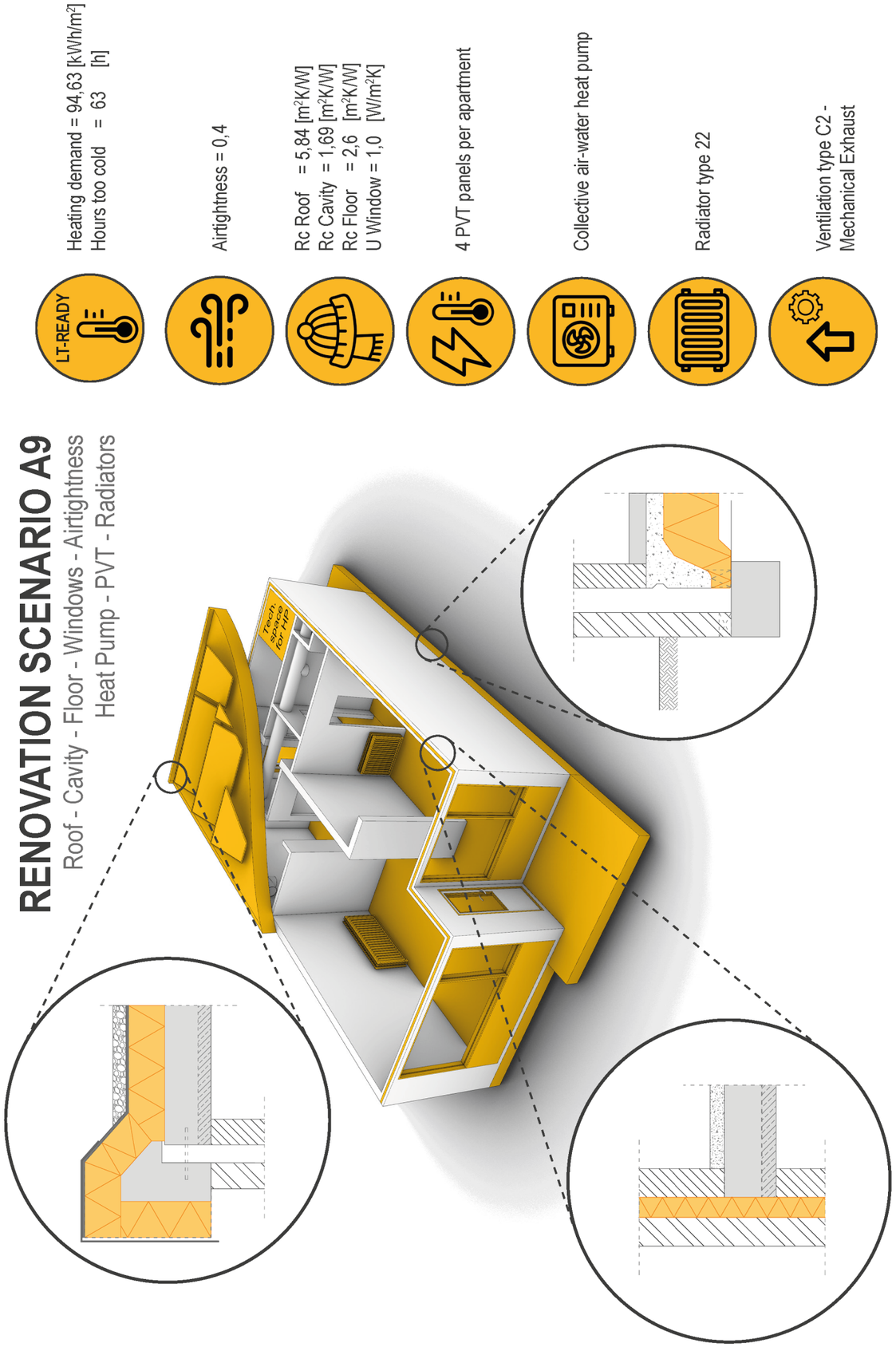
The participants are in agreement about the usability of the general framework. When asked how they would utilize this framework in their own process, the following response was given: one of the options is to use the equal weights decision analysis to benchmark their policy, and then ask the steering group and project team for their input on the pairwise comparison for a decision analysis with balanced weights, and compare those two as a reflective tool for their policy. This is seen as a good opportunity to kickstart the project with a focussed discussion, as well as a support to developing the project strategy.

The fact that no large issues were addressed during the decision analysis of the workshop, and results of the pairwise comparison for criteria weights and TOPSIS for ranking were obtained and presented quick and easy lead to the conclusion that the workshop was a success, and that for this case study both the framework and tool are validated on its usability. Another implicit validating argument for the usability of the framework was the invitation of the participants to do this workshop again for another group of stakeholders within their company, whom could also benefit from this decision support framework.

Improvement suggestions

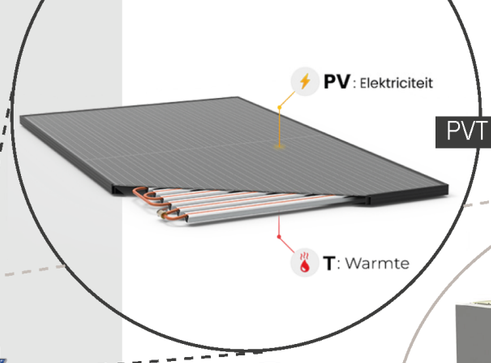
The participants provided several suggestions to improve the framework. The first one is introducing a feedback loop. This feedback loop was removed from the simplified framework, since all the arrows could be distracting, but is present in the elaborated decision

support framework. This validates the existence of the iterative aspects of the process. The second suggestion was to switch framework step 1 (building analysis & benchmarking) with step 2 (identifying decision parameters). This would enhance the natural work process representation, since step 2 is program related while step 1 is project related. The third suggestion was to introduce an element in the decision support tool that can filter out non-feasible renovation scenarios based on project specifics. For example, tenants should be able to stay at home, eliminating several renovation options. The fourth suggestion was introducing a framework step before or parallel to the building analysis & benchmarking, which would be the risk assessment, as decision criteria alone cannot make risk factors explicit. A thorough risk analysis could highlight potential issues more clearly. This suggestion relates to the filter of renovation measures based on what is feasible and what not.

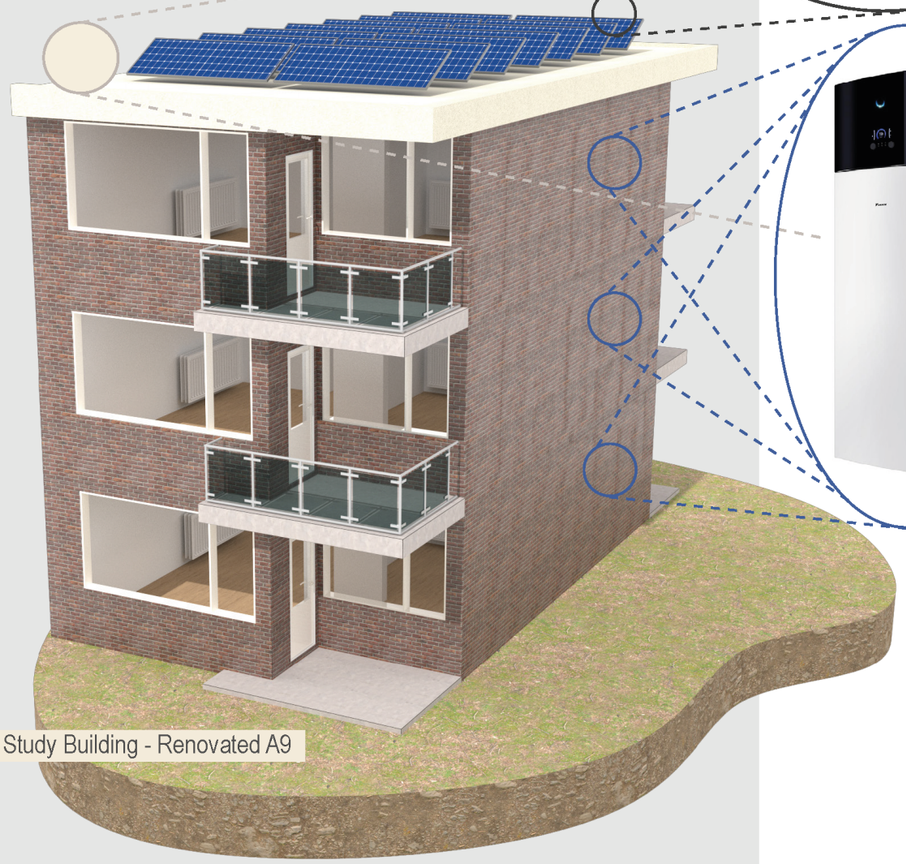


RENOVATION SCENARIO A9

Roof - Cavity - Floor - Windows - Airtightness
Heat Pump - PVT - Radiators



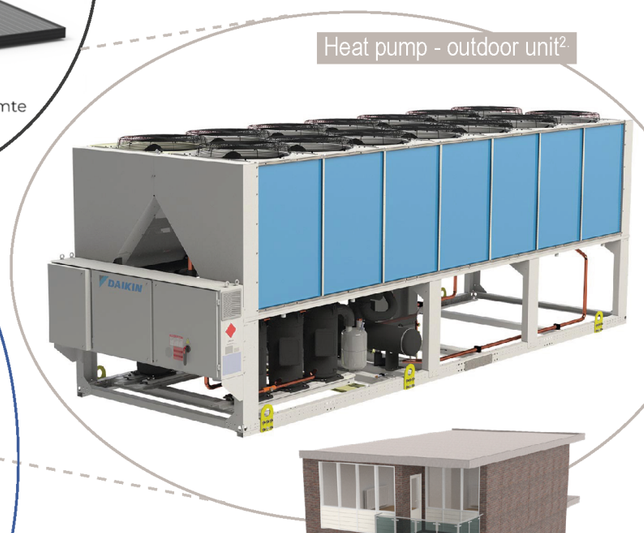
PVT panel[1.]



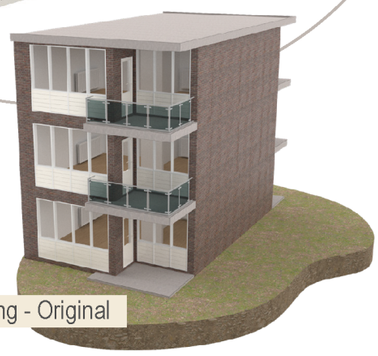
Case Study Building - Renovated A9



Heat pump - indoor unit [3.]



Heat pump - outdoor unit[2.]



Case Study Building - Original

The Decision Support Tool suggest renovation scenario A9 the overall best performing alternative. This scenario includes the placement of a collective air-water heat pump, of which the outdoor unit can be placed on the roof (not in render). Every apartment has an individual indoor unit placed in the indoor storage. The PVT panels are connected to the air-water heat pump as an energy source. The radiators type 21 are replaced by radiator type 22 to increase the heating capacity to reach LT-readiness, together with the renovation measures on the building envelope scale.

1. Taken from https://www.qsilence.com/qpanel
2.& 3. Taken from https://www.daikin.nl/warmtepomp

DISCUSSION & CONCLUSION

8. DISCUSSION

The results of this research have provided insight into how the decision-making process of selecting a LTH-renovation scenario can be supported by developing a decision support framework and tool based on a multi-criteria decision-making approach utilizing the pairwise comparison and TOPSIS method. Nonetheless, the results of this research should be interpreted with caution due to the limitations of the current research. This chapter provides a reflection on the research results, a discussion on the limitations as well as recommendations for future research.

8.1 Discussion on workshop results

The workshop aimed to validate the low-temperature heating decision support framework and tool on their function by focussing on the practical applicability and effectiveness in real-world scenarios. The workshop consisted of a presentation where the framework is applied to the case study, an exercise using the decision support tool, and a semi-structured group interview to evaluate and gain feedback on its functionality and usability. The participants of the workshops are 4 expert stakeholders in the field of residential energy renovations who were involved in the decision-making process of the case study. The stakeholders had the role of either a program manager or project leader, from either a social housing organization or an energy transition focussed on the built environment company.

One of the key findings of the workshop is that the stakeholders unanimously agreed on that the LTH-DS framework accurately represents their real-world decision-making process, describing it as clear, concise and structured. The participants were of the opinion that the application of the framework and tool have delivered a thorough analysis of the case study, especially on the environmental aspects. The framework and tool are considered supportive of the decision-making process through the method of pairwise comparison and TOPSIS. Especially the pairwise comparison method is noticed and praised for its potential and ability to reflect on policy and preferences in a quick and analytical manner. The tool is considered promising to reach a more informed decision, as well as instigating targeted discussions at an early stage of the project. It is viewed as a valuable reflective tool which has the potential to refine existing policies. The participants expressed interest in using the tool for other projects within their company, indicating the frameworks' potential for broader application.

Based on these workshop findings, it can thus be concluded that both the framework and the tool are promising in terms of supporting the decision-making process on selecting a low-temperature heating renovation scenario, which aligns with published research that uses MCDM in the field of energy renovations. This confirms the first part of this research hypothesis, which stated that the selection process of LT-renovation concepts as well as the decision-making process can be supported through a decision support framework and tool. For this specific stakeholder group the theory that the framework and tool is able to balance the preferences and providing a satisfactory ranking is confirmed. The hypothesis that this framework and tool can contribute to shortening the process is not literally verified, but the statement that this framework with tool can contribute to targeted discussion at an early stage of the project is a positive indicator for this.

8.2 Discussion on ranking results

The hypothesis of the framework stated that evaluating renovation alternatives across decision criteria from all three pillars of sustainability could lead to a suggested optimal alternative that is not the obvious choice. The obvious choice from a traditional perspective would be the scenario that has the lowest investment costs relative to the highest energy performance, in that case A4 since it has the lowest investment costs per increase in energy label. However, when looking at all decision aspects a new scenario emerges as the best performing alternative: A9. This scenario has neither the lowest investment costs, nor has it the best performance score on the heating demand. Yet, when taking into consideration the performance scores of all decision criteria combined, this is the suggested optimal according to the TOPSIS method. This is gives a positive indication to the confirmation of the hypothesis. The sensitivity analysis confirms the robustness of the ranking results, contributing to the reliability of this confirmation. An additional cross-validation of the TOPSIS method could contribute to further validation of the robustness of the ranking results. Also, expansion of the validation by testing with multiple stakeholder groups can contribute to a higher level of certainty on the statements and findings of this research.

Incorporating stakeholders preferences through balanced criteria weights in the decision analysis led to new suggestions on what is considered the optimal alternative compared to the original decision analysis evaluating on just the performance of the alternatives. This suggests that integrating stakeholder preferences can have a significant impact on the perceived optimal solution. The sensitivity analysis shows that the decision criterion on investment costs, renovation nuisance and rent increment are critical criteria. As long as the LT-ready criteria are not significantly underrepresented in preference, it is likely that alternatives with strong LT-ready performance will be suggested as the optimal choice when evaluating the renovation alternatives through TOPSIS.

8.3 Innovation

One of the novel aspects of this research is the fact that many decision criteria can be compared at once, not only on estimated performance but also while incorporating the preferences of the stakeholders. Traditionally only costs vs energy benefits are compared, sometimes with some additional unquantified vague decision criteria, where decision makers select a scenario based on their gut feeling. This framework and tool can support the decision making process by confirming or debunking their gut feeling based on quantified performance and preferences, leading to a better informed decision.

Another innovative aspect of this research is that the decision support framework is specified to LTH. One of the findings from the literature research on LTH renovations is that it is expected that by 2050 almost all buildings will be connected to a renewable heating source to reach the climate goals. These renewable sources are often (U)LT sources, emphasizing the need for the energy transition of the existing building stock, preparing them for LTH. Having a decision support framework and tool that can help select suitable LTH renovation scenarios directly contributes to the heating transition, preparing the existing building stock for gas free heating.

8.4 Limitations of research & suggestions for future research

Pinpointing the limitations of this research can help identify areas of improvement, leading to useful recommendations for future research. The following limitations are determined:

1. **Select validation group.**
   The validation process was conducted with a small group of stakeholders, which constrains the generalizability of the findings. The insights and feedback gathered are specific to the participants involved and may not be representative of a broader range of stakeholders. Conducting additional research with a more diverse stakeholder group would enhance the reliability and applicability of the research outcomes.
2. **Single case study.**
   In addition to the first limitation, the validation process is based on just one single case study. Although the results from this single application is promising, a more extensive validation involving multiple case studies (and multiple stakeholder groups) is necessary to strengthen the credibility of the research. For future studies it could be considered to apply the framework and tool to ongoing cases rather than completed projects, to better capture the decision-support function during the actual process.
3. **Thermal comfort quantification.**
   This researched measures thermal comfort based on the amount of hours underheated in the living room area. However, a more complete scope of thermal comfort would be addressing the risk of overheating during summertime as well.
4. **Method used for Decision Support Tool.**
   Both pairwise comparison and TOPSIS are empirically validated methods. However, the results of those methods require a sensitivity check to test its reliability. Cross-validation with other MCDM methods could provide a more definitive assessment. Significant differences in ranking across methods could indicate an unreliability in the ranking results, while small differences would suggest robustness of the results. A risk of the TOPSIS method is that the results are interpreted as absolute, since it provides a clear numerical ranking. The tool tries to capture subjective preferences, qualitative and quantitative decision criteria and translate those into numerical performance values to obtain a ranking. However, the ranking results should be placed in the perspective of the tools aim: supporting the decision-making process, not replacing the decision-making process. It should be seen as an addition to make the process more transparent and efficient, not as a replacement for the discussion or the process.
5. **Accuracy of quantified performance data.**
   The accuracy of the ranking results from the decision support tool are influenced by the precision of the quantified decision criteria. The ranking results are only as valuable as the input data provided. For the application of the case study, some decision criteria were quantified through in-depth simulations (e.g. heating demand & thermal comfort), while others were estimated (e.g. rent increment, renovation nuisance). This leads to an imbalanced level

of accuracy across the decision criteria, introducing the risk of noise and inconsistency. Consequently, conclusions drawn from the ranking results should be approached with caution, though they remain promising. For future studies it would be useful to make sure that every quantified value has the same level of accuracy to ensure more reliable ranking results.

6. **Inconsistent criteria weights.**
During the workshop, only 1 out of 4 participants provided consistent criteria weights (consistency threshold 10%). This inconsistency can affect the reliability of the final ranking. Future research could focus on the effort required to achieve consistent criteria weights, as well as investigate the impact of inconsistent criteria weights on the final rankings.
7. **Decision parameters.**
The decision support tool restricted the pairwise comparison of the decision criteria per category to limit the amount of comparisons, as well as nudge the users to making a holistic, informed decision. This approach might not accurately reflect the real-world scenario, where the importance of social, economic and environmental aspects can vary, especially in a technical field like energy renovations. However, adopting this approach does potentially lead to new insights, broadening the perspective on which renovation scenarios are currently being selected.
8. **Subjectivity of categorization.**
Placing the decision criteria in a certain category is a subjective process (e.g. is energy costs an economic or social criterion?). Determining which criteria is placed in what category influences the mutual comparison, which then influences the ranking of the alternatives. However, decision-making is an inherently subjective matter. Nonetheless, it can be made transparent and informed by objective performance by making the decision aspects explicit.
9. **Role vs. personal preferences.**
During the analysis of the workshop results, it became clear that some participants completed the pairwise comparison based on their personal preferences rather than policy preferences. This fuzziness could have had an influence on the ranking results. For future research, it is important to clearly state the perspective from which the participants should complete the pairwise comparison.

Apart from the mentioned recommendations related to the identified limitations, the following recommendations could improve the research:

1. **Incorporate stakeholders feedback.**
Processing the feedback provided by the participants of the workshop will lead to a framework and tool that is more robust, practical and in alignment with the real-world scenario.
2. **Optimizing the usability of the decision support tool.**
The tool could be improved by implementing MATLAB or Python which could reduce the risk of errors associated with the Excel tool, since this provides more flexibility and automation in the usability. This includes functions like scaling the amount of decision criteria and adjusting the amount of alternatives for the decision analysis.
3. **Optimizing the interface of the framework and tool.**
Visualizing the framework as a roadmap and combining the sub-quantification tools into a user-friendly website would improve the user experience. This would enable a more intuitive use of the framework and tool, broadening the applicability by making it accessible to users with less expertise in the field of decision making in energy renovations. This could also include more intuitive visualisation of the ranking of the alternatives, and the comparison of performance between certain decision criteria.
4. **Developing a tool to generate LT-ready scenarios.**
Due to time constraints this research did not focus in great detail on the development of LTH-renovation scenarios. Developing a tool to generate alternatives based on different renovation approaches could be a valuable addition to the existing framework and decision support tool.
5. **From theory to practice.**
The data in this research is based on simulations that try to approach the real-world scenario. However, to make certain that the suggested LTH-renovation scenarios will work in practice, pilot studies should be done before implementing the use of the framework and tool on a wider scale.

9. CONCLUSION

The global dependency on fossil fuels in the energy sector causes alarming levels of greenhouse gas emissions, creating an urgency and necessity to transition to renewable energy sources. Up to 90% of all residential dwellings in the Netherlands use natural gas as their primary source of energy, of which 76% is used to cover the space heating demand. One of the challenges in transitioning from fossil fuels to renewable energy for the space heating demand is the difference in temperature: a switch needs to be made from high-temperature heating systems to low-temperature heating systems. This research addressed the complexity of the decision-making process in selecting suitable renovation scenarios for multi-family buildings in the Netherlands to prepare them for gas-free, low-temperature heating. The following research question was central to the study:

"How can the decision-making process of selecting an energy renovation concept be supported that aims to make existing residential apartment buildings compatible with low-temperature heating?**"**

To answer this main question, several sub-research questions were developed related to low-temperature heating renovations, decision-support in energy renovations and the combination of those two topics.

1. How can an existing residential building be made compatible for low-temperature heating?
This research adopted two indicators for LT-readiness: an equal or reduced space heating demand as well as an equal or improved thermal comfort level when comparing the new LT-situation to the original HT-situation. Some buildings have a large overcapacity of the heating system, potentially eliminating the need for renovation. Other buildings that are not yet LT-ready are in need of renovation to facilitate this. Renovation measures that can compensate for the reduced heating capacity at LT-supply can take place on the building envelope or building installation scale. For example, adding insulation to the wall, floor or roof, upgrading windows and doors and improving airtightness, or installing low-temperature radiators, underfloor heating or implementing mechanical or balanced ventilation systems with heat recovery. Different combinations of these measures can lead to LTH-renovation scenarios.

2. Which decision-making phases can be identified in energy renovation processes?
Common phases in the decision-making process in energy renovations is the problem definition paired with building analysis, the identification of decision parameters, specifying the relative importance of those parameters (often based on stakeholders' preferences), developing renovation alternatives, quantifying the performance of the renovation scenarios based on the decision criteria, and evaluating the alternatives based on their performance through decision analysis. When stakeholders are in agreement, a final alternative is selected and the next phase of implementation can start. Before reaching this final decision, the afore mentioned phases are often iterated and adapted according to the needs of the decision-makers. Specific decision-making aspects for LTH renovation projects is the evaluation of LT-readiness of the building at an early stage to check if there is a need for renovation, and another evaluation of LT-readiness after the development of the renovation scenarios to guarantee a suitable solution.

The most suitable methods to evaluate which renovation alternative is the most optimal solution considering the performance is the multi-criteria decision-making method TOPSIS. This method is adopted in this research to support and structure the decision analysis.

3. What are the key decision parameters in energy renovations?
Based on a literature review a decision-tree for LTH energy renovations is developed. The decision-tree provides structure and overview which supports the identification of key decision parameters and adopts a holistic perspective for the making of a more informed decision. The three pillars of sustainability are the base of the tree, leading to decision objectives like 'improving the energy performance', 'optimizing the cost-benefits' and 'improving indoor comfort', prompting several decision criteria like 'energy demand', 'payback period' and 'thermal comfort'. The decision-tree is a guidance for stakeholders to quickly identify their decision parameters. However, every renovation project is unique, so the decision parameters should be tailored to the needs of the

decision-maker. Nevertheless, to guarantee decision-support for LTH, there are two non-negotiable decision criteria: heating demand and thermal comfort. By always incorporating these two criteria the evaluation of LT-readiness can be facilitated. All selected decision criteria have to be quantified for the decision analysis. This can be supported through energy performance simulations and other software and calculation tools, or when dealing with qualitative criteria by developing descriptive scales to estimate the performance of a renovation scenario. Ensuring a comparable level of accuracy in the performance data per decision criteria safeguards the reliability of the TOPSIS ranking.

4. Who are the stakeholders involved in LTH renovation projects and what is their role?

There are 18 types of stakeholders identified from literature review who are involved in the decision-making process of renovation projects. These include the occupants of the building, who can be tenants or owner-occupants, the owner of the building, which can be a social housing association, investor or a private-owner, and the team involved in the development and implementation of the project, like project managers, consultants, net operators, municipality and contractors. These stakeholders are categorized on four types of influence on the decision-making process, which is decision-maker, informant, authorizer and implementer. Each stakeholder has their own role and interests, which can lead to conflicting priorities of decision criteria. For example, a social housing corporation may prioritize limiting investment costs, while the tenants focus is on thermal comfort improvements. The pairwise comparison method is an excellent approach to identify the preferences of the different stakeholders, to obtain balanced criteria weights which represent the relative importance of decision criteria in an analytical manner. These criteria weights are incorporated into the TOPSIS method for a decision analysis where the alternatives are not only analysed based on their performance, but also on the preferences of the involved stakeholders.

5. How can the acquired knowledge on LTH and Decision-Support be combined in a way that supports the assessment and selection of LT-renovation scenarios?

The answers to the previous sub-questions led to the development of a decision-support framework and tool, designed to streamline and aid stakeholders in the selection process for LTH renovation concepts. The framework is based on a general MCDM framework and adapted to specifically support the decision-making process of LTH-renovation scenarios. Several steps of the framework are supported by tools like the LTH-grasshopper tool to benchmark the original scenario, check LT-readiness and simulate the LT-performance of the developed scenarios. The decision support tool aids in the pairwise comparison and TOPSIS calculations to identify the most optimal LT-renovation scenario through ranking. This tool provides a quick and analytical way to decision analysis. Both the framework and the tool are validated on its decision support function and usability through a case study application and workshop with four expert stakeholders in the field of residential energy renovations. The main findings of the workshop was that the framework is an accurate representation of their real-world decision-making process, that the pairwise comparison is an excellent method to make the preferences explicit, and that the decision analysis provided by the tool would be an innovative addition and support to their existing process. The stakeholders see potential to use the tool for reflection purposes on their policy. Some minor improvements were suggested which could improve the usability and applicability of the framework and tool.

Based on the information provided on the sub-questions, the main research question can be answered.

The decision-making process of selecting an energy renovation concept that aims to make existing residential apartment buildings compatible with LTH can be supported through the use of a comprehensive decision-support framework and accompanying tools. The framework provides a structured approach to the process through identification and analysis, data collection, scenario generation and evaluation. This structured process ensures that all relevant decision-making aspects are considered systematically. Incorporating MCDM methods and adopting a holistic approach supports the making of a well-informed decision. The use of the LTH-grasshopper tool simulating heating demand and thermal comfort quickly provides essential performance data to identify suitable LTH-renovation scenarios. The decision support tool ranks the renovation alternatives based on the performance and preferences, facilitating a transparent and data-driven selection process.
In conclusion, the decision support framework and tools developed in this thesis provide a comprehensive and structured approach to the selection of a LTH-renovation scenario for multi-family buildings in the Netherlands. This provides guidance in the complexity and potentially reduces the time of the decision-making process, accelerating the rate of energy-efficient renovations. The use of this low-temperature heating decision support framework can thus contribute to mitigating climate change and ensure a more sustainable future.

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APPENDIX A

Dutch Building Stock Analysis

A.1 Property types & ownership distribution

The Dutch Building stock in 2018 consists of roughly 7.5 million homes. The Netherlands Enterprise Agency (2022) identified 8 common building types:

1. Detached houses
2. Semi-detached houses
3. Terraced houses (middle)
4. Terraced houses (corner)
5. Maisonette houses
6. Gallery apartment
7. Staircase apartment
8. Apartment (other)

Type 1-4 are considered single-family homes, type 5-8 are considered multi-family homes. Single family homes are ground-level based where multi-family homes are stacked buildings. Table A.1 provides data on the amount of dwellings per type, figure A.1 illustrates an overview of the share of the building stock per dwelling type. This clearly illustrates that the Dutch building stock consists for the largest part of single-family homes, with terraced houses as the most common dwelling type.

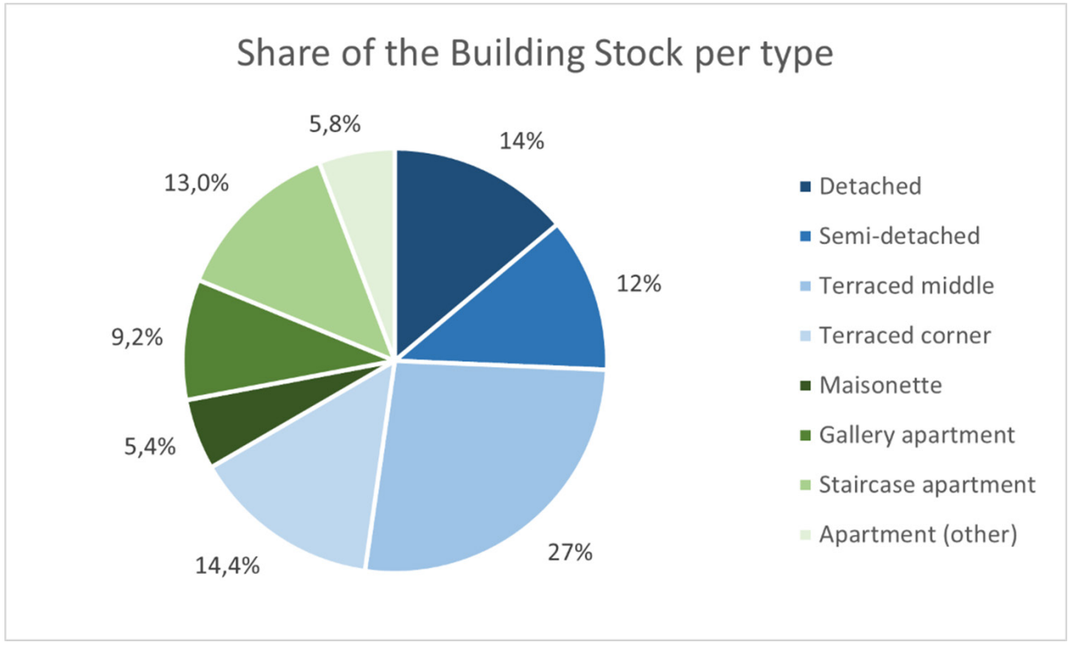


Figure A1 - Dutch Building Stock 2018, share of stock per dwelling type. Based on data from Netherlands Enterprise Agency (2022) – Voorbeeldwoningen 2022

Data on ownership distribution provided by the Netherlands Statistics (2023b) is illustrated figure A.2. This shows that almost 3/5 of the Dutch building stock is owner-occupied, compared to 1/3 owned by social housing associations and approximately 1/8 owned by other landlords. Data on ownership distribution per building type from the Netherlands Enterprise Agency (2022) can be found in table A.1 and is illustrated in figure A.3. Roughly 78% of all single family homes is owner-occupied, while roughly 75% of all multi-family homes are rentals.

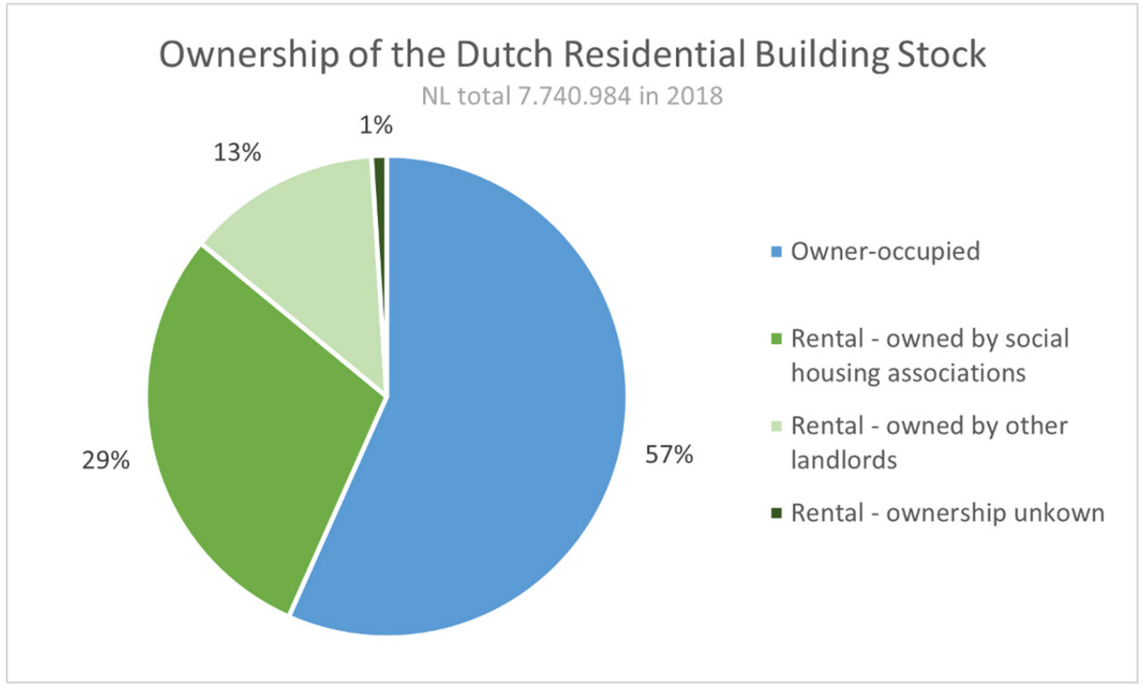


Figure A2 - Ownership of the Dutch Residential Building Stock in 2018 Based on data from Netherlands Statistics (2023b)

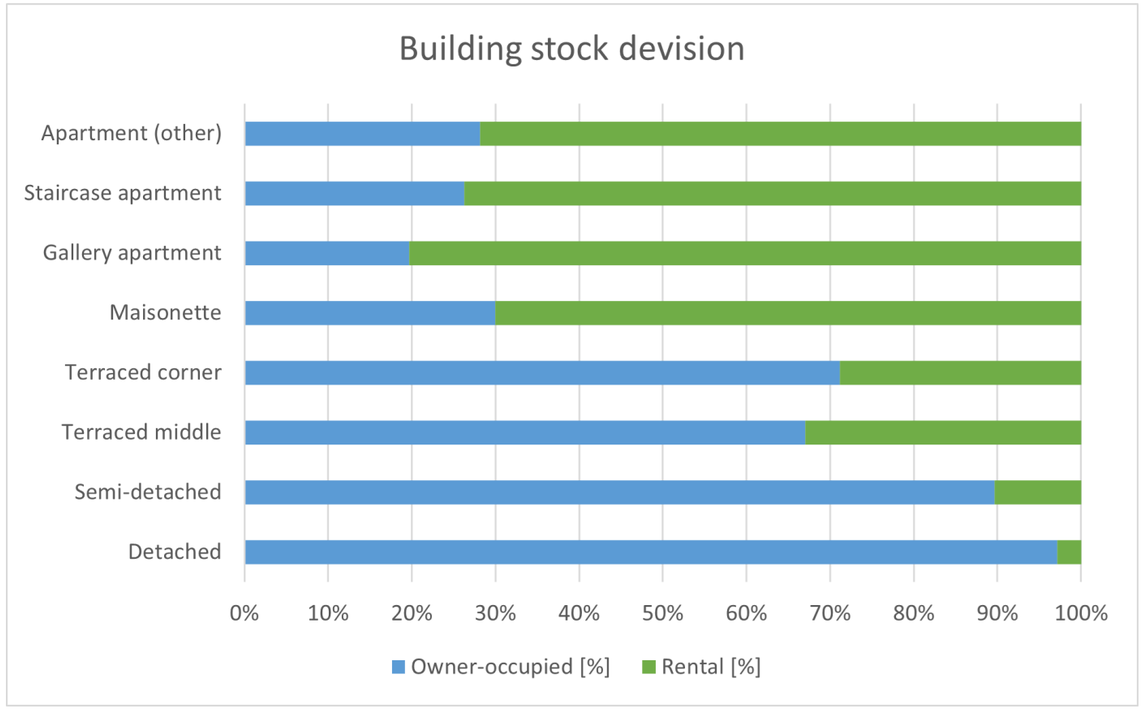


Figure A3 - Residential Building Stock owner-occupied versus rental ratio per building type. Based on data from Netherlands Enterprise Agency – Voorbeeldwoningen (2022)

Voorbeeldwoningen 2022 Building type	Amount of Dwellings	Building stock [%]	Owner-occupied [%]	Rental [%]	Average heat demand [kWh/m²]	De Standaard [kWh/m²]	Deviation from 'de standaard' [kWh/m²]
Detached	**1.040.500**	**14%**	**97%**	**3%**			
before 1965	418.000	5,6%	88,0%	12,0%	213,6	92,8	120,8
1965-1974	128.500	1,7%	100,0%	0,0%	204,9	87,8	117,1
1975-1991	201.000	2,7%	95,0%	5,0%	157,3	90,3	67,0
1992-2005	196.000	2,6%	100,0%	0,0%	122,2	90,2	32,0
2006-2014	66.000	0,9%	100,0%	0,0%	104,4	84,7	19,7
2015-2018	31.000	0,4%	100,0%	0,0%	91,4	93,6	-2,2
Semi-detached	**883.000**	**12%**	**90%**	**10%**			
before 1965	330.000	4,4%	80,0%	20,0%	197	80,5	116,5
1965-1974	101.500	1,4%	94,0%	6,0%	183,5	75,8	107,7
1975-1991	217.000	2,9%	93,0%	7,0%	139,1	79,2	59,9
1992-2005	152.000	2,0%	93,0%	7,0%	108	78,0	30,0
2006-2014	60.500	0,8%	99,0%	1,0%	94,3	76,1	18,2
2015-2018	22.000	0,3%	79,0%	21,0%	72,2	64,2	8,0
Terraced middle	**1.983.500**	**27%**	**67%**	**33%**			
before 1946	333.500	4,5%	73,0%	27,0%	160,7	107,8	52,9
1946-1964	235.500	3,2%	52,0%	48,0%	162,5	61,6	100,9
1965-1974	407.000	5,4%	61,0%	39,0%	141,9	57,5	84,4
1975-1991	573.000	7,7%	70,0%	30,0%	108,4	57,0	51,4
1992-2005	262.000	3,5%	73,0%	27,0%	81,4	61,0	20,4
2006-2014	129.000	1,7%	75,0%	25,0%	74,5	58,3	16,2
2015-2018	43.500	0,6%	65,0%	35,0%	68,8	62,0	6,8
Terraced corner	**1.070.000**	**14,4%**	**71%**	**29%**			
before 1946	125.000	1,7%	84,0%	16,0%	259,6	169,2	90,4
1946-1964	136.500	1,8%	55,0%	45,0%	208,2	84,2	124,0
1965-1974	251.000	3,4%	52,0%	48,0%	183,6	75,6	108,0
1975-1991	362.000	4,8%	61,0%	39,0%	132,3	75,8	56,5
1992-2005	118.500	1,6%	83,0%	17,0%	110,7	81,8	28,9
2006-2014	56.500	0,8%	73,0%	27,0%	91,8	76,9	14,9
2015-2018	20.500	0,3%	90,0%	10,0%	79,4	76,7	2,7
Maisonette	**403.000**	**5,4%**	**30%**	**70%**			
before 1965	233.000	3,1%	46,0%	54,0%	154,9	45,0	109,9
1965-1974	5.000	0,1%	12,0%	88,0%	157,7	50,8	106,9
1975-1991	96.000	1,3%	16,0%	84,0%	93,6	47,6	46,0
1992-2005	48.500	0,6%	57,0%	43,0%	76	45,0	31,0
2006-2014	19.500	0,3%	52,0%	48,0%	58,8	48,2	10,6
2015-2018	1.000	<0,1%	0,0%	100,0%	51,2	48,2	3,0
Gallery apartment	**682.000**	**9,2%**	**20%**	**80%**			
before 1965	83.000	1,1%	15,0%	85,0%	144,4	45,0	99,4
1965-1974	209.000	2,8%	19,0%	81,0%	111,2	45,0	66,2
1975-1991	117.000	1,6%	21,0%	79,0%	90,2	45,0	45,2
1992-2005	139.000	1,9%	28,0%	72,0%	75,4	45,0	30,4
2006-2014	103.500	1,4%	32,0%	68,0%	66	45,0	21,0
2015-2018	30.500	0,4%	3,0%	97,0%	35	45,0	-10,0
Staircase apartment	**977.000**	**13,0%**	**26%**	**74%**			
before 1946	282.500	3,8%	27,0%	73,0%	176,6	104,4	72,2
1946-1964	246.500	3,3%	17,0%	83,0%	154,2	55,7	98,5
1965-1974	136.000	1,8%	28,0%	72,0%	120,7	45,4	75,3
1975-1991	197.500	2,6%	16,0%	84,0%	98,3	49,1	49,2
1992-2005	68.500	0,9%	38,0%	62,0%	79,3	48,0	31,3
2006-2014	35.500	0,5%	55,0%	45,0%	73,7	48,3	25,4
2015-2018	10.500	0,1%	3,0%	97,0%	83,8	59,7	24,1
Apartment (other)	**431.000**	**5,8%**	**28%**	**72%**			
before 1965	44.000	0,6%	20,0%	80,0%	121	45,0	76,0
1965-1974	33.000	0,4%	10,0%	90,0%	118,3	45,0	73,3
1975-1991	98.000	1,3%	30,0%	70,0%	85,1	45,0	40,1
1992-2005	128.000	1,7%	52,0%	48,0%	75,9	45,0	30,9
2006-2014	109.500	1,5%	29,0%	71,0%	65,6	45,0	20,6
2015-2018	18.500	0,3%	28,0%	72,0%	56,5	45,0	11,5

Table A1 - Dutch Building Stock – Distribution, ownership & heat demand per dwelling type

A.2 De Standaard, Streefwaarden & Voorbeeldwoningen 2022

The Netherlands Enterprise Agency [Rijksdienst voor Ondernemend Nederland, RVO] (2023) has published ‘de Standaard’, which is a limit value for the heat demand of a dwelling. If the heat demand is equal or lower than de Standaard, that indicates that the building is ready to switch from natural gas to LT-renewable sources like geothermal, aquathermal and heat pumps. If the heating demand is higher than de Standaard, that indicates that the building requires energy improvement measures like insulating the walls, floors and/or roofs, changing the windows, changing the ventilation system or improving the air tightness. De Streefwaarden are guideline insulation values for different building elements to indicate future-proofness so that renewable LT-heating can be enabled. Not all Streefwaarden need to be implemented to reach de Standaard.

De Standaard is dependent on the compactness factor of a dwelling, which is influenced by the ratio of the indoor floor surface area [A_g] and the transmission area of elements that separate the inside area from outside [A_{is}], like the façade, roof and ground floor. Table A.2 provides information on how de Standaard is calculated based on different building types and building year. All calculations for de Standaard are based on NEN-norm NTA8800 and expressed in kWh/m^2. Buildings built before 1945 do not have a cavity wall, therefore de Standaard is less strict then for buildings built after 1945. Table A.3 provides the values for the Streefwaarden per building element.

Building type	Standaard Compactness Ratio [Als/Ag]	Net heat demand [kWh/m2 per year]
Single-family homes up and until 1945	<1,00	= 60
	≥ 1,00	= 60 + 105 * (Als/Ag - 1,0)
Single-family homes after 1945	<1,00	= 43
	≥ 1,00	= 43 + 40 * (Als/Ag - 1,0)
Multi-family homes up and until 1945	<1,00	= 95
	≥ 1,00	= 95 + 70 * (Als/Ag - 1,0)
Multi-family homes after 1945	<1,00	= 45
	≥ 1,00	= 45 + 45 * (Als/Ag - 1,0)

Table A2 - De Standaard. Ref. Netherlands Enterprise Agency (2023) – Standaard en Streefwaarden voor Woningisolatie

Building Element	Streefwaarden - Insulation Value
Roof	Rc 8 m2K/W (approx. 35cm insulation)
Floor	Rc 3,5 m2K/W (approx. 14cm insulation)
Façade	Rc 6 m2K/W (approx. 26 cm insulation)
Panel	U 1,4 W/m²K (insulated panel)
Window & window frames	U 1,0 W/m²K (Triple glazing with new frames)
Front door	U 1,4 W/m²K (insulated front door)
Ventilation	Balanced ventilation system with heat recovery (D1), or CO2 demand driven ventilation system (C2)
Air tightness	qv;10=0,4 dm3/sm² (improved air tightness of windows, doors and façade-roof connection by a professional)

Table A3 - Streefwaarden. Ref. Netherlands Enterprise Agency (2023) – Standaard en Streefwaarden voor Woningisolatie

The Netherlands Enterprise Agency (2022) also published Voorbeeldwoningen 2022, which is a report on 51 sample homes for existing dwellings that represents the Dutch building stock up to 2019. Per building type and building period data on the building characteristics and energy performance is provided. Information and data on the 51 Voorbeeldwoningen are summarized in table A.1.

The first column describes the building type and building period. The second column provides information on the amount of dwellings per building type distinguished by building period, both graphically and in absolute numbers. The third column has data on the percentage of the building stock per type and period. The fourth and fifth column express the owner-occupancy and rental percentage respectively. The sixth column provides data on the average heat demand in kWh/m^2, where the seventh column is the calculated Standaard according to the NTA8800. The last column is the average heat demand of the building type subtracted by the calculated Standaard for that building type, which provides the deviation from de Standaard. A high deviation from de Standaard suggests the need for extensive renovations, while a low deviation from de Standaard suggest minor renovations to be sufficient to switch to LTH. A negative deviation suggest that the dwelling is LT-ready.

Figure A.4 is a graph where the multi-family type homes are ranged on the heat demand deviation from their calculated Standaard. This provides insight on which common building types requires the highest level of insulation improvement, while showing the amount of dwellings that need this renovation. For example, maisonette houses built between 1965 and 1974 require on average a heat demand reduction of over 100 kWh/m^2, but there are only 5.000 dwellings to be considered for that type. This means that the extensive renovation of maisonette houses between 1965-1974 will be a relatively small part of solving the problem. Contradictory to that example are staircase apartments built between 1946 and 1965, where it involves almost 250.000 homes that require on average nearly a 90 kWh/m^2 reduction in heat demand to become LT-ready. The decreasing trendlines of the graph can be explained by the step by step improvements of building regulations, slowly introducing standards on size and climate conditions like insulation and ventilation. These regulations can be found in het Bouwbesluit. New constructions have to comply with BENG-regulations, which are nearly zero energy buildings, those buildings comply with de Standaard.

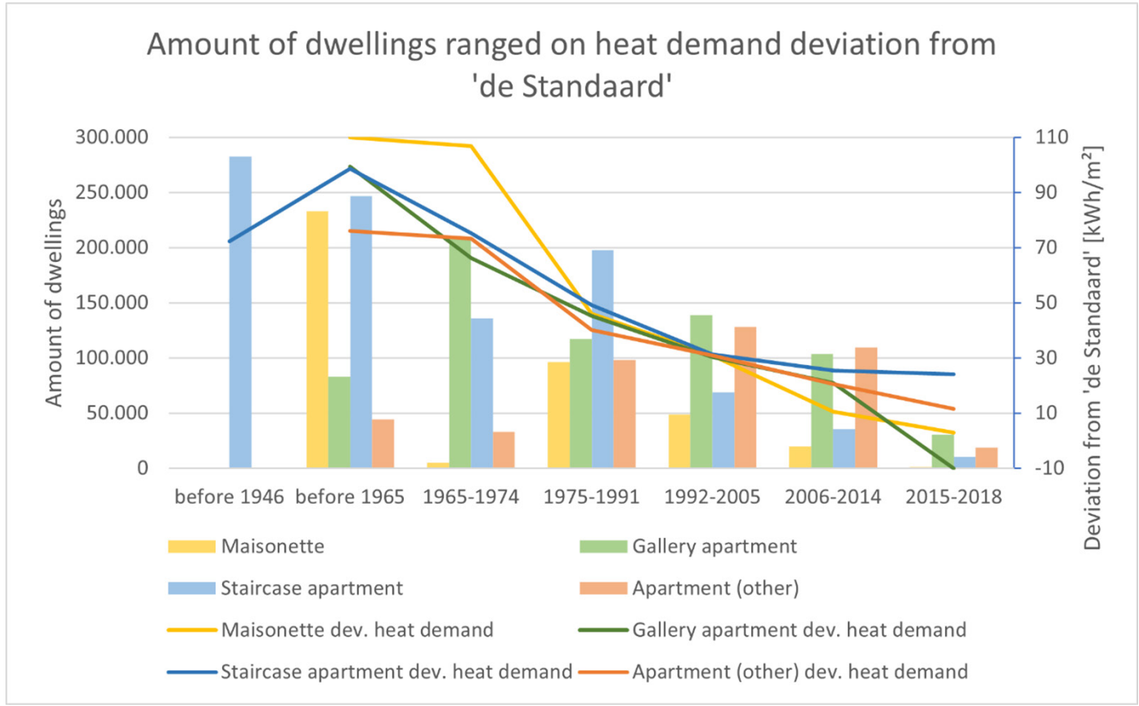


Figure A5 - Amount of Dwellings ranged on Heat Demand deviation from ‘de Standaard’. Based on data from Table A.1

APPENDIX B

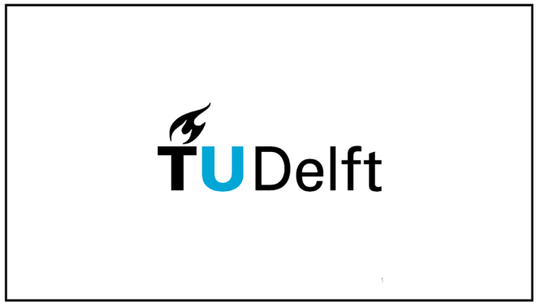
Data Collection

Benodigde data voor gebouwanalyse onderzoek LTV toepassing

Nr.	Data	Opmerkingen	Minimaal benodigde data	Gewenste data
Algemene informatie				
A 1	Gebouwtype		Soort wooncomplex, bijvoorbeeld 'portiekwoning' of 'gallerijflat'	
A 2	Bouwjaar		Bouwjaar	
A 3	Aantal verdiepingen		Aantal verdiepingsvloeren, inclusief kelder en/of zolder	
A 4	Aantal appartementen		Totaal aantal appartementen in complex	
A 5	Aantal kamers		Aantal kamers per appartement, en op welke verdiepingsvloer(en)	
A 6	Oriëntatie		Gebouworiëntatie lange zijde	
A 7	Renovatie			Indien het gebouw eerder is gerenoveerd, wat voor renovaties en in welk jaar
Bouwtekeningen en -gegevens				
B 1	Bouwtekeningen	Zowel origineel als na renovatie indien beschikbaar		Plattegronden, doorsnedes, detailtekeningen
B 2	Gebouwgegevens	Gegevens per appartement en voor totale complex	Vloeroppervlakte Inhoud (volume) Hoogte Vormfactor WWR (window to wall ratio) Rc begane grondvloer Rc gevel Rc dak	Oppervlakte gesloten geveldelen Oppervlakte open geveldelen
B 3	Isolatiewaarden en materiaalgebruik	Indien gerenoveerd, zowel de originele waarden als gerenoveerde waarden. Indien beschikbaar met materiaalspecificaties.	U-waarde raam (kozijn+glas) U-waarde deur	Gedetailleerde gegevens over materiaalgebruik, -dikte en constructie
Gebouwinstallaties (warmte, ventilatie, water)				
C 1	Ventilatiesysteem	Toepassing ventilatiesysteem, bijvoorbeeld natuurlijke ventilatie, mechanische ventilatie, balansventilatie, en hoe deze is toegepast (centraal of decentraal, welke ruimtes)	Systeemtype, ventilatiecapaciteit	Uitgebreide systeemspecificaties
C 2	Kierdichting	Luchtdichtheid van gebouw (Qv10 in L/s)	Infiltratievoud per uur bij 10 Pa	
C 3	Warmtebron (primair)	Toepassing primaire warmtebron (bijvoorbeeld gas gestookte CV ketel, warmtenet, warmtepomp)	Type warmtebron	
C 4	Warmtedistributie in woning	Toepassing warmtedistributie/afgifte (bijvoorbeeld radiatoren, convectoren, vloerverwarming)	Type warmteafgifte-installaties (radiatortypes)	
C 5	Locatie van warmteafgifte per kamer	Plek van radiator (bijvoorbeeld direct onder raam, muur naast raam etc.)	Locatie van warmteafgifte-installaties	
C 6	Warmtecapaciteit	Geïnstalleerde warmtecapaciteit van totale systeem en geïnstalleerde warmtecapaciteit per kamer	Warmtecapaciteit originele warmtesysteem	
C 7	Instellingstemperatuur verwarming	Minimaal gebruikelijke instellingstemperatuur (bijvoorbeeld 21 graden Celcius)	Minimale instellingstemperatuur temperatuur ruimteverwarming	Voorkeursinstelling temperatuur ruimteverwarming
C 8	Aanvoer- en retourtemperatuur	Aanvoertemperatuur warmtesysteem (bijvoorbeeld HT - 90 graden Celcius) en retourtemperatuur na verwarmen (bijvoorbeeld 60 graden Celcius)	Aanvoertemperatuur	Aanvoer- en retourtemperatuur
C 9	Warmwatervoorziening	Toepassing warmwateropwekking	Systeemtype, bron	
Warmte/gebruikersprofiel woning				
D 1	Bewonersaantal		Aantal bewoners per appartement	Algemene informatie gebruikersprofiel (inzicht energiegebruik)
D 2	Interne warmtelast		Schatting van interne warmtelast per appartement door bewoners, verlichting en apparaten (in Watt)	Aanwezigheidsschema (uren aanwezig, moment van de dag)
Energieverbruik				
E 1	Energielabel			Originele energielabel en energielabel na renovatie
E 2	Jaarlijks energieverbruik		Jaarlijkse warmtevraag in kWh per vierkante meter	Jaarlijkse gas-, electriciteits-, en waterverbruik en voor welke toepassing (verwarming, koken etc.)
E 3	Binnenluchttemperatuur			Gemeten data over binnenluchttemperatuur indien beschikbaar

APPENDIX C

Workshop slides



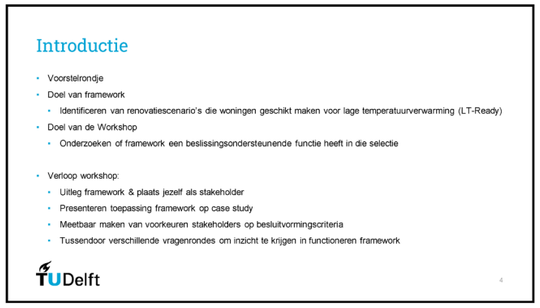
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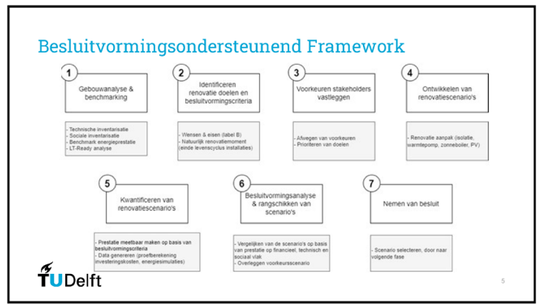
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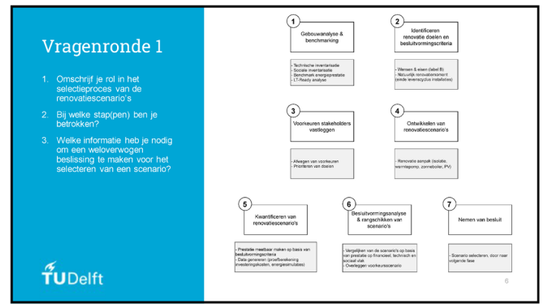
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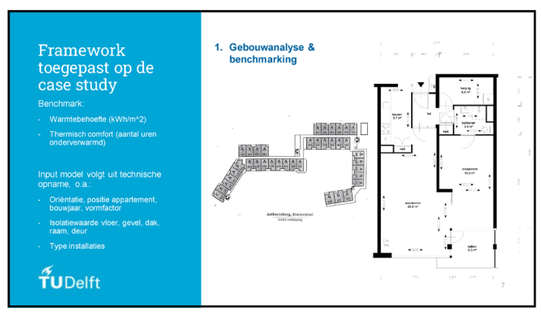
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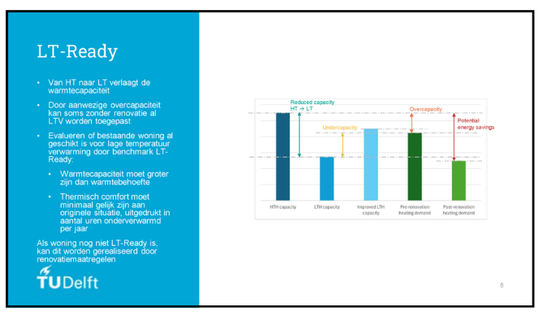
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6



7



8

2. Identificeren renovatiedoelen & besluitvormingscriteria

Categorie (duurzaam)		Doelen case study		Besluitvormingscriteria case study	Kwantificering	Benchmark	% de optimale waarde de mix of max waarde?
S1	Milieu	O1	Appartementencomplex energetisch verbeteren naar energielabel B	C1 Warmtevraag/ha appartementen	kWh/(m²·j) per jaar gemiddeld appartement	< originele situatie	Min
				C2 Energielabel	A++=1, A+=2, ... G=7	Label B of hoger	Min
		O2	Milieuimpact minimaliseren	C3 Energie-Index	[-]	≤ 1,40	Min
				C4 Aandeel hernieuwbare energie	%	> 0	Max
				C5 Energiebesparing (gas)	m³/j per gemiddeld appartement	> 0	Max
S2	Economie	O3	Minimaliseren investeringskosten	C6 Energetische investeringskosten	€	?	Min
		O4	Optimaliseren kosten-baten	C7 Investering per labelstap per woning	€	<€7.000	Min
				C8 Life cycle costs (LCC 30 jaar)	€	<€0	Max
				C9 Terugverdientijd (simpel)	jaar	<20 jaar?	Min
S3	Sociaal	O5	Verbeteren comfort	C10 Thermisch comfort	uren (zonderwaarschuwing) per gemiddeld appartement	< originele situatie	Min
		O6	Minimaliseren overlast voor huurders	C11 Overlast door werkzaamheden	?	?	Min
		O7	Optimaliseren woonlasten voor huurders	C12 Energiekosten besparing	€/maand per gemiddeld appartement	?	Max
				C13 Huurverhoging	€/maand	<€25,50	Min

TUDelft

9

3. Voorkeuren stakeholders vastleggen

- Projectplan presenteert energielabel als belangrijkste criteria
- Straks input over verschillende voorkeuren, voor nu uitgaan dat elk criteria even belangrijk is

Categorie (duurzaam)		Doelen case study		Besluitvormingscriteria case study
S1	Milieu	O1	Appartementencomplex energetisch verbeteren naar energielabel B	C1 Warmtevraag/ha appartementen
				C2 Energielabel
		O2	Milieuimpact minimaliseren	C3 Energie-Index
				C4 Aandeel hernieuwbare energie
				C5 Energiebesparing (gas)
S2	Economie	O3	Minimaliseren investeringskosten	C6 Energetische investeringskosten
		O4	Optimaliseren kosten-baten	C7 Investering per labelstap per woning
				C8 Life cycle costs (LCC 30 jaar)
				C9 Terugverdientijd (simpel)
S3	Sociaal	O5	Verbeteren comfort	C10 Thermisch comfort
		O6	Minimaliseren overlast voor huurders	C11 Overlast door werkzaamheden
		O7	Optimaliseren woonlasten voor huurders	C12 Energiekosten besparing
				C13 Huurverhoging

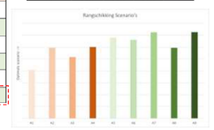
TUDelft

10

6.Besluitvormings-analyse & rangschikken scenario's

	Gebouwschil			Gebouwinstallaties			
	Isolatie (EA, gevel, vloer)	Open gevelvlakken (ramen, deuren)	Kierdichting	Warmtepompwikkel (HR 107, warmtepomp, PVT, zonneboiler)	Warmte-afgiftesysteem (radiatoren extra paneel)	Ventilatiesysteem (Mechanische afvoer, balansventilatie, WTW, CO2 gestuurd)	Elektriciteit (zonnepanelen, LED verlichting)
A1	Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,5	HR 107	Bestaande radiatoren	Mechanische afvoer	LED verlichting
A2	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	HR 107	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A3	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A4	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A5	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Balansventilatie Warmteterugwinning CO2 gestuurd	Mechanische afvoer	Zonnepanelen LED verlichting
A6	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A7	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen woning (U 1,2)	0,7	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A8	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1,2	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting
A9	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting

	S+	S-	PI	RANK
A1	0,090	0,062	0,408	5
A2	0,052	0,076	0,596	6
A3	0,066	0,070	0,517	8
A4	0,059	0,080	0,603	5
A5	0,046	0,087	0,654	4
A6	0,045	0,087	0,661	4
A7	0,036	0,094	0,723	2
A8	0,057	0,084	0,595	7
A9	0,037	0,098	0,725	1

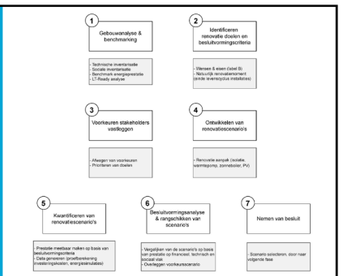


TUDelft

17

Vragenronde 2

1. Weergeeft het framework het besluitvormingsproces dat jullie voor de case study hebben gevolgd?
2. Hoe wegen jullie normaal gesproken de belangen af? Hoe sluiten jullie een compromis?



TUDelft

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4. Ontwikkelen renovatiescenario's

	Gebouwschil			Gebouwinstallaties			
	Isolatie (EA, gevel, vloer)	Open gevelvlakken (ramen, deuren)	Kierdichting	Warmtepompwikkel (HR 107, warmtepomp, PVT, zonneboiler)	Warmte-afgiftesysteem (radiatoren extra paneel)	Ventilatiesysteem (Mechanische afvoer, balansventilatie, WTW, CO2 gestuurd)	Elektriciteit (zonnepanelen, LED verlichting)
A1	Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,5	HR 107	Bestaande radiatoren	Mechanische afvoer	LED verlichting
A2	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	HR 107	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A3	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A4	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A5	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Balansventilatie Warmteterugwinning CO2 gestuurd	Mechanische afvoer	Zonnepanelen LED verlichting
A6	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A7	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen woning (U 1,2)	0,7	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A8	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1,2	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting
A9	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting

TUDelft

11

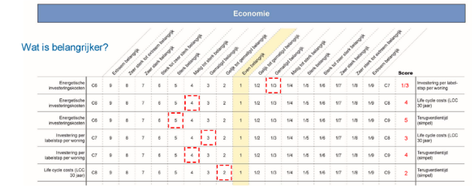
4. Ontwikkelen renovatiescenario's

	Gebouwschil			Gebouwinstallaties			
	Isolatie (EA, gevel, vloer)	Open gevelvlakken (ramen, deuren)	Kierdichting	Warmtepompwikkel (HR 107, warmtepomp, PVT, zonneboiler)	Warmte-afgiftesysteem (radiatoren extra paneel)	Ventilatiesysteem (Mechanische afvoer, balansventilatie, WTW, CO2 gestuurd)	Elektriciteit (zonnepanelen, LED verlichting)
A1	Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,5	HR 107	Bestaande radiatoren	Mechanische afvoer	LED verlichting
A2	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	HR 107	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A3	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A4	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen corridor (U 1,7)	1,2	Warmtepomp PVT Zonneboiler	Bestaande radiatoren	Mechanische afvoer	Zonnepanelen LED verlichting
A5	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Balansventilatie Warmteterugwinning CO2 gestuurd	Mechanische afvoer	Zonnepanelen LED verlichting
A6	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A7	Dak (Rc 5,84), Spouwisolatie (Rc 1,69)	Ramen woning (U 1,2)	0,7	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Mechanische afvoer	Zonnepanelen LED verlichting
A8	Buitenkant gevel (Rc 6,3)	Ramen woning (U 1,2)	1,2	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting
A9	Dak (Rc 5,84), Spouwisolatie (Rc 1,69) Vloer (Rc 2,5)	Ramen woning (U 1,2)	0,4	Warmtepomp PVT Zonneboiler	Radiatoren met extra paneel	Balansventilatie Warmteterugwinning CO2 gestuurd	Zonnepanelen LED verlichting

TUDelft

12

Meetbaar maken voorkeuren – Pairwise comparison



TUDelft

19

Vragenronde 3a

1. Hoe effectief geeft de Decision Matrix tool jullie voorkeur voor een renovatiescenario weer?
2. In welke mate zijn jullie het eens of oneens met de voorgestelde scenario's na het inbouwen van jullie voorkeuren?

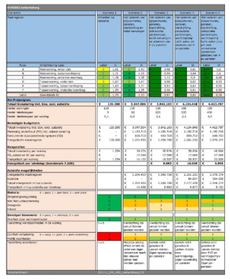


TUDelft

20

5. Kwantificeren renovatiescenario's

- Meetbaar maken van de besluitvormingscriteria
- Data genereren als input om besluit te kunnen maken
- Ondersteund door software, rekentools en onderzoek
- Verschil in gedetailleerdheid van kwantificatie



TUDelft

14

Weging

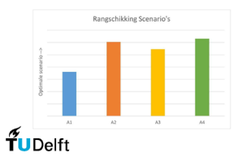
	Wegingsfactoren gecombineerd											
	Milieu			Economie			Sociaal					
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
Stakeholder 1	45%	7%	3%	55%	30%	41%	4%	45%	11%	35%	6%	41%	17%
Stakeholder 2	44%	7%	4%	57%	33%	55%	4%	39%	3%	67%	12%	32%	20%
Stakeholder 3	34%	18%	14%	10%	25%	46%	23%	16%	16%	42%	10%	41%	7%
Stakeholder 4	31%	3%	3%	23%	40%	29%	10%	56%	5%	26%	10%	58%	6%
Stakeholder 5													
Balanced Criteria Weights	39%	9%	6%	35%	32%	33%	11%	39%	18%	35%	10%	43%	12%
Final Balanced Criteria Weights	12,8%	3,0%	2,0%	4,9%	10,7%	10,9%	3,7%	12,9%	5,9%	11,7%	3,2%	14,3%	4,1%

TUDelft

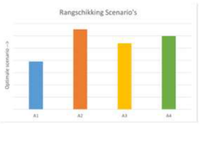
21

Rangschikking originele scenario's incl. weging

	S+	S-	PI	RANK
A1	0,109	0,061	0,361	4
A2	0,054	0,083	0,605	2
A3	0,066	0,079	0,546	3
A4	0,063	0,108	0,632	1



	S+	S-	PI	RANK
A1	0,104	0,067	0,391	4
A2	0,048	0,091	0,654	1
A3	0,071	0,083	0,540	3
A4	0,070	0,104	0,599	2



TUDelft

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5. Kwantificeren renovatiescenario's

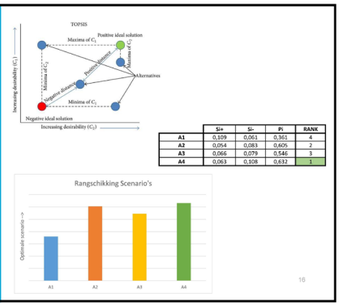
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Warmtevraag/ha	Energielabel	Energie-Index	Aandeel hernieuwbare energie	Energiebesparing (gas)	Energetische investeringskosten	Investering per labelstap per woning	Life cycle costs (LCC 30 jaar)	Terugverdientijd (simpel)	Thermisch comfort	Overlast door werkzaamheden	Energiekosten besparing	Huurverhoging
	kWh/m²/j per gemiddeld appartement	A++=1, A+=2, ... G=7	[-]	%	m³/j per gemiddeld appartement	€	€	€	jaar	uren (zonderwaarschuwing) per gemiddeld appartement	Vertraal (1, ..., veel)	€/maand per gemiddeld appartement	€/maand
A0	206,00	C	1,66	0	0	0	0	0	0	525	?	0	0
A1	174,34	C	1,46	0,0%	210	€ 1.260.533,01	€ 27.462	€ 142.105,19	32	525	1	€ 5,13	€ 7
A2	151,76	A	1,38	11,0%	407	€ 1.006.737,31	€ 13.732	€ 137.953,67	18	525	1	€ 20,81	€ 9
A3	122,80	A	1,01	23,0%	645	€ 1.544.388,39	€ 9.923	€ 137.097,11	25	913	1	€ 20,81	€ 15
A4	112,00	A++	0,49	38,7%	645	€ 2.254.026,66	€ 5.471	€ 130.959,50	22	929	1	€ 26,51	€ 23
A5	59,92	A++	0,21	38,2%	1127	€ 3.133.626,00	€ 7.606	€ 123.490,32	18	1.245	1	€ 26,51	€ 22
A6	124,00	A++	0,49	38,2%	332	€ 1.722.413,91	€ 7.125	€ 144.240,16	30	271	1	€ 26,51	€ 23
A7	116,41	A++	0,47	38,2%	378	€ 1.591.745,39	€ 6.266	€ 137.956,16	24	310	1	€ 26,51	€ 22
A8	94,63	A++	0,37	38,2%	661	€ 1.782.503,88	€ 4.754	€ 127.848,30	35	63	1	€ 26,51	€ 22
A9	94,63	A++	0,37	38,2%	661	€ 1.782.503,88	€ 4.754	€ 127.848,30	35	63	1	€ 26,51	€ 22

TUDelft

15

6.Besluitvormings-analyse & rangschikken scenario's

- Projectplan biedt geschreven onderbouwing voor keuzeadvies renovatiescenario 4
- Second best volgens projectplan is scenario 2
- Decision Matrix tool biedt dezelfde suggestie als projectplan bij gelijke geschiktheid van criteria



	S+	S-	PI	RANK
A1	0,109	0,061	0,361	4
A2	0,054	0,083	0,605	2
A3	0,066	0,079	0,546	3
A4	0,063	0,108	0,632	1

TUDelft

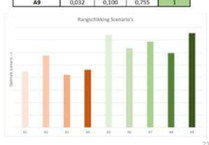
16

Rangschikking incl. nieuwe scenario's

	S+	S-	PI	RANK
A1	0,090	0,062	0,408	5
A2	0,052	0,076	0,596	6
A3	0,066	0,070	0,517	8
A4	0,059	0,089	0,601	5
A5	0,046	0,097	0,679	3
A6	0,045	0,087	0,661	4
A7	0,036	0,094	0,723	2
A8	0,057	0,084	0,595	7
A9	0,037	0,098	0,725	1



	S+	S-	PI	RANK
A1	0,084	0,068	0,447	8
A2	0,056	0,077	0,577	6
A3	0,080	0,059	0,422	9
A4	0,079	0,068	0,463	7
A5	0,035	0,100	0,740	2
A6	0,047	0,082	0,635	4
A7	0,040	0,088	0,688	3
A8	0,055	0,082	0,596	5
A9	0,032	0,100	0,755	1

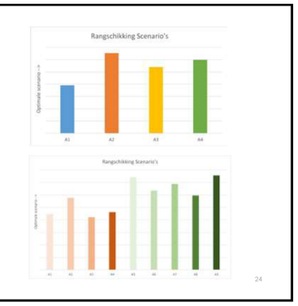


TUDelft

23

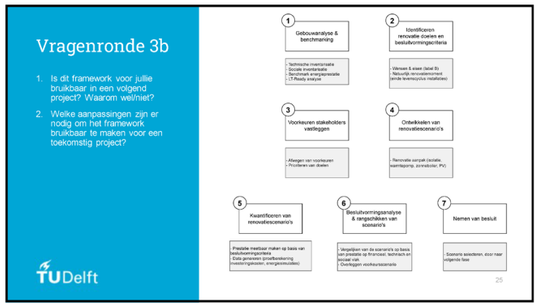
Vragenronde 3a

1. Hoe effectief geeft de Decision Matrix tool jullie voorkeur voor een renovatiescenario weer?
2. In welke mate zijn jullie het eens of oneens met de voorgestelde scenario's na het inbouwen van jullie voorkeuren?



TUDelft

24



25



26

APPENDIX D

Pairwise Comparison Sheets

Milieu

		Extreem belangrijk	Zeer sterk tot extreem belangrijk	Zeer sterk belangrijk	Sterk tot zeer sterk belangrijk	Sterk belangrijk	Matig tot sterk belangrijk	Gematigd belangrijk	Gelijk tot gematigd belangrijk	Even belangrijk	Gelijk tot gematigd belangrijk	Gematigd belangrijk	Matig tot sterk belangrijk	Sterk belangrijk	Sterk tot zeer sterk belangrijk	Zeer sterk belangrijk	Zeer sterk tot extreem belangrijk	Extreem belangrijk	Score	
Warmtebehofte	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C2		Energielabel
Warmtebehofte	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C3		Energie-Index
Warmtebehofte	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Aandeel hernieuwbare energie (EP3)
Warmtebehofte	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energiebesparing (gas)
Energielabel	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C3		Energie-Index
Energielabel	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Aandeel hernieuwbare energie (EP3)
Energielabel	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energiebesparing (gas)
Energie-Index	C3	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Aandeel hernieuwbare energie (EP3)
Energie-Index	C3	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energiebesparing (gas)
Aandeel hernieuwbare energie (EP3)	C4	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energiebesparing (gas)

Hoe belangrijk is het criterion links ten opzichte van criterion rechts ?

Role : _____

Economie

		Extreem belangrijk	Zeer sterk tot extreem belangrijk	Zeer sterk belangrijk	Sterk tot zeer sterk belangrijk	Sterk belangrijk	Matig tot sterk belangrijk	Gematigd belangrijk	Gelijk tot gematigd belangrijk	Even belangrijk	Gelijk tot gematigd belangrijk	Gematigd belangrijk	Matig tot sterk belangrijk	Sterk belangrijk	Sterk tot zeer sterk belangrijk	Zeer sterk belangrijk	Zeer sterk tot extreem belangrijk	Extreem belangrijk		
																			Score	
Energetische investeringskosten	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C7	Investering per label-stap per woning
Energetische investeringskosten	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C8	Life cycle costs (LCC 30 jaar)
Energetische investeringskosten	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9	Terugverdientijd (simpel)
Investering per labelstap per woning	C7	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C8	Life cycle costs (LCC 30 jaar)
Investering per labelstap per woning	C7	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9	Terugverdientijd (simpel)
Life cycle costs (LCC 30 jaar)	C8	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9	Terugverdientijd (simpel)

Hoe belangrijk is het criterion links ten opzichte van criterion rechts ?

Role : _____

Social

		Extreem belangrijk	Zeer sterk tot extreem belangrijk	Zeer sterk belangrijk	Sterk tot zeer sterk belangrijk	Sterk belangrijk	Matig tot sterk belangrijk	Gematigd belangrijk	Gelijk tot gematigd belangrijk	Even belangrijk	Gelijk tot gematigd belangrijk	Gematigd belangrijk	Matig tot sterk belangrijk	Sterk belangrijk	Sterk tot zeer sterk belangrijk	Zeer sterk belangrijk	Zeer sterk tot extreem belangrijk	Extreem belangrijk		
																			Score	
Thermisch comfort	C11	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C12	Overlast door werkzaamheden (renovatieduur)
Thermisch comfort	C11	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C13	Energiekosten besparing
Thermisch comfort	C11	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C14	Huurverhoging
Overlast door werkzaamheden (renovatieduur)	C12	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C13	Energiekosten besparing
Overlast door werkzaamheden (renovatieduur)	C12	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C14	Huurverhoging
Energiekosten besparing	C13	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C14	Huurverhoging

Hoe belangrijk is het criterion links ten opzichte van criterion rechts ?

Role : _____

APPENDIX E

Data Sets

Sample Number	Construction Year	Orientation	mpactness Ra	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
1	1976-1991	270	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	127,92	102
2	1976-1991	270	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	194,32	179
3	1976-1991	270	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	158,01	482
4	1976-1991	270	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	245,13	292
5	1976-1991	270	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	216,64	530
6	1976-1991	270	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	309,29	359
7	1976-1991	280	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	127,23	102
8	1976-1991	280	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	193,08	179
9	1976-1991	280	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	157,28	486
10	1976-1991	280	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	243,98	292
11	1976-1991	280	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	215,60	529
12	1976-1991	280	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	307,74	360
13	1976-1991	350	0,55	1	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	126,50	102
14	1976-1991	350	0,95	2	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	188,19	183
15	1976-1991	350	1,25	3	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	157,10	491
16	1976-1991	350	1,55	4	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	243,02	297
17	1976-1991	350	1,65	5	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	211,29	531
18	1976-1991	350	1,95	6	41,73	0,15	0,69	2,5	1,8	3,4	1,95	3	21	301,50	364
Average														**206,88**	**326**

File 0_benchmark_output – benchmark

Sample Number	Construction Year	Orientation	Compactness Ratio	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
														206,88	326
1	1976-1991	270	0,545697	1	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	106,76	62
2	1976-1991	270	0,948155	2	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	154,42	107
3	1976-1991	270	1,245277	3	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	141,43	426
4	1976-1991	270	1,545277	4	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	210,77	226
5	1976-1991	270	1,648155	5	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	183,91	475
6	1976-1991	270	1,948155	6	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	257,01	276
7	1976-1991	280	0,545697	1	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	106,20	62
8	1976-1991	280	0,948155	2	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	153,34	107
9	1976-1991	280	1,245277	3	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	140,74	424
10	1976-1991	280	1,545277	4	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	209,73	225
11	1976-1991	280	1,648155	5	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	182,97	474
12	1976-1991	280	1,948155	6	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	255,60	279
13	1976-1991	350	0,545697	1	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	105,63	63
14	1976-1991	350	0,948155	2	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	149,73	108
15	1976-1991	350	1,245277	3	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	140,62	437
16	1976-1991	350	1,545277	4	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	208,87	227
17	1976-1991	350	1,648155	5	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	179,66	480
18	1976-1991	350	1,948155	6	41,73	0,15	1,69	2,5	1,7	3,4	1,5	3	200	250,77	281
														174,34	**263**
19	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	99,17	53
20	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	140,84	97
21	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	134,03	421
22	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	172,22	144
23	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	170,57	467
24	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	213,36	192
25	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	98,67	53
26	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	139,87	97
27	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	133,37	420
28	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	171,27	144
29	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	169,67	464
30	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	212,07	192
31	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	98,15	53
32	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	136,65	99
33	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	133,24	429
34	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	170,45	146
35	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	166,44	470
36	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	207,57	194
														153,76	**230**

File 0_benchmark_output - case study A1 and A2 HT

Sample Number benchmark	Construction Year	Orientation	Compactness Ratio	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
														206,88	325,56
1	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	83,26	454
2	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	112,93	800
3	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	110,69	844
4	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	135,91	1056
5	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	136,30	1124
6	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	164,14	1338
7	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	82,71	450
8	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	112,02	782
9	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	110,12	842
10	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	135,04	1046
11	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	135,60	1106
12	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	163,14	1304
13	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	82,39	447
14	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	109,16	751
15	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	110,14	839
16	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	134,43	1034
17	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	132,97	1081
18	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	200	159,42	1251
														122,80	**919**
19	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	66,55	203
20	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	86,80	406
21	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	98,66	606
22	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	126,11	937
23	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	116,23	748
24	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	144,48	1140
25	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	66,16	196
26	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	85,98	399
27	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	98,12	600
28	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	125,32	928
29	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	115,54	738
30	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	143,55	1113
31	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	66,05	199
32	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	84,22	384
33	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	98,19	608
34	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	124,90	915
35	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	113,53	736
36	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	200	140,87	1082
														105,63	**663**
37	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	45,78	68
38	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	66,04	237
39	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	76,76	389
40	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	105,88	735
41	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	94,72	533
42	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	124,27	958
43	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	45,59	67
44	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	65,42	231
45	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	76,30	388
46	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	105,24	729
47	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	94,10	533
48	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	123,40	932
49	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	45,65	70
50	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	64,36	217
51	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	76,47	402
52	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	104,99	726
53	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	92,30	539
54	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	200	121,13	899
														84,91	**481**
55	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	68,15	271
56	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	90,59	508
57	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	97,47	651
58	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	104,00	670
59	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	115,67	828
60	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	125,03	949
61	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	67,77	266
62	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	89,77	500
63	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	96,93	649
64	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	103,32	666
65	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	114,98	822
66	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	124,12	934
67	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	67,61	266
68	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	87,70	483
69	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	96,93	660
70	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	102,91	666
71	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	112,41	809
72	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	200	121,19	890
														99,25	**638**
73	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	47,53	94
74	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	70,08	328
75	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	75,70	437
76	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	83,74	493
77	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	94,29	625
78	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	104,81	730
79	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	47,35	92
80	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	69,46	322
81	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	75,25	439
82	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	83,24	486
83	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	93,64	620
84	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	103,99	720
85	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	47,39	94
86	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	68,15	310
87	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	75,37	445
88	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	83,02	488
89	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	91,44	616
90	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	200	101,68	705
														78,67	**447**

Sample Number benchmark	Construction Year	Orientation	Compactness Ratio	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
														206,88	325,56
91	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	76,34	327
92	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	100,06	570
93	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	106,65	739
94	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	142,04	1147
95	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	127,65	937
96	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	163,92	1348
97	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	75,82	322
98	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	99,18	564
99	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	106,09	729
100	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	141,19	1133
101	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	126,96	928
102	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	162,96	1322
103	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	75,61	322
104	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	96,99	541
105	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	106,19	742
106	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	140,67	1133
107	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	124,96	918
108	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	200	159,97	1278
														118,51	**833**
109	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	55,51	131
110	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	79,51	384
111	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	84,89	508
112	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	121,81	961
113	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	106,27	724
114	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	143,65	1210
115	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	55,23	131
116	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	78,75	377
117	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	84,41	505
118	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	121,06	946
119	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	105,61	713
120	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	142,73	1177
121	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	55,21	134
122	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	77,23	368
123	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	84,56	519
124	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	120,67	937
125	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	103,68	712
126	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	200	140,07	1147
														97,83	**644**
127	1976-1991	270	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	62,24	188
128	1976-1991	270	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	80,69	409
129	1976-1991	270	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	66,35	211
130	1976-1991	270	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	87,80	498
131	1976-1991	270	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	83,99	425
132	1976-1991	270	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	105,02	707
133	1976-1991	280	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	61,94	186
134	1976-1991	280	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	79,96	402
135	1976-1991	280	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	65,98	209
136	1976-1991	280	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	87,25	491
137	1976-1991	280	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	83,26	420
138	1976-1991	280	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	104,19	698
139	1976-1991	350	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	61,83	188
140	1976-1991	350	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	78,25	386
141	1976-1991	350	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	65,85	210
142	1976-1991	350	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	86,99	491
143	1976-1991	350	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	81,39	406
144	1976-1991	350	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	200	101,88	681
														80,27	**400**
145	1976-1991	270	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	41,62	64
146	1976-1991	270	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	59,98	208
147	1976-1991	270	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	45,46	67
148	1976-1991	270	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	67,32	302
149	1976-1991	270	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	63,17	211
150	1976-1991	270	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	84,72	524
151	1976-1991	280	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	41,48	63
152	1976-1991	280	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	59,50	200
153	1976-1991	280	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	45,29	66
154	1976-1991	280	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	67,01	297
155	1976-1991	280	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	62,64	206
156	1976-1991	280	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	84,01	516
157	1976-1991	350	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	41,54	62
158	1976-1991	350	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	58,57	195
159	1976-1991	350	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	45,34	68
160	1976-1991	350	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	66,95	297
161	1976-1991	350	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	61,57	202
162	1976-1991	350	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	6	200	82,44	504
														59,92	**225**
163	1976-1991	270	0,545697	1	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	44,88	73
164	1976-1991	270	0,948155	2	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	63,70	274
165	1976-1991	270	1,245277	3	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	47,70	83
166	1976-1991	270	1,545277	4	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	76,97	441
167	1976-1991	270	1,648155	5	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	66,03	273
168	1976-1991	270	1,948155	6	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	94,36	680
169	1976-1991	280	0,545697	1	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	44,72	72
170	1976-1991	280	0,948155	2	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	63,18	261
171	1976-1991	280	1,245277	3	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	47,53	83
172	1976-1991	280	1,545277	4	41,73	3,5	1,7	3,5	1,4	1,4	0,4	6	200	76,58	442
173	1976-1991	280	1,648155	5	41,73	3,5	1,7	3,5	1,4	1,4

Sample Number	Construction Year	Orientation	Compactness Ratio	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
benchmark														**206,88**	**325,56**
1	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	98,57	58
2	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	136,28	144
3	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	132,86	425
4	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	158,96	462
5	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	164,72	491
6	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	183,96	796
7	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	98,06	58
8	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	135,30	143
9	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	132,20	424
10	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	158,00	462
11	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	163,82	488
12	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	182,78	781
13	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	97,56	58
14	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	132,08	145
15	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	132,08	433
16	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	157,19	462
17	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	160,60	494
18	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,7	3,4	1,2	3	21	178,59	765
														144,65	**394**
19	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	76,57	13
20	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	103,01	36
21	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	116,64	360
22	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	148,70	313
23	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	140,37	379
24	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	167,42	524
25	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	76,22	13
26	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	102,26	35
27	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	116,03	360
28	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	147,88	312
29	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	139,54	379
30	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	166,33	519
31	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	75,94	13
32	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	100,33	36
33	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	116,00	370
34	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	147,33	314
35	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	137,13	391
36	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	3	21	163,24	511
														124,50	**271**
37	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	51,01	3
38	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	76,31	17
39	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	87,54	324
40	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	125,77	169
41	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	111,45	358
42	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	147,51	268
43	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	50,85	3
44	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	75,78	17
45	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	87,09	324
46	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	125,14	169
47	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	110,75	359
48	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	146,55	265
49	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	50,75	4
50	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	74,63	17
51	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	87,16	338
52	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	124,76	169
53	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	108,77	370
54	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,0	3,4	1,0	6	21	144,00	265
														99,21	**191**
55	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	78,96	25
56	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	108,60	63
57	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	115,47	384
58	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	124,33	125
59	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	140,15	409
60	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	149,16	247
61	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	78,62	25
62	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	107,85	63
63	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	114,88	386
64	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	123,66	124
65	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	139,33	409
66	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	148,14	246
67	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	78,29	23
68	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	105,60	63
69	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	114,77	397
70	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	123,11	127
71	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	136,41	415
72	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	3	21	144,84	244
														118,45	**210**
73	1976-1991	270	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	53,31	10
74	1976-1991	270	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	81,93	36
75	1976-1991	270	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	86,47	357
76	1976-1991	270	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	98,91	78
77	1976-1991	270	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	111,33	392
78	1976-1991	270	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	126,27	134
79	1976-1991	280	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	53,16	10
80	1976-1991	280	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	81,39	36
81	1976-1991	280	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	86,04	359
82	1976-1991	280	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	98,45	78
83	1976-1991	280	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	110,65	392
84	1976-1991	280	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	125,45	134
85	1976-1991	350	0,545697	1	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	53,03	10
86	1976-1991	350	0,948155	2	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	80,01	35
87	1976-1991	350	1,245277	3	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	86,05	367
88	1976-1991	350	1,545277	4	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	98,08	76
89	1976-1991	350	1,648155	5	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	108,33	394
90	1976-1991	350	1,948155	6	41,73	0,15	1,69	5,84	1,0	3,4	0,7	6	21	122,94	135
														92,32	**169**

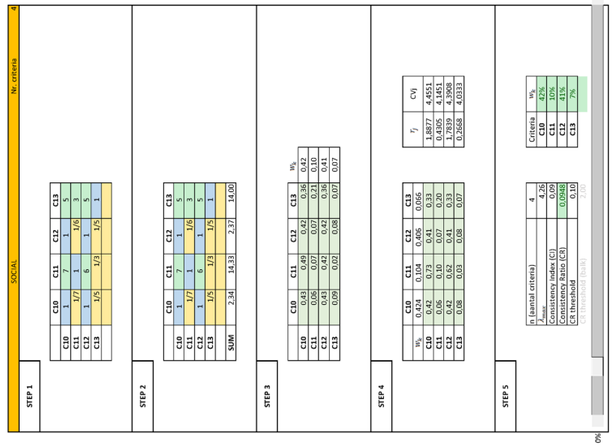
File 3_benchmark_output - case study A3-A11 LT Part 1

Sample Number	Construction Year	Orientation	Compactness Ratio	Position	WWR	Rc_GF	RC_Wall	Rc_roof	U_window	U_door	infil	Vent_Type	Temp_set	Heating_demand	Cold_hours
benchmark														**206,88**	**325,56**
91	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	88,98	29
92	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	119,94	79
93	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	127,11	395
94	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	164,33	573
95	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	154,48	428
96	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	183,45	834
97	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	88,51	29
98	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	119,06	79
99	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	126,46	393
100	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	163,39	571
101	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	153,61	428
102	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	182,31	827
103	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	88,13	28
104	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	116,61	78
105	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	126,42	412
106	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	162,72	572
107	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	151,10	442
108	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	3	21	178,89	809
														138,64	**389**
109	1976-1991	270	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	62,85	11
110	1976-1991	270	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	93,61	40
111	1976-1991	270	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	98,09	372
112	1976-1991	270	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	143,79	319
113	1976-1991	270	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	126,84	399
114	1976-1991	270	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	166,61	568
115	1976-1991	280	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	62,62	11
116	1976-1991	280	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	92,93	40
117	1976-1991	280	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	97,60	371
118	1976-1991	280	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	143,01	319
119	1976-1991	280	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	126,08	398
120	1976-1991	280	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	165,51	566
121	1976-1991	350	0,545697	1	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	62,42	11
122	1976-1991	350	0,948155	2	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	91,26	40
123	1976-1991	350	1,245277	3	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	97,63	385
124	1976-1991	350	1,545277	4	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	142,49	322
125	1976-1991	350	1,648155	5	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	123,87	407
126	1976-1991	350	1,948155	6	41,73	0,15	6,3	2,5	1,7	3,4	1,2	6	21	162,44	554
														114,43	**285**
127	1976-1991	270	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	71,21	17
128	1976-1991	270	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	95,33	44
129	1976-1991	270	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	76,17	39
130	1976-1991	270	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	103,87	78
131	1976-1991	270	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	99,42	75
132	1976-1991	270	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	126,33	130
133	1976-1991	280	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	70,95	17
134	1976-1991	280	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	94,68	44
135	1976-1991	280	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	75,83	40
136	1976-1991	280	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	103,38	78
137	1976-1991	280	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	98,76	74
138	1976-1991	280	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	125,51	129
139	1976-1991	350	0,545697	1	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	70,67	17
140	1976-1991	350	0,948155	2	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	92,88	45
141	1976-1991	350	1,245277	3	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	75,54	37
142	1976-1991	350	1,545277	4	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	102,97	76
143	1976-1991	350	1,648155	5	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	96,76	72
144	1976-1991	350	1,948155	6	41,73	2,6	1,69	5,84	1,0	3,4	0,4	3	21	123,01	130
														94,63	**63**

File 3_benchmark_output - case study A3-A11 LT Part 2

APPENDIX F

Pairwise comparison matrices Stakeholder 1-4



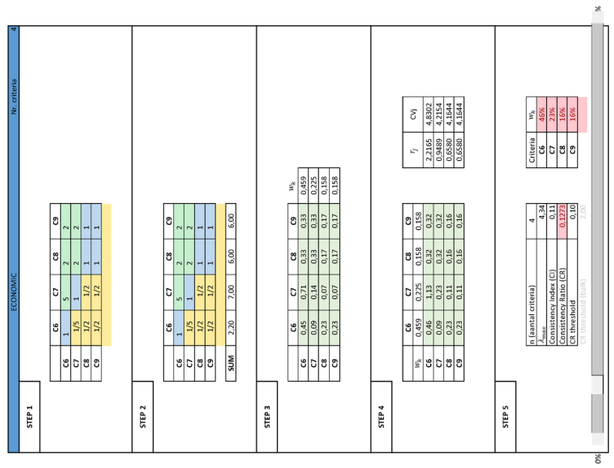
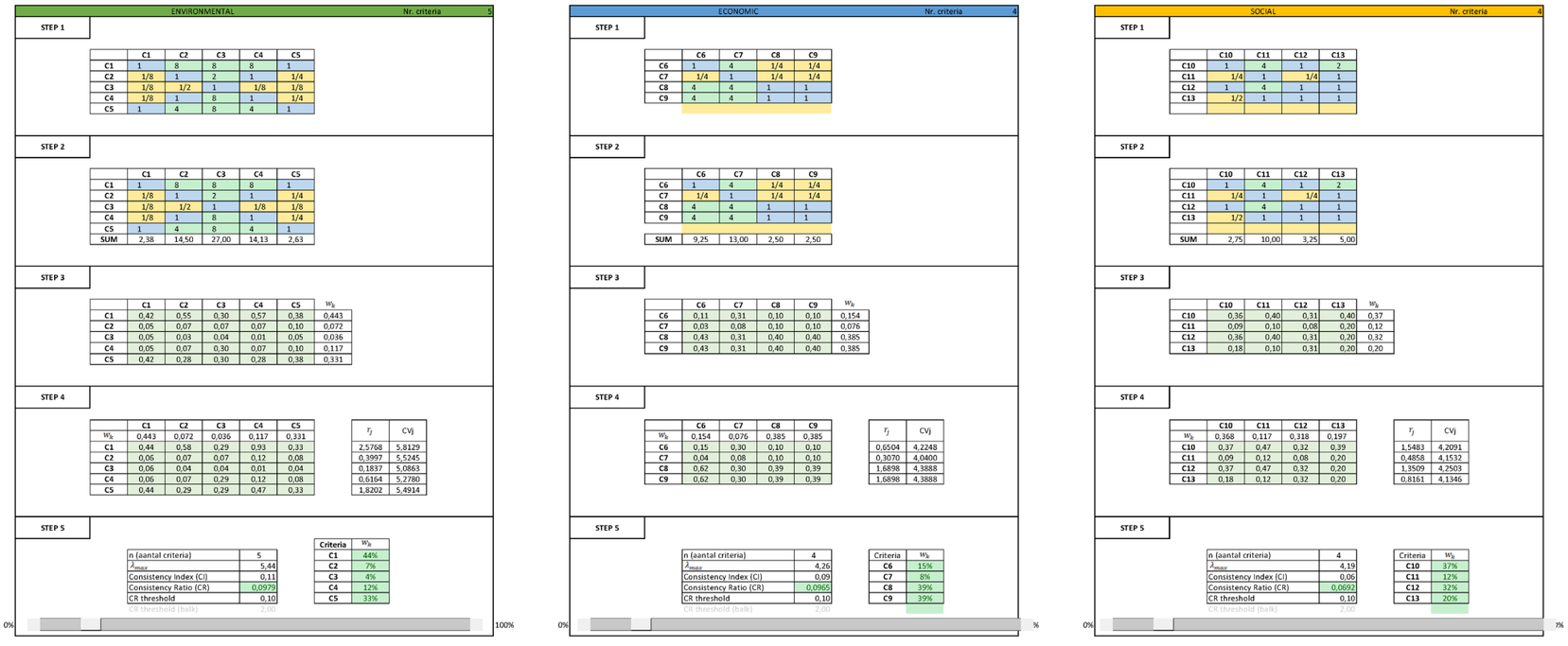


Figure F.1 - Stakeholder 1_project leader_Criteria weights results



Figure F.2 - Stakeholder 2_program manager_Criteria weights results



ENVIRONMENTAL — Nr. criteria 5

STEP 1

	C1	C2	C3	C4	C5
C1	1	8	8	8	1
C2	1/8	1	2	1	1/4
C3	1/8	1/2	1	1/8	1/8
C4	1/8	1	8	1	1/4
C5	1	4	8	4	1

STEP 2

	C1	C2	C3	C4	C5
C1	1	8	8	8	1
C2	1/8	1	2	1	1/4
C3	1/8	1/2	1	1/8	1/8
C4	1/8	1	8	1	1/4
C5	1	4	8	4	1
SUM	2,38	14,50	27,00	14,13	2,63

STEP 3

	C1	C2	C3	C4	C5	w_k
C1	0,42	0,55	0,30	0,57	0,38	0,443
C2	0,05	0,07	0,07	0,07	0,10	0,072
C3	0,05	0,03	0,04	0,01	0,05	0,036
C4	0,05	0,07	0,30	0,07	0,10	0,117
C5	0,42	0,28	0,30	0,28	0,38	0,331

STEP 4

	C1	C2	C3	C4	C5
w_k	0,443	0,072	0,036	0,117	0,331
C1	0,44	0,58	0,29	0,93	0,33
C2	0,06	0,07	0,07	0,12	0,08
C3	0,06	0,04	0,04	0,01	0,04
C4	0,06	0,07	0,29	0,12	0,08
C5	0,44	0,29	0,29	0,47	0,33

r_j	CVj
2,5768	5,8129
0,3997	5,5245
0,1837	5,0863
0,6164	5,2780
1,8202	5,4914

STEP 5

n (aantal criteria)	5
λ_{max}	5,44
Consistency Index (CI)	0,11
Consistency Ratio (CR)	0,0979
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C1	44%
C2	7%
C3	4%
C4	12%
C5	33%

0% 100%

ECONOMIC — Nr. criteria 4

STEP 1

	C6	C7	C8	C9
C6	1	4	1/4	1/4
C7	1/4	1	1/4	1/4
C8	4	4	1	1
C9	4	4	1	1

STEP 2

	C6	C7	C8	C9
C6	1	4	1/4	1/4
C7	1/4	1	1/4	1/4
C8	4	4	1	1
C9	4	4	1	1
SUM	9,25	13,00	2,50	2,50

STEP 3

	C6	C7	C8	C9	w_k
C6	0,11	0,31	0,10	0,10	0,154
C7	0,03	0,08	0,10	0,10	0,076
C8	0,43	0,31	0,40	0,40	0,385
C9	0,43	0,31	0,40	0,40	0,385

STEP 4

	C6	C7	C8	C9
w_k	0,154	0,076	0,385	0,385
C6	0,15	0,30	0,10	0,10
C7	0,04	0,08	0,10	0,10
C8	0,62	0,30	0,39	0,39
C9	0,62	0,30	0,39	0,39

r_j	CVj
0,6504	4,2248
0,3070	4,0400
1,6898	4,3888
1,6898	4,3888

STEP 5

n (aantal criteria)	4
λ_{max}	4,26
Consistency Index (CI)	0,09
Consistency Ratio (CR)	0,0965
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C6	15%
C7	8%
C8	39%
C9	39%

0% %

SOCIAL — Nr. criteria 4

STEP 1

	C10	C11	C12	C13
C10	1	4	1	2
C11	1/4	1	1/4	1
C12	1	4	1	1
C13	1/2	1	1	1

STEP 2

	C10	C11	C12	C13
C10	1	4	1	2
C11	1/4	1	1/4	1
C12	1	4	1	1
C13	1/2	1	1	1
SUM	2,75	10,00	3,25	5,00

STEP 3

	C10	C11	C12	C13	w_k
C10	0,36	0,40	0,31	0,40	0,37
C11	0,09	0,10	0,08	0,20	0,12
C12	0,36	0,40	0,31	0,20	0,32
C13	0,18	0,10	0,31	0,20	0,20

STEP 4

	C10	C11	C12	C13
w_k	0,368	0,117	0,318	0,197
C10	0,37	0,47	0,32	0,39
C11	0,09	0,12	0,08	0,20
C12	0,37	0,47	0,32	0,20
C13	0,18	0,12	0,32	0,20

r_j	CVj
1,5483	4,2091
0,4858	4,1532
1,3509	4,2503
0,8161	4,1346

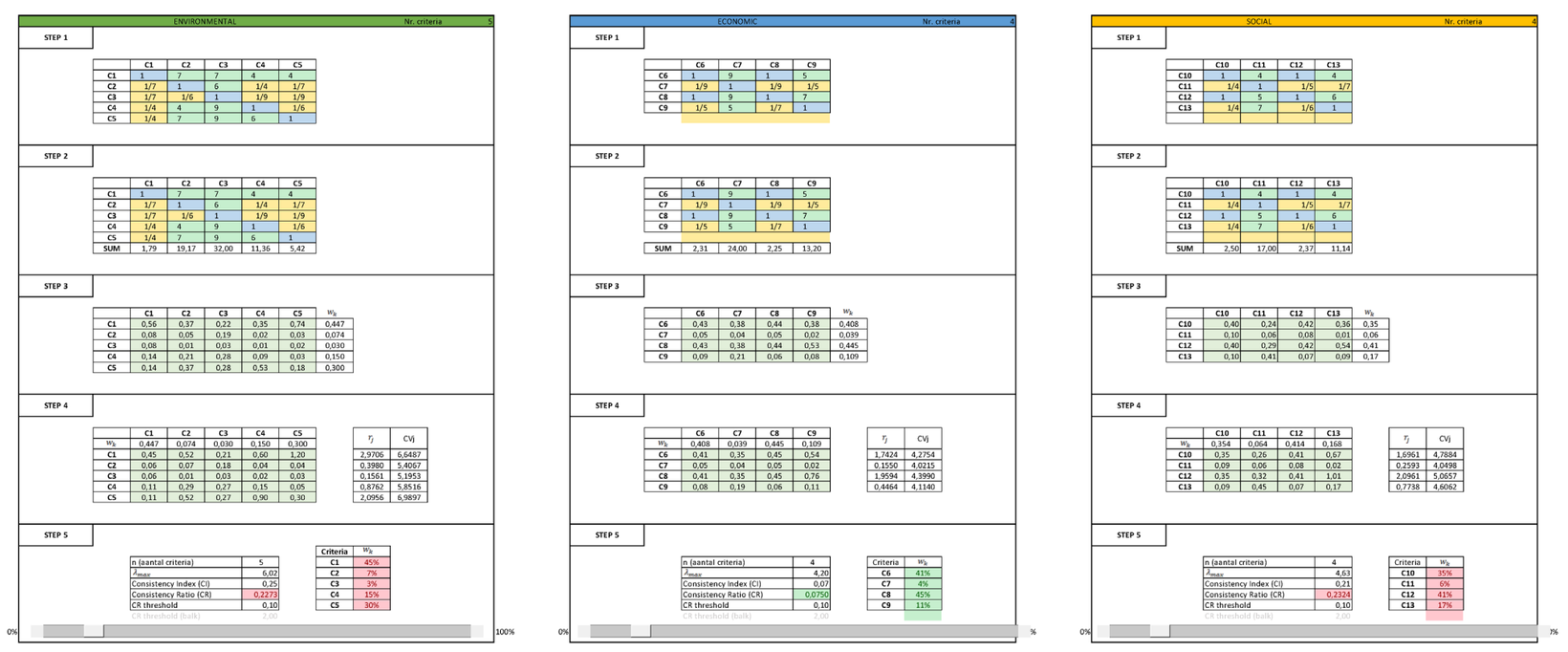
STEP 5

n (aantal criteria)	4
λ_{max}	4,19
Consistency Index (CI)	0,06
Consistency Ratio (CR)	0,0692
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C10	37%
C11	12%
C12	32%
C13	20%

0% %

Figure F.3 - Stakeholder 3_program manager_Criteria weights results



ENVIRONMENTAL — Nr. criteria 5

STEP 1

	C1	C2	C3	C4	C5
C1	1	7	7	4	4
C2	1/7	1	6	1/4	1/7
C3	1/7	1/6	1	1/9	1/9
C4	1/4	4	9	1	1/6
C5	1/4	7	9	6	1

STEP 2

	C1	C2	C3	C4	C5
C1	1	7	7	4	4
C2	1/7	1	6	1/4	1/7
C3	1/7	1/6	1	1/9	1/9
C4	1/4	4	9	1	1/6
C5	1/4	7	9	6	1
SUM	1,79	19,17	32,00	11,36	5,42

STEP 3

	C1	C2	C3	C4	C5	w_k
C1	0,56	0,37	0,22	0,35	0,74	0,447
C2	0,08	0,05	0,19	0,02	0,03	0,074
C3	0,08	0,01	0,03	0,01	0,02	0,030
C4	0,14	0,21	0,28	0,09	0,03	0,150
C5	0,14	0,37	0,28	0,53	0,18	0,300

STEP 4

	C1	C2	C3	C4	C5
w_k	0,447	0,074	0,030	0,150	0,300
C1	0,45	0,52	0,21	0,60	1,20
C2	0,06	0,07	0,18	0,04	0,04
C3	0,06	0,01	0,03	0,02	0,03
C4	0,11	0,29	0,27	0,15	0,05
C5	0,11	0,52	0,27	0,90	0,30

r_j	CVj
2,9706	6,6487
0,3980	5,4067
0,1561	5,1953
0,8762	5,8516
2,0956	6,9897

STEP 5

n (aantal criteria)	5
λ_{max}	6,02
Consistency Index (CI)	0,25
Consistency Ratio (CR)	0,2273
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C1	45%
C2	7%
C3	3%
C4	15%
C5	30%

0% 100%

ECONOMIC — Nr. criteria 4

STEP 1

	C6	C7	C8	C9
C6	1	9	1	5
C7	1/9	1	1/9	1/5
C8	1	9	1	7
C9	1/5	5	1/7	1

STEP 2

	C6	C7	C8	C9
C6	1	9	1	5
C7	1/9	1	1/9	1/5
C8	1	9	1	7
C9	1/5	5	1/7	1
SUM	2,31	24,00	2,25	13,20

STEP 3

	C6	C7	C8	C9	w_k
C6	0,43	0,38	0,44	0,38	0,408
C7	0,05	0,04	0,05	0,02	0,039
C8	0,43	0,38	0,44	0,53	0,445
C9	0,09	0,21	0,06	0,08	0,109

STEP 4

	C6	C7	C8	C9
w_k	0,408	0,039	0,445	0,109
C6	0,41	0,35	0,45	0,54
C7	0,05	0,04	0,05	0,02
C8	0,41	0,35	0,45	0,76
C9	0,08	0,19	0,06	0,11

r_j	CVj
1,7424	4,2754
0,1550	4,0215
1,9594	4,3990
0,4464	4,1140

STEP 5

n (aantal criteria)	4
λ_{max}	4,20
Consistency Index (CI)	0,07
Consistency Ratio (CR)	0,0750
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C6	41%
C7	4%
C8	45%
C9	11%

0% %

SOCIAL — Nr. criteria 4

STEP 1

	C10	C11	C12	C13
C10	1	4	1	4
C11	1/4	1	1/5	1/7
C12	1	5	1	6
C13	1/4	7	1/6	1

STEP 2

	C10	C11	C12	C13
C10	1	4	1	4
C11	1/4	1	1/5	1/7
C12	1	5	1	6
C13	1/4	7	1/6	1
SUM	2,50	17,00	2,37	11,14

STEP 3

	C10	C11	C12	C13	w_k
C10	0,40	0,24	0,42	0,36	0,35
C11	0,10	0,06	0,08	0,01	0,06
C12	0,40	0,29	0,42	0,54	0,41
C13	0,10	0,41	0,07	0,09	0,17

STEP 4

	C10	C11	C12	C13
w_k	0,354	0,064	0,414	0,168
C10	0,35	0,26	0,41	0,67
C11	0,09	0,06	0,08	0,02
C12	0,35	0,32	0,41	1,01
C13	0,09	0,45	0,07	0,17

r_j	CVj
1,6961	4,7884
0,2593	4,0498
2,0961	5,0657
0,7738	4,6062

STEP 5

n (aantal criteria)	4
λ_{max}	4,63
Consistency Index (CI)	0,21
Consistency Ratio (CR)	0,2324
CR threshold	0,10
CR threshold (bulk)	2,00

Criteria	w_k
C10	35%
C11	6%
C12	41%
C13	17%

0% %

Figure F.4 - Stakeholder 4_project leader_Criteria weights results

APPENDIX G

Sensitivity Analysis

BASE CASE - Equal weights

	Pi	RANK
A1	0,408	9
A2	0,596	6
A3	0,517	8
A4	0,601	5
A5	0,679	3
A6	0,661	4
A7	0,723	2
A8	0,595	7
A9	0,725	1

Table G.1 - Equal weights ranking

	A1	A2	A3	A4	A5	A6	A7	A8	A9
Equal Weights Ranking	9	6	8	5	3	4	2	7	1
Priority C1	9	7	8	6	1	4	3	5	2
Priority C2	9	7	8	5	4	3	1	6	2
Priority C3	9	8	7	6	2	4	3	5	1
Priority C4	9	8	7	5	4	3	1	6	2
Priority C5	9	8	7	6	1	4	3	5	2
Priority C6	3	1	6	5	8	7	2	9	4
Priority C7	9	7	8	5	4	3	1	6	2
Priority C8	9	6	8	7	4	3	1	5	2
Priority C9	9	7	6	4	2	5	3	8	1
Priority C10	7	6	9	8	3	4	2	5	1
Priority C11	5	3	2	1	8	7	4	9	6
Priority C12	9	8	7	4	2	5	3	6	1
Priority C13	7	1	8	4	2	6	5	9	3

Table G.3 - Shift in ranking when prioritizing a criterion one-at-a-time

	C1 = 26,7%		C2 = 26,7%		C3 = 26,7%		C4 = 26,7%		C5 = 26,7%	
	Heating demand		Energy Label		Energy-Index		Renewable Energy Share		Energy savings (gas)	
	Pi	RANK	Pi	RANK	Pi	RANK	Pi	RANK	Pi	RANK
A1	0,379	9	0,275	9	0,288	9	0,340	9	0,329	9
A2	0,510	7	0,569	7	0,414	8	0,552	8	0,445	8
A3	0,505	8	0,512	8	0,432	7	0,584	7	0,493	7
A4	0,526	6	0,751	5	0,671	6	0,693	5	0,511	6
A5	0,702	1	0,786	4	0,775	2	0,733	4	0,742	1
A6	0,558	4	0,807	3	0,717	4	0,757	3	0,529	4
A7	0,622	3	0,848	1	0,761	3	0,808	1	0,590	3
A8	0,527	5	0,749	6	0,709	5	0,687	6	0,526	5
A9	0,690	2	0,828	2	0,785	1	0,785	2	0,691	2

	C6 = 28,3%		C7 = 28,3%		C8 = 28,3%		C9 = 28,3%	
	Investment cost		Investment per labelstep		Life Cycle Cost		Payback Period	
	Pi	RANK	Pi	RANK	Pi	RANK	Pi	RANK
A1	0,605	3	0,227	9	0,431	9	0,386	9
A2	0,660	1	0,667	7	0,560	6	0,530	7
A3	0,566	6	0,666	8	0,439	8	0,551	6
A4	0,582	5	0,762	5	0,546	7	0,589	4
A5	0,532	8	0,800	4	0,638	4	0,724	2
A6	0,536	7	0,809	3	0,648	3	0,570	5
A7	0,621	2	0,849	1	0,692	1	0,691	3
A8	0,406	9	0,736	6	0,633	5	0,481	8
A9	0,598	4	0,841	2	0,681	2	0,744	1

	C10 = 28,3%		C11 = 28,3%		C12 = 28,3%		C13 = 28,3%	
	Thermal Comfort		Renovation Nuisance		Energy Cost Savings		Rent Increment	
	Pi	RANK	Pi	RANK	Pi	RANK	Pi	RANK
A1	0,584	7	0,574	5	0,207	9	0,480	7
A2	0,707	6	0,708	3	0,593	8	0,612	1
A3	0,256	9	0,759	2	0,652	7	0,464	8
A4	0,318	8	0,839	1	0,816	4	0,507	4
A5	0,804	3	0,427	8	0,839	2	0,526	2
A6	0,742	4	0,509	7	0,783	5	0,485	6
A7	0,806	2	0,705	4	0,818	3	0,503	5
A8	0,707	5	0,379	9	0,731	6	0,464	9
A9	0,895	1	0,534	6	0,842	1	0,514	3

Table G.2 - Sensitivity Analysis - prioritizing a criterion one-at-a-time with +20%

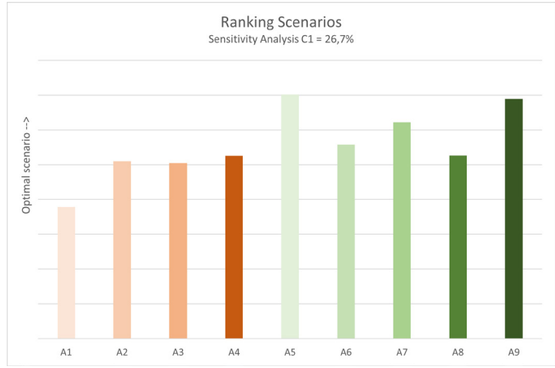


Figure G.1 - Ranking C1 heating demand 26,7%

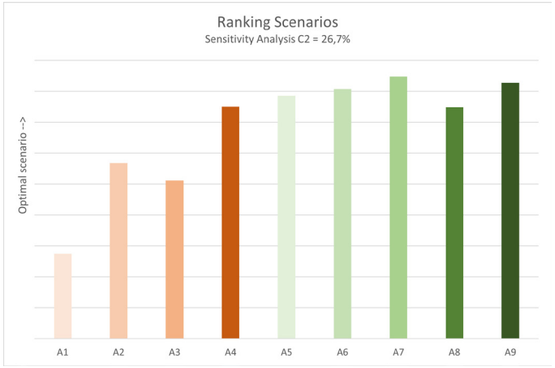


Figure G.2 - Ranking C2 energy label 26,7%

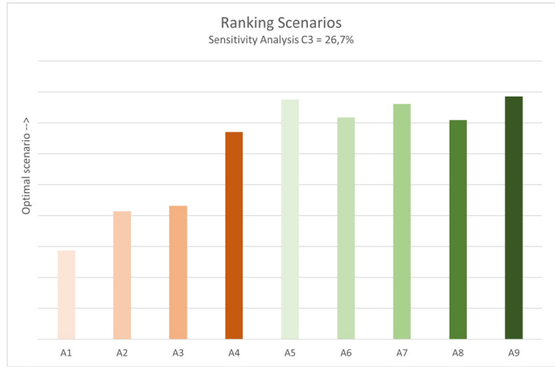


Figure G.3 - Ranking C3 energy-index 26,7%

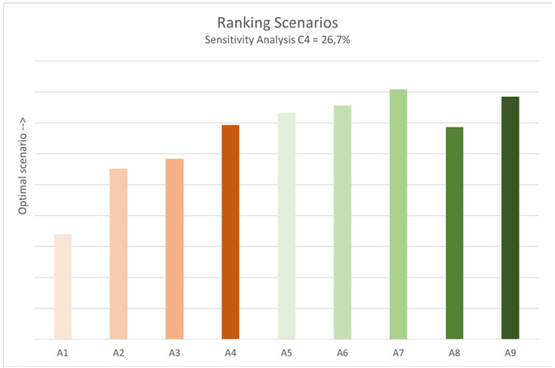


Figure G.4 - Ranking C4 renewable energy share 26,7%

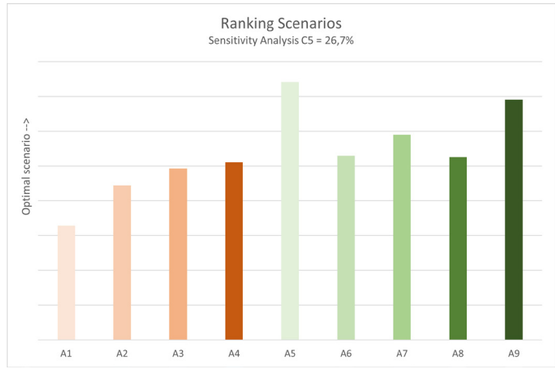


Figure G.5 - Ranking C5 energy savings (gas) 26,7%

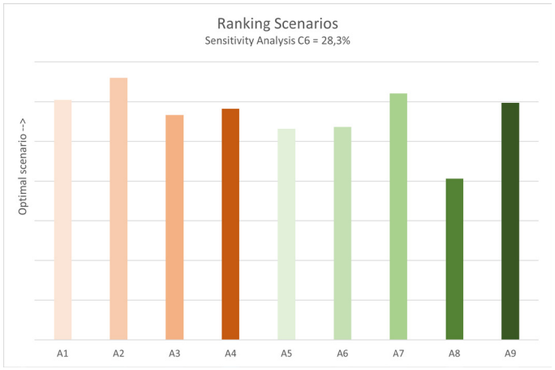


Figure G.6 - Ranking C6 investment cost 28,3%

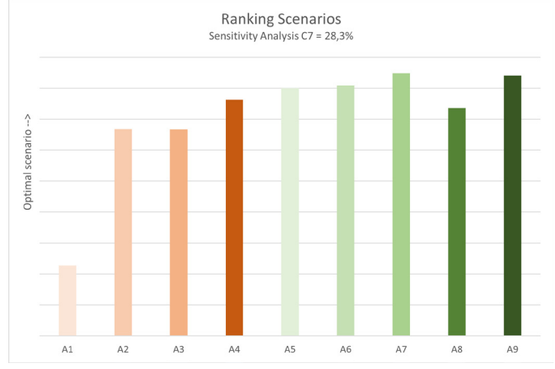


Figure G.7 - Ranking C7 investment cost per labelstep 28,3%

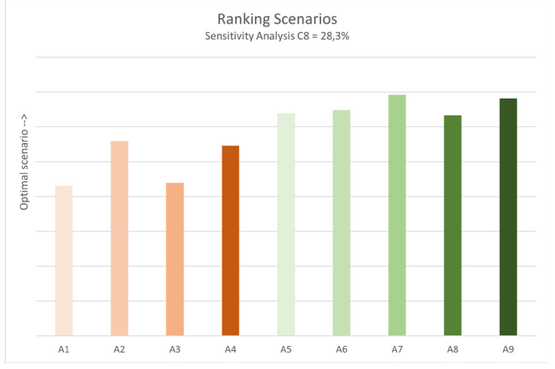


Figure G.8 - Ranking C8 life cycle cost (LCC) 28,3%

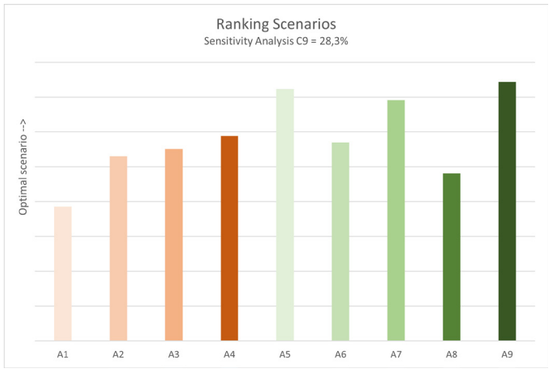


Figure G.9 - Ranking C9 payback period 28,3%

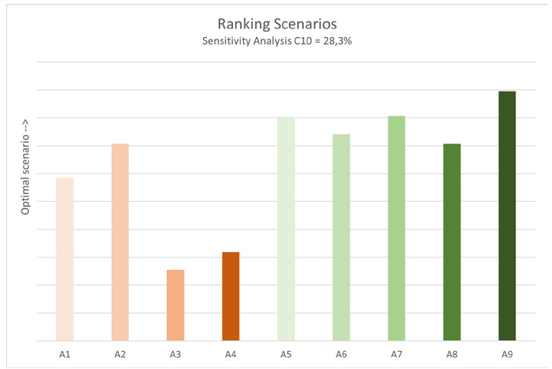


Figure G.10 - Ranking C10 thermal comfort 28,3%

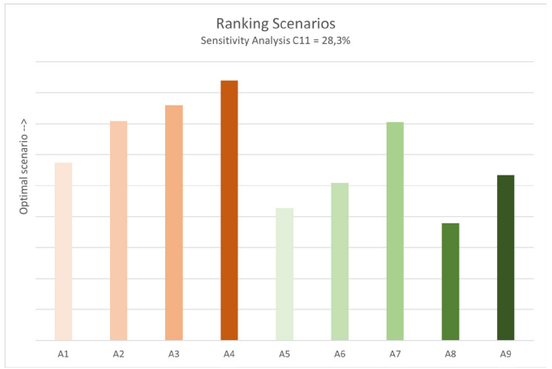


Figure G.11 - Ranking C11 renovation nuisance 28,3%

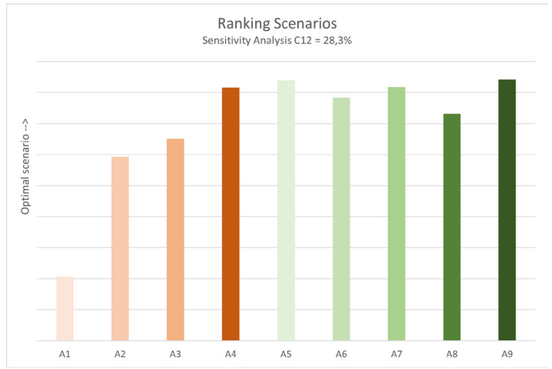


Figure G.12 - Ranking C12 energy cost savings 28,3%

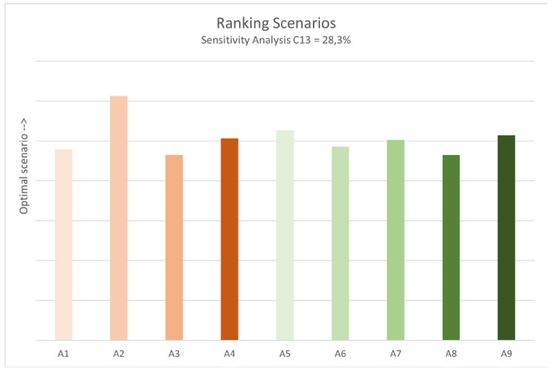


Figure G.13 - Ranking C13 rent increment 28,3%

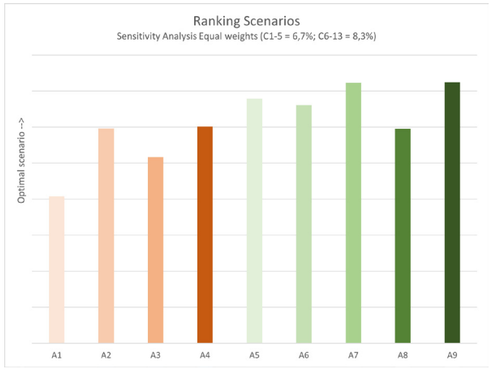


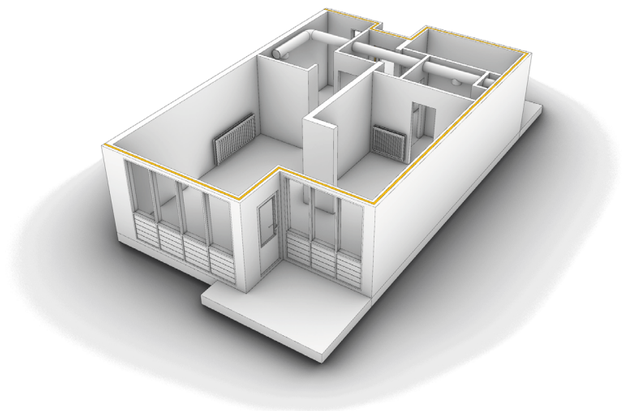
Figure G.14 - Ranking equal weights

APPENDIX H

Renovation Alternatives Visualized

RENOVATION SCENARIO A1

Cavity - Airtightness
HT-HR 107 Boiler



HT — Heating demand = 174,34 [kWh/m²]
Hours too cold = 263 [h]

Airtightness = 1,5

Rc Roof = 2,5 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,8 [W/m²K]

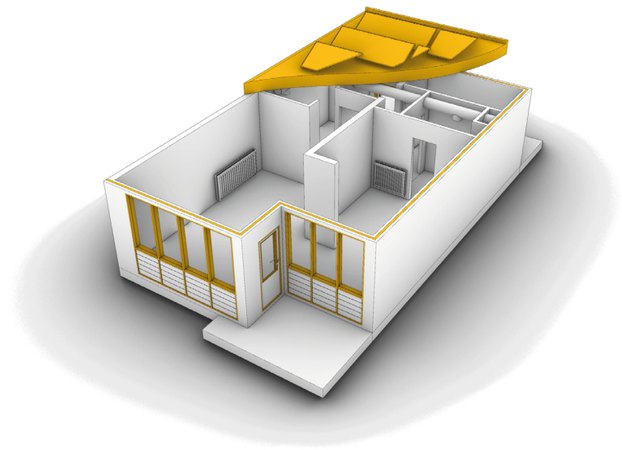
HR 107 boiler (HT)

Radiator type 21

Ventilation type C2 - Mechanical Exhaust

RENOVATION SCENARIO A2

Roof - Cavity - Airtightness
HT-HR 107 Boiler - PV panels



HT — Heating demand = 153,76[kWh/m²]
Hours too cold = 230 [h]

Airtightness = 1,2

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,7 [W/m²K]

4 PV panels per apartment

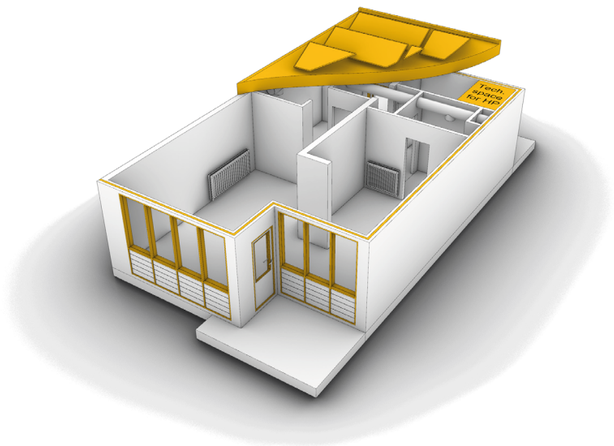
HR 107 boiler (HT)

Radiator type 21

Ventilation type C2 - Mechanical Exhaust

RENOVATION SCENARIO A3

Roof - Cavity - Airtightness
Heat pump - PV panels



LT-READY

Heating demand = 122,80 [kWh/m²]
Hours too cold = 919 [h]

Airtightness = 1,2

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,7 [W/m²K]

4 PV panels per apartment

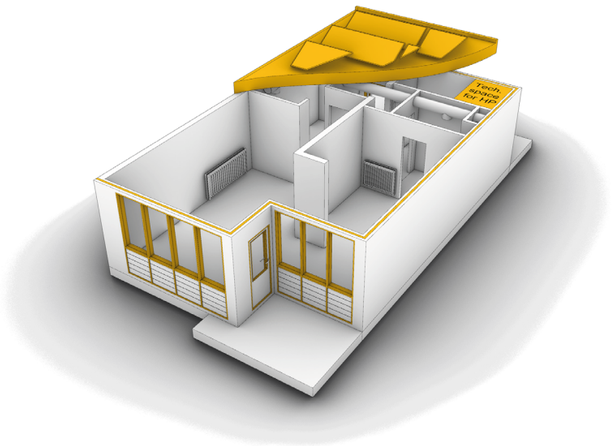
Collective air-water heat pump

Radiator type 21

Ventilation type C2 -
Mechanical Exhaust

RENOVATION SCENARIO A4

Roof - Cavity - Airtightness
Heat Pump - PVT panels



LT-READY

Heating demand = 122,80 [kWh/m²]
Hours too cold = 919 [h]

Airtightness = 1,2

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,7 [W/m²K]

4 PVT panels per apartment

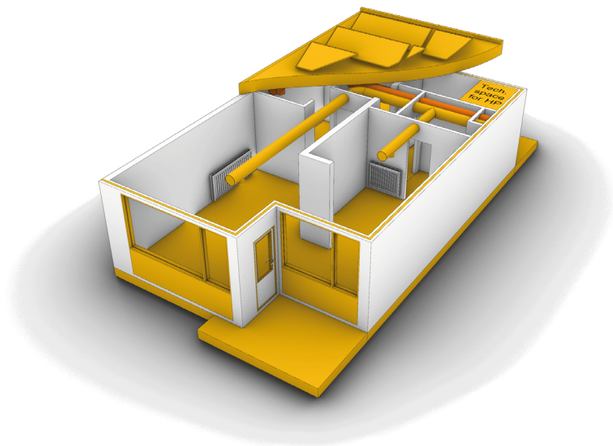
Collective air-water heat pump

Radiator type 21

Ventilation type C2 -
Mechanical Exhaust

RENOVATION SCENARIO A5

Roof - Cavity - Floor - Windows - Airtightness
Heat Pump - PVT panels - D2



LT-READY

Heating demand = 59,92 [kWh/m²]
Hours too cold = 225 [h]

Airtightness = 0,4

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 2,6 [m²K/W]
U Window = 1,0 [W/m²K]

4 PVT panels per apartment

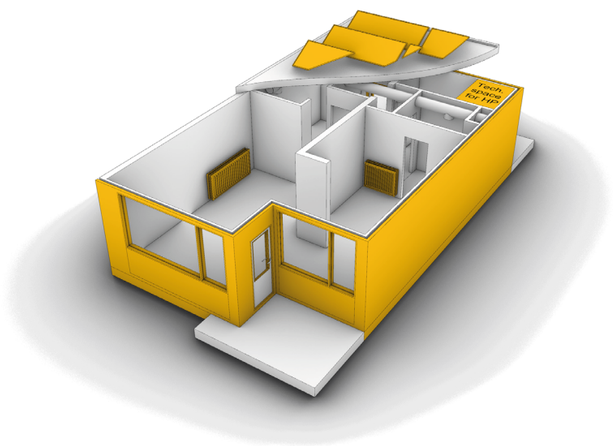
Collective air-water heat pump

Radiator type 21

Ventilation type D5 - Balanced

RENOVATION SCENARIO A6

Wall exterior - Windows - Airtightness
Heat Pump - PVT panels - Radiators



LT-READY

Heating demand = 124,50 [kWh/m²]
Hours too cold = 271 [h]

Airtightness = 1,0

Rc Roof = 2,5 [m²K/W]
Rc Wall = 6,3 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,0 [W/m²K]

4 PVT panels per apartment

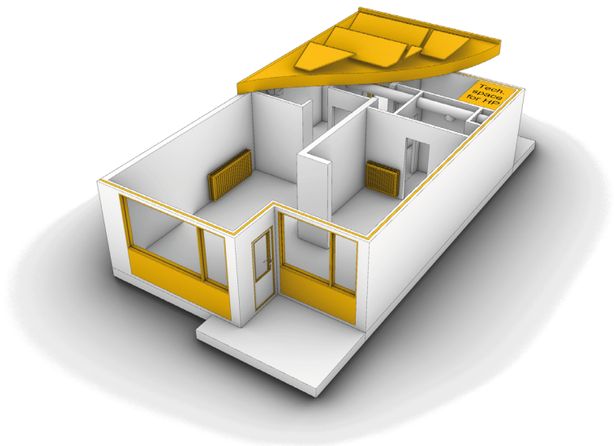
Collective air-water heat pump

Radiator type 22

Ventilation type C2 -
Mechanical Exhaust

RENOVATION SCENARIO A7

Roof - Cavity - Windows - Airtightness
Heat Pump - PVT panels - Radiators



LT-READY

Heating demand = 118,45 [kWh/m²]
Hours too cold = 210 [h]

Airtightness = 0,7

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,0 [W/m²K]

4 PVT panels per apartment

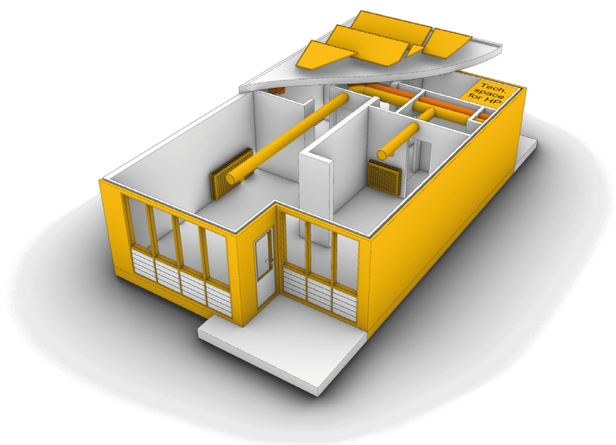
Collective air-water heat pump

Radiator type 22

Ventilation type C2 -
Mechanical Exhaust

RENOVATION SCENARIO A8

Wall exterior - Airtightness
Heat Pump - PVT panels - Radiators - D2



LT-READY

Heating demand = 114,43 [kWh/m²]
Hours too cold = 285 [h]

Airtightness = 1,2

Rc Roof = 2,5 [m²K/W]
Rc Wall = 6,3 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,7 [W/m²K]

4 PVT panels per apartment

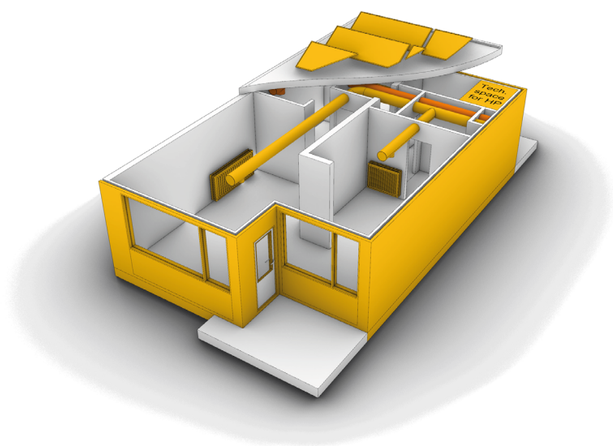
Collective air-water heat pump

Radiator type 22

Ventilation type D5 - Balanced

RENOVATION SCENARIO A10

Wall exterior - Windows - Airtightness
Heat Pump - PVT panels - Radiators - D2



LT-READY

Heating demand = 99,21 [kWh/m²]
Hours too cold = 191 [h]

Airtightness = 1,0

Rc Roof = 2,5 [m²K/W]
Rc Wall = 6,3 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,0 [W/m²K]

4 PVT panels per apartment

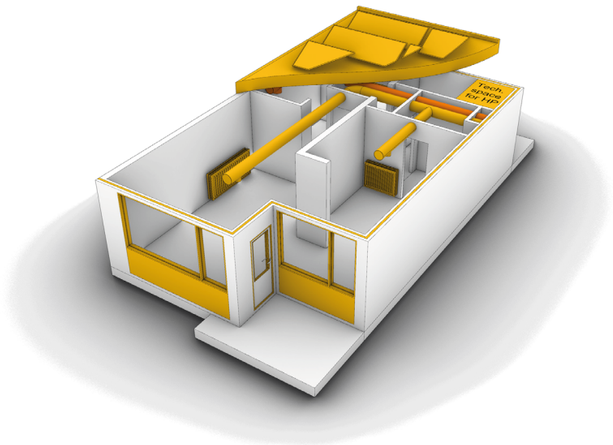
Collective air-water heat pump

Radiator type 22

Ventilation type D5 - Balanced

RENOVATION SCENARIO A11

Roof - Cavity - Windows - Airtightness
Heat Pump - PVT panels - Radiators - D2



LT-READY

Heating demand = 92,32 [kWh/m²]
Hours too cold = 169 [h]

Airtightness = 0,7

Rc Roof = 5,84 [m²K/W]
Rc Cavity = 1,69 [m²K/W]
Rc Floor = 0,15 [m²K/W]
U Window = 1,0 [W/m²K]

4 PVT panels per apartment

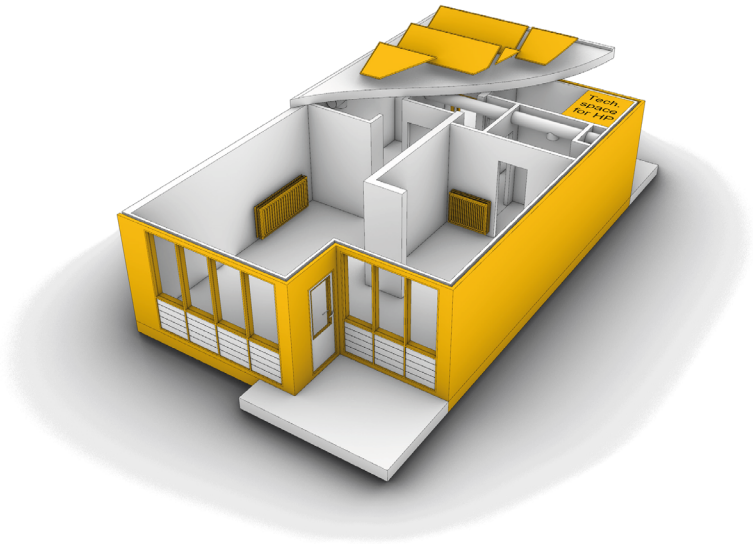
Collective air-water heat pump

Radiator type 22

Ventilation type D5 - Balanced

RENOVATION SCENARIO A12

Wall Exterior - Airtightness
Heat Pump - PVT panels - Radiators



LT-READY

Heating demand = 138,64 [kWh/m^2]
Hours too cold = 389 [h]

Airtightness = 1,2

Rc Roof = 2,5 [m^{2}K/W]
Rc Wall = 6,3 [m^{2}K/W]
Rc Floor = 0,15 [m^{2}K/W]
U Window = 1,7 [W/m^{2}K]

4 PVT panels per apartment

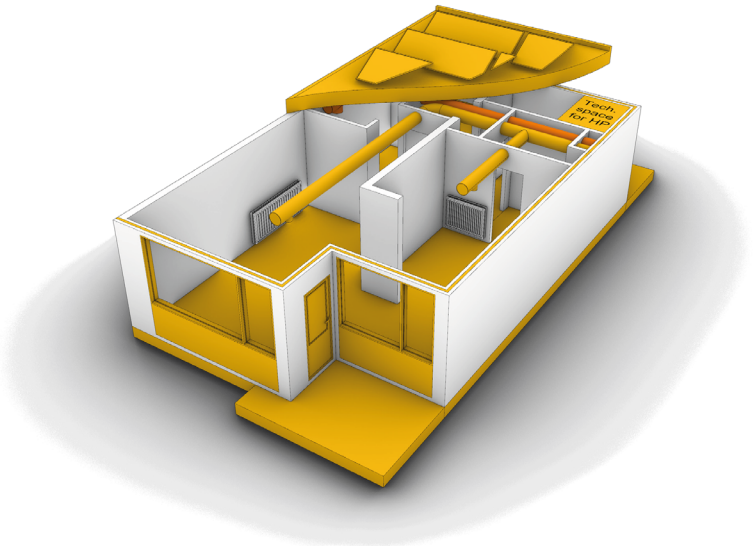
Collective air-water heat pump

Radiator type 22

Ventilation type C2 - Mechanical Exhaust

RENOVATION SCENARIO A13

Roof - Cavity - Floor - Doors - Windows - Airtightness
Heat Pump - PVT panels - D2



LT-READY

Heating demand = 65,10 [kWh/m^2]
Hours too cold = 298 [h]

Airtightness = 0,4

Rc Roof = 3,5 [m^{2}K/W]
Rc Wall = 1,7 [m^{2}K/W]
Rc Floor = 3,5 [m^{2}K/W]
U Door = 1,4 [W/m^{2}K]
U Window = 1,4 [W/m^{2}K]

4 PVT panels per apartment

Collective air-water heat pump

Radiator type 21

Ventilation type D5 - Balanced