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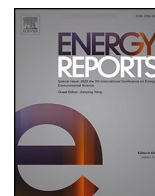
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Preparing for lower-temperature heating: A multi-criteria decision-making framework for energy renovations of existing Dutch dwellings

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ABSTRACT

Transitioning existing dwellings to lower temperature heating (LTH) is crucial for achieving the Dutch goal of making 1.5 million homes gas-free (i.e., independent of natural gas-based heating) by 2030. This transition often necessitates energy renovations, which present significant decision-making challenges in selecting appropriate solutions. Consequently, this study introduces a systematic framework based on multi-criteria decision-making (MCDM) approach to support selecting suitable renovation options for preparing Dutch dwellings for LTH supplied by sustainable heating systems. The framework is methodically developed by generalising typical steps from existing literature and identifying essential decision-making aspects for framework development. It was then theoretically tailored to the specific context of LTH-ready renovations. The framework involves six steps: data collection and benchmarking, evaluating LTH readiness, establishing decision-making preferences and generating renovation solutions, filtering LTH feasible options, quantifying their performance, and ranking them using the TOPSIS method. Furthermore, the theoretical framework was applied to a case study of a multi-family social house (MFH) in the Netherlands to demonstrate its practical usability and to incorporate real-world context in decision-making. While the framework's applicability has been validated for this specific case, further application across different contexts is necessary to generalise its usability. The proposed framework comprehensively evaluates renovation solutions needed to transition to LTH based on environmental, economic, and social criteria, thereby addressing energy poverty and occupant comfort concerns. This supports stakeholders in making informed decisions and accelerating energy renovations for a decarbonised built environment.

1. Introduction

Decarbonising the residential heating sector is pivotal for achieving a climate-neutral built environment. To this end, the Netherlands aims to prepare 1.5 million dwellings for gas-free heating by 2030, targeting an annual transformation rate of 200,000 homes (Dutch Ministry of Economic Affairs and Climate, 2019). Among the various alternatives available, district heating (DH) systems with lower temperature supply (below 75°C) offer a promising solution for providing sustainable heat, particularly to densely populated urban centres (Doračić et al., 2020; Harrestrup and Svendsen, 2015; Zach et al., 2019). Lowering the temperature in the heat networks allows for integrating sustainable heating sources such as geothermal, aquathermal, and waste heat while also improving distribution and production efficiency (Averfalk et al., 2017; Brand and Svendsen, 2013; Harrestrup and Svendsen, 2015). Additionally, at the building level, lower temperature heating (LTH) can enhance thermal comfort and indoor environmental quality (Eijdem

et al., 1999; Ovchinnikov et al., 2017; Wang et al., 2016). Nonetheless, transitioning existing buildings with high heating demands to LTH poses significant challenges.

Lowering the supply temperature reduces the heating power of the existing space heating system, such as radiators designed to operate on a high temperature (HT) supply of more than 75°C (Østergaard and Svendsen, 2018; Ovchinnikov et al., 2017; Tunzi et al., 2016). This reduction can lead to an inability to offset the heat losses of existing dwellings, resulting in thermal discomfort for occupants. Moreover, dwellings with high heat demands pose further challenges in supply temperature reduction as they necessitate maintaining higher temperatures across the network to meet peak demand (Harrestrup and Svendsen, 2015). This complicates the planning of future DH systems with sustainable heat sources unless peak demands from these dwellings are reduced. Consequently, many existing dwellings would require energy renovations to adapt to LTH supplied by DH systems (Acheilas et al., 2020).

This study characterises energy renovations as building-level

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Nomenclature

AHP	Analytical Hierarchy Process
DH	District Heating
ÉLECTRE	Élimination Et Choix Traduisant la Réalité
EI	Energy Index
HT	High-Temperature
KPI	Key Performance Indicator
LT	Low Temperature
LTH	Lower Temperature Heating
MODM	Multi-Objective Decision-Making
MADM	Multi-Attribute Decision Making
MCDM	Multi-Criteria Decision-Making
MFH	Multi-Family House
NIS	Negative Ideal Solution
PIS	Positive Ideal Solution
PPD	Predicted Percentage of Dissatisfied
PROMETHEE	Preference Ranking Organisation METHod for Enrichment
PV	Photovoltaic panels
PVT	Photovoltaic Thermal collectors
TOPSIS	Technique of Order of Preference by Similarity to Ideal Solutions

modifications aimed at lowering heating demands and facilitating the readiness of dwellings for LTH using sustainable energy sources (Asdrubali and Desideri, 2018; TKI Urban energy, 2019). However, the decision-making process for selecting the appropriate renovation solutions required for preparing the dwellings for LTH is challenging. Firstly, there is a lack of standard criteria for assessing the readiness of a dwelling for LTH (Wahi et al., 2023a). This assessment is crucial to determine the need and intervention level required to prepare a dwelling for LTH. Secondly, if energy renovations are needed, the plethora of available renovation solutions makes it challenging to select the most suitable ones (Jafari and Valentin, 2018; Kamari et al., 2018; Si et al., 2016). Even though each solution uniquely could prepare the dwelling for LTH, evaluating the numerous options can lead to analysis paralysis. Furthermore, the lack of time, expertise (D'Oca et al., 2018; Mjörnell et al., 2014) and a clear overview of priorities (Jensen et al., 2013) complicates the evaluation process, creating barriers to energy renovations.

Thirdly, these challenges are exacerbated by the involvement of multiple stakeholders in the decision-making process. Each stakeholder has different preferences and agendas, making it difficult to reach a consensus and establish shared goals (D'Oca et al., 2018; Husiev et al., 2023; Jensen et al., 2013). Moreover, the heterogeneity of the dwelling stock adds complexity, as each dwelling has different renovation requirements (Husiev et al., 2023; Prieto et al., 2024). These combined challenges create difficulties for property owners, especially those managing larger portfolios, such as municipalities or housing corporations, in assessing renovation needs and determining the appropriate level of intervention (TKI Urban energy, 2019). Consequently, the lack of informed decision-making results in informational barriers (Jensen et al., 2018; Prieto et al., 2024) impeding renovation rates and ultimately affecting the pace of the energy transition in the built environment.

To explore these challenges, researchers have extensively discussed the systematic application of Multi-Criteria Decision-Making (MCDM) methods (Cajot et al., 2017; Nielsen et al., 2016; Pohekar and Ramachandran, 2004; Siksnyte-Butkiene et al., 2020). These methods are instrumental in selecting renovation concepts by balancing the interests of diverse stakeholders and evaluating the performance of various renovation scenarios, incorporating both qualitative and quantitative

factors (Pohekar and Ramachandran, 2004). A variety of tools and frameworks have been developed to facilitate the selection of renovation solutions and streamline the decision-making process (Jensen et al., 2018; Nielsen et al., 2016). While many studies have utilised MCDM methods, there remains a critical need to further investigate how this approach can enhance decision-making within the context of LTH renovations. This gap highlights the necessity for a holistic approach that supports decision-making and scenario selection in LTH renovation projects. Consequently, this study aims to develop a comprehensive framework to guide the selection of renovation solutions to prepare dwellings for the transition towards LTH (with DH systems).

1.1. Methodology and outline of the study

This study proposes a decision support framework, based on the MCDM approach to assist in selecting the appropriate renovation solutions for preparing dwellings for LTH. To develop this framework, the study adapts the methodological steps suggested by Partelow (Partelow, 2023). These steps include generalisation and theoretical fitting, leading to the development of the framework. Subsequently, the application and implication phases follow, corresponding to the practical application of the framework.

The generalisation step involves reviewing existing studies that utilise the MCDM approach in energy renovations. Further, it synthesises the typical steps and processes required. Section 2 elaborates on this process, identifying essential decision-making aspects for framework development. Subsequently, Section 3 details the theoretical fitting, which tailors these generalised decision-making aspects to the specific LTH context, thereby introducing the proposed framework. In the application phase, the developed framework is applied to a real case in order to evaluate its applicability.

Section 4 demonstrates the application of the proposed framework through a case study based on a multi-family social housing rental complex in the Netherlands. This case study, renovated to utilise a low temperature (LT) supply of 55°C, provides a context that closely mirrors real-world conditions. The framework was applied to the building's state prior to these renovations. Section 5 discusses the implications of the proposed framework in supporting decision-making for LTH, drawing on insights gained from the case study application. Finally, Section 6 summarises the outcomes, explores the framework's limitations, and proposes avenues for future research.

This study significantly contributes to advancing decision-making processes for preparing Dutch dwellings for LTH. By incorporating criteria specific to LTH readiness, it emphasises actionable metrics to evaluate a dwelling's preparedness beyond the scope of traditional decision-making approaches. Crucially, the proposed framework offers an advanced approach by systematically guiding the prioritisation and selection of renovation solutions—balancing environmental, economic, and social dimensions—for a more holistic assessment of possible renovation options.

A notable strength of this work is its practical demonstration through a real-world case study of a multi-family house (MFH). This application showcases the framework's ability to address the complexities of renovation decision-making, enabling stakeholders to navigate competing priorities and identify effective solutions. By facilitating informed decision-making, the study supports the acceleration of energy renovations and promotes the transition toward a decarbonised built environment.

2. Generalisation: decision-support frameworks

The decision-making process for selecting the appropriate renovation solutions is widely acknowledged in the literature as both challenging and complex due to several interconnected factors (Amorocho and Hartmann, 2022; Jafari and Valentin, 2018; Rosenfeld and Shohet, 1999; Si et al., 2016). As described earlier, the vast array of available

options, along with their interaction with existing building systems, makes the selection process overwhelming (Laguna Salvadó et al., 2022; Ma et al., 2012; Taillandier et al., 2016; Zavadskas et al., 2008). Additionally, the involvement of various stakeholders in the decision-making process adds another layer of complexity (Amorocho and Hartmann, 2022; Laguna Salvadó et al., 2022). As noted by Jensen and Maslesa (Jensen and Maslesa, 2015), each stakeholder prioritises different aspects of the renovation. Consequently, identifying and establishing these diverse preferences and criteria can be a challenge, especially when there are conflicting interests to balance (Amorocho and Hartmann, 2022; Cajot et al., 2017; Pohekar and Ramachandran, 2004; Si et al., 2016). Moreover, integrating these varied preferences to evaluate and rank different solutions further complicates the decision-making process (Amorocho and Hartmann, 2022; Khadra et al., 2020; Mulliner et al., 2016; Seddiki et al., 2016).

In response to these challenges, researchers have proposed various decision-support tools and frameworks covering specific decision-making aspects. These aspects, which stem from the identified challenges, include incorporating stakeholders' interests, balancing conflicting interests, generating alternatives, and conducting multi-criteria assessments. Further, these same elements align with the six decision-making areas identified by Nielsen (Nielsen et al., 2016) in an extensive review of 46 existing decision-support tools. The following subsections describe the decision-making aspects in detail.

2.1. Incorporating stakeholder's interests

In energy renovation decision-making, stakeholders with direct interests and the ability to influence outcomes are frequently involved (Cajot et al., 2017). Consequently, representing stakeholders' interests becomes essential to the decision-making process. This representation is typically established during the objectives and criteria-setting phase (Amorocho and Hartmann, 2022; Laguna Salvadó et al., 2022; Nielsen et al., 2016). According to Ferreira et al. (2013), the rational core of the process is identifying renovation objectives and criteria through consultation with the relevant stakeholders. This step is crucial, as subsequent decision-making stages are structured around the renovation goals established during this phase (Laguna Salvadó et al., 2022).

A renovation objective can be defined as the reflection of the decision makers' intent or purpose of the renovations (Kamari et al., 2018; Lu et al., 2007). These objectives are often translated into specific, measurable qualitative or quantitative criteria, defining the key performance indicators (KPIs) necessary to assess and manage the renovation objectives (Amorocho and Hartmann, 2022; Kyllilä et al., 2016; Lu et al., 2007; Pramangioulis et al., 2019; Sen and Yang, 1998). The majority of the research emphasises a holistic sustainability assessment, incorporating technical, social, economic and environmental objectives as primary renovation goals (Amorocho and Hartmann, 2022; Khadra et al., 2020; Serrano-Jiménez et al., 2021; Si et al., 2016; Wang et al., 2009; Zavadskas et al., 2008). As the number and complexity of decision-making criteria increase, organising and logically presenting them becomes essential. Therefore, a decision tree is often employed, where objectives are arranged hierarchically and lead to specific criteria (Amorocho and Hartmann, 2022; Cajot et al., 2017; Nielsen et al., 2016; Si et al., 2016).

Several frameworks explored in the literature discuss encapsulating the renovation objectives, associated criteria, and KPIs (Amorocho and Hartmann, 2022; Jafari and Valentin, 2018; Kamari et al., 2017). Nevertheless, the overall approach can be generalised by first identifying the objectives representing the renovation problem, followed by defining the criteria and selecting relevant performance indicators. Various methods, including literature reviews, expert recommendations (Cajot et al., 2017), value maps (Kamari et al., 2017) or the Delphi method (Nielsen et al., 2016; Seddiki et al., 2016; Si et al., 2016), can be employed to reach a consensus among stakeholders on the renovation objectives and associated decision criteria.

2.2. Prioritising preferences among conflicting interests

Derived from the renovation objectives, the decision criteria reflect the preferences of the decision-makers. These preferences, or the prioritisation of criteria, are fundamental for evaluating and comparing alternatives. Establishing these priorities involves determining weights for the criteria in order to signify their relative importance (Choo et al., 1999; Nielsen et al., 2016; Wang et al., 2009). However, different decision-makers may assign varying values to the decision criteria, resulting in conflicting priorities or weights for the same criteria (Boix-Cots et al., 2023; Cajot et al., 2017; Haralambopoulos and Politidis, 2003; Seddiki et al., 2016). Resolving these differences in preferences is crucial, as they influence the final decision (Nielsen et al., 2016). According to Lu et al. (2007), in complex group decision-making problems, individual preferences within a group can be consolidated into single collective preferences or weights.

Additionally, the methods of weighting criteria can be categorised as subjective, objective or a combination of both, as outlined by Wang et al. (2009). Most studies employ the Analytical Hierarchy Process (AHP) method (Nielsen et al., 2016) developed by Saaty and Katz (1990). This method uses subjective scores from pairwise comparisons along with normalised eigenvectors to compute the relative weights of the criteria. Further, AHP is widely used because it also serves as a multi-criteria decision analysis method (Cajot et al., 2017).

As suggested by Amorocho and Hartmann (2022), the AHP method is effective for eliciting preferences from a group of decision-makers. It extracts criteria weights from individual decision-makers, which can then be averaged to determine aggregate decision weights for all selected criteria. Alternatively, Seddiki et al. (2016) propose using the subjective SWING method, where individual decision-makers assign weights to criteria. This is followed by a separate ranking of alternatives and a weighted sum to determine the global ranking. Ultimately, the chosen method for weighting criteria will depend on the available information and the specific multi-criteria method selected for evaluating alternatives (Sen and Yang, 1998).

2.3. Generation of renovation alternatives

Developing multiple renovation alternatives is a crucial component of the decision-support framework for energy renovation. The generation process is primarily driven by the renovation objectives and the preferences of the stakeholders (Cajot et al., 2017; Daniel and Ghiaus, 2023; Seddiki et al., 2016). It often incorporates technical consideration and constructional constraints, which are identified during the diagnosis of the building's existing condition (Laguna Salvadó et al., 2022; Nielsen et al., 2016; Rosenfeld and Shohet, 1999; Serrano-Jiménez et al., 2021; Zavadskas et al., 2008). Additionally, the process is informed by insights from the relevant literature and empirical studies (Hashempour et al., 2020; Romani et al., 2022), as well as data from digital databases (Jaggs and Palmer, 2000) supported by algorithms (Kamari et al., 2018). While generating a variety of alternatives is feasible, it is essential to streamline these options to reduce the time and effort spent on decision-making. A practical approach involves applying an initial filter to exclude solutions not aligning with established renovation objectives, or those failing to meet specific essential criteria. This selective filtering ensures that only viable alternatives are carried forward for evaluation using the appropriate MCDM methods (Wahi et al., 2023b).

2.4. Multi-criteria assessment

The selection of an appropriate MCDM method is essential for evaluating renovation alternatives based on multiple criteria and stakeholder preferences. These methods are broadly categorised based on decision-making needs (Pohekar and Ramachandran, 2004; Sen and Yang, 1998). For instance, Multi-Attribute Decision Making (MADM) methods are typically employed when choosing from a limited set of

renovation options (Kumar et al., 2017; Triantaphyllou, 2000). Conversely, if the focus is on synthesising solutions that satisfy the objectives, Multi-Objective Decision Making (MODM) methods are employed (Kumar et al., 2017; Triantaphyllou, 2000). In the context of this study, selecting appropriate renovation solutions for LTH is considered a MADM problem, making the associated methods most suitable. For clarity, MADM and MCDM will be used interchangeably in this study.

A variety of MCDM methods are utilised in energy renovation and energy planning decision problems. Commonly discussed methods include AHP, *Technique of Order of Preference by Similarity to Ideal Solutions* (TOPSIS), *Preference Ranking Organisation METHod for Enrichment* (PROMETHEE), and *Élimination Et Choix Traduisant la Réalité* (ÉLECTRE) (Cajot et al., 2017; Kumar et al., 2017; Pohekar and Ramachandran, 2004; Villalba et al., 2024). According to Triantaphyllou (2000), selecting an appropriate MCDM model from an available method can itself be viewed as an MCDM problem. The selection depends on various factors such as the quantity and type of information available, the decision-maker's knowledge, and familiarity with the methods. Additionally, the characteristics of the problem and the number of criteria and alternatives being evaluated are significant in the selection process (Kumar et al., 2017; Lu et al., 2007; Sen and Yang, 1998; Triantaphyllou, 2000).

Based on the reviewed literature, it can be concluded that the novelty of any decision-support framework lies in its application context. All studies address the decision-making aspects following a systematic approach, which can be generalised into six essential steps, as Fig. 1 illustrates. However, it should not be considered a linear process but rather a set of iterative building blocks. Consequently, these generalised building blocks will form the basis for developing the decision-support framework for LTH-ready renovations, as described in the next section.

3. Theoretical fitting: proposed decision-support framework

This section introduces the comprehensive framework designed to support decision-making in selecting appropriate renovation options for existing Dutch homes, enabling the use of LTH from the DH system. The development of this framework incorporates the decision-making aspects discussed in the previous section. Our earlier study (Wahi et al., 2023b) developed an assessment approach for evaluating LTH readiness and determining the need for renovations. In addition, this approach provided a systematic way to organise renovation alternatives and narrow down the number of viable options.

However, while these reduced options are effective in making a dwelling LTH-ready, they require further multi-criteria analysis to

determine the most appropriate renovation solutions. Therefore, the proposed framework integrates and expands upon the previously developed assessment approach. The generalised steps outlined in the preceding section guide the development of this framework, which is tailored specifically for selecting LTH-ready solutions. Fig. 2 illustrates the developed decision-making framework.

3.1. Step 1: Identification and diagnosis

The first step in the decision-support framework is the preparatory work to identify and structure the most pressing issues that need to be addressed through building renovation (Jensen et al., 2018; Zavadskas et al., 2008). During this initial phase, it is vital to identify all relevant stakeholders, along with their roles in the decision-making process (Amarocho and Hartmann, 2022). Additionally, conducting a thorough inspection and diagnosis of the dwellings is essential to establish the benchmarks for the existing conditions. This enables the comparison of developed renovation alternatives (Step 4) against these benchmarks based on decision criteria defined in Step 3 (Jensen et al., 2018; Laguna Salvadó et al., 2022).

The information collected during this stage is fundamental in identifying the renovation problem and setting the initial ambitions, wish list and boundary conditions for the renovation project (Amarocho and Hartmann, 2022; Ferreira et al., 2013; Konstantinou and Knaack, 2011; Laguna Salvadó et al., 2022; Ma et al., 2012; Nielsen et al., 2016). However, gathering diverse forms of data from multiple sources can be challenging and may complicate establishing clear goals, as noted by Laguna Salvadó et al. (2022). In order to streamline this process, a pre-retrofit survey can be employed to gather and structure information effectively (Ma et al., 2012). Further, Kamari et al. (Kamari et al., 2017) suggested a list of 30 essential factors that can be addressed through a pre-retrofit survey to determine the building's potential for renovation and clearly capture the specific renovation challenges.

To facilitate the evaluation of a dwelling's potential to be heated with a lower temperature supply from DH systems, a comprehensive one-page datasheet has been developed (Appendix A.1). This datasheet gathers essential data, building upon our previous studies on decision-making parameters for LTH-ready renovations (Wahi et al., 2023a) and the assessment approach to determine necessary intervention levels (Wahi et al., 2023b). By ensuring practicality and efficiency, it aids stakeholders in collecting data on the dwelling in question. Subsequently, the collected data is used to establish an energy model and benchmark the performance of the existing dwelling under HT supply conditions. To achieve this, a parametric simulation workflow in the Rhino Grasshopper environment is employed, utilising Ladybug and

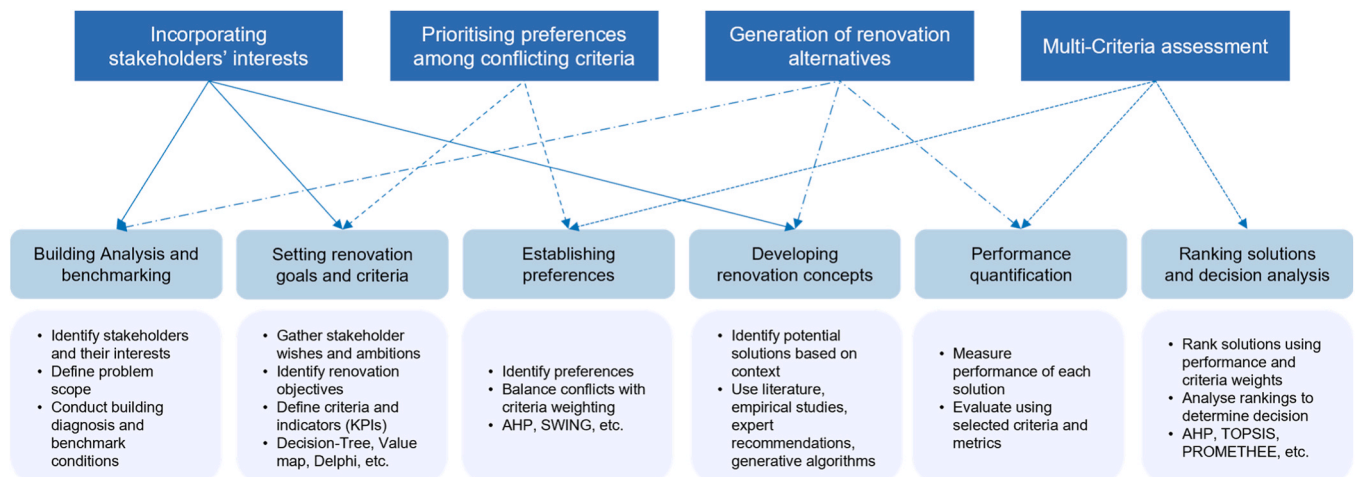


Fig. 1. Generalised decision-making steps derived from literature mapped to the specific decision-making aspect.

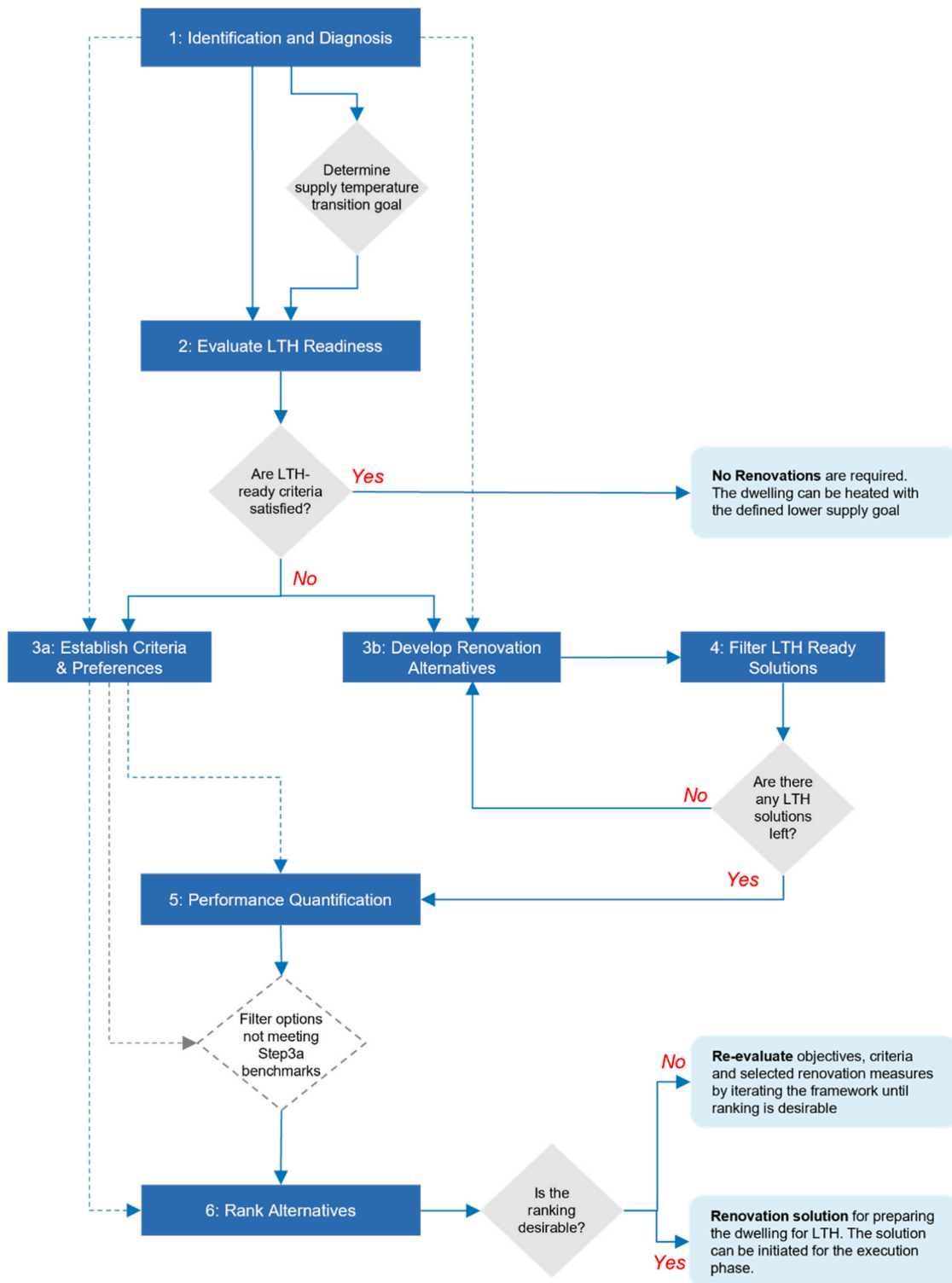


Fig. 2. Proposed decision support framework for selecting renovations to prepare dwellings for LTH.

Honeybee plugins for energy simulations, as outlined in our previous study (Wahi et al., 2024a). This benchmarking is crucial for evaluating the LTH readiness of the dwelling and determining the need for renovation, as discussed in the subsequent step.

3.2. Step 2: Evaluate LTH readiness

In this step, the dwelling’s readiness for LTH is assessed using the LTH-ready criteria defined in our earlier study (Wahi et al., 2023b).

Accordingly, a dwelling is considered LTH-ready if the space heating demand and thermal comfort are maintained or improved under lower temperatures compared to its benchmark performance. The assessment involves simulating the dwelling using the parametric simulation workflow under the lower supply transition goals established in Step 1. The KPIs studied include the annual space heating demand (kWh/m²) and occupied cold hours below the threshold of 20% Predicted Percentage of Dissatisfied (PPD) as described by Peeters et al. (2009) Further, the simulated performance under lower temperatures is

compared with the benchmark performance under HT supply, which is established in Step 1. If the dwelling meets the assessment criteria, it does not require renovations and can be supplied with LTH. Conversely, if the dwelling does not meet the LTH-ready criteria, the renovation project must progress, following the subsequent steps in the framework.

3.3. Step 3a: Establish criteria and preferences

From the analysis conducted in the previous steps, it is determined whether or not energy renovations are necessary to prepare the dwelling for LTH. If yes, then this assessment will provide stakeholders with valuable information, enabling them to refine the renovation objectives that were initially established. Consequently, to effectively evaluate renovation alternatives (developed in Step 3b), it is crucial to define and prioritise the decision-making criteria related to these objectives. This prioritisation is achieved through criteria weighting, which assesses the relative importance of each criterion.

To facilitate this process, a decision criteria tree has been developed based on the studies reviewed during the generalisation stage. Table 1 provides an overview of the decision tree, arranged hierarchically with sustainability pillars, including environmental, economic, and social categories, at the highest level, followed by specific renovation objectives. The third level specifies the decision criteria necessary to achieve these objectives. It is essential to note that this decision tree is a flexible tool and not exhaustive; it can be expanded based on the additional preferences of the decision-maker (Si et al., 2016).

The decision tree includes two mandatory decision criteria: space heating demand and thermal comfort. These criteria are indispensable for ruling out solutions that cannot prepare the dwelling for LTH (Step

Table 1

Overview of decision tree with three levels of hierarchy- sustainability goals, renovation objectives and associated decision criteria. These are derived from the literature reviewed at the generalisation stage (Amarocho and Hartmann, 2022; Khadra et al., 2020; Nielsen et al., 2016; Si et al., 2016; Wahi et al., 2023a; Wang et al., 2009).

Sustainability Pillars	Objectives	Criteria
Environmental	To minimise the operational and primary energy demand	Space heating demand ^a
		Annual net energy consumption
	To reduce environmental impact due to direct and indirect embodied emissions	Total Primary energy consumption
		Renewable energy generation
Economic	To improve affordability	Energy savings
	To optimise cost-benefits	Global warming potential
Social	To improve indoor comfort	Estimation of embodied energy
		Estimation of carbon emissions
	To improve social acceptability	Total investment costs
		Available local and national subsidies
		Rent increment
		Payback period
		Life cycle costs
		Thermal comfort ^a
		Visual comfort/daylight
		Acoustical Comfort
		Indoor air quality
		Aesthetics
		Renovation duration
		Energy Costs

^a Space heating demand and thermal comfort as non-negotiable criteria for evaluating LTH readiness.

4). It is also recommended to establish KPIs and benchmarks for each criterion. For criteria that are qualitative, performance estimation can be achieved using descriptive scales. Furthermore, it is necessary to clarify whether higher or lower performance values are advantageous. For instance, with investment costs (€), a lower value is preferable, whereas for gas savings (m³), a higher value is more favourable. This differentiation is critical during the ranking of alternatives using the MCDM method in step 6.

Once the decision criteria and their quantification methods are established, the relative importance of each criterion can be assessed. This involves quantifying stakeholders' subjective preferences through pairwise comparisons, a well-established technique that reduces cognitive complexity by focusing on two criteria at a time (Pohekar and Ramachandran, 2004; Saaty and Katz, 1990). For multiple stakeholders, separate pairwise comparisons are conducted to obtain individual criteria weights, representing each stakeholder's preferences. These individual weights are then aggregated to create balanced weights for each criterion. The following steps, as suggested by various authors (Amarocho and Hartmann, 2022; Lu et al., 2007; Pohekar and Ramachandran, 2004; Sen and Yang, 1998; Si et al., 2016; Tae-Woo et al., 2018; Wang et al., 2009), can be followed for conducting the pairwise comparisons:

1. Construct the criterion matrix.
2. Assign the relative importance of each criterion using Saaty's recommended 1–9 subjective scale (Saaty and Katz, 1990).
3. Normalise these importance values and derive the corresponding criteria weights.
4. Ensure the robustness of the criteria weights by determining consistency ratio.

3.4. Step 3b: Developing renovation alternatives

In this stage, all potential renovation solutions for a given dwelling context are developed. As described in Section 1, the range of renovation options can be vast, potentially leading to decision paralysis. To mitigate this, it is essential to structure the generation of solutions. As a result, this study employs a sub-framework, as outlined in our previous study (Wahi et al., 2023b), which aids in organising various renovation solutions based on scenarios, strategies and measures.

Renovation scenarios are alternative situations for achieving specific renovation objectives. Depending on the required level of renovation intervention, these can be categorised as basic, moderate, or deep. Basic interventions involve no changes to the building envelope, although they may include changes to the building systems, such as replacing existing radiators. Moderate interventions might involve targeted improvements, for example, post-cavity insulation or updating glazing. On the other hand, deep interventions entail comprehensive modifications, such as installing a new roof. These scenarios further incorporate single or multiple renovation strategies, which are building-level approaches tailored to each scenario. Strategies may target the building envelope, systems, or controls in order to prepare the dwelling for LTH. Lastly, each renovation strategy informs specific renovation measures, which are the tangible products required to implement the strategy. As these measures involve specific products, their attributes, such as cost, thermal properties, and environmental impacts, can be detailed, aiding in evaluating each renovation measure against the selection criteria.

While the sub-framework is designed to organise renovation solutions, generating these solutions remains challenging. To address this, the study utilises the relative importance of building-level features in determining the readiness of the dwelling for a specific supply temperature condition, as derived from our recent study (Wahi et al., 2024a). These feature importances serve as a tool to identify where improvements are most needed and allow for strategic combinations based on the required intervention level. Fig. 3 illustrates the sub-framework to organise the solutions as well as the relative importance of the

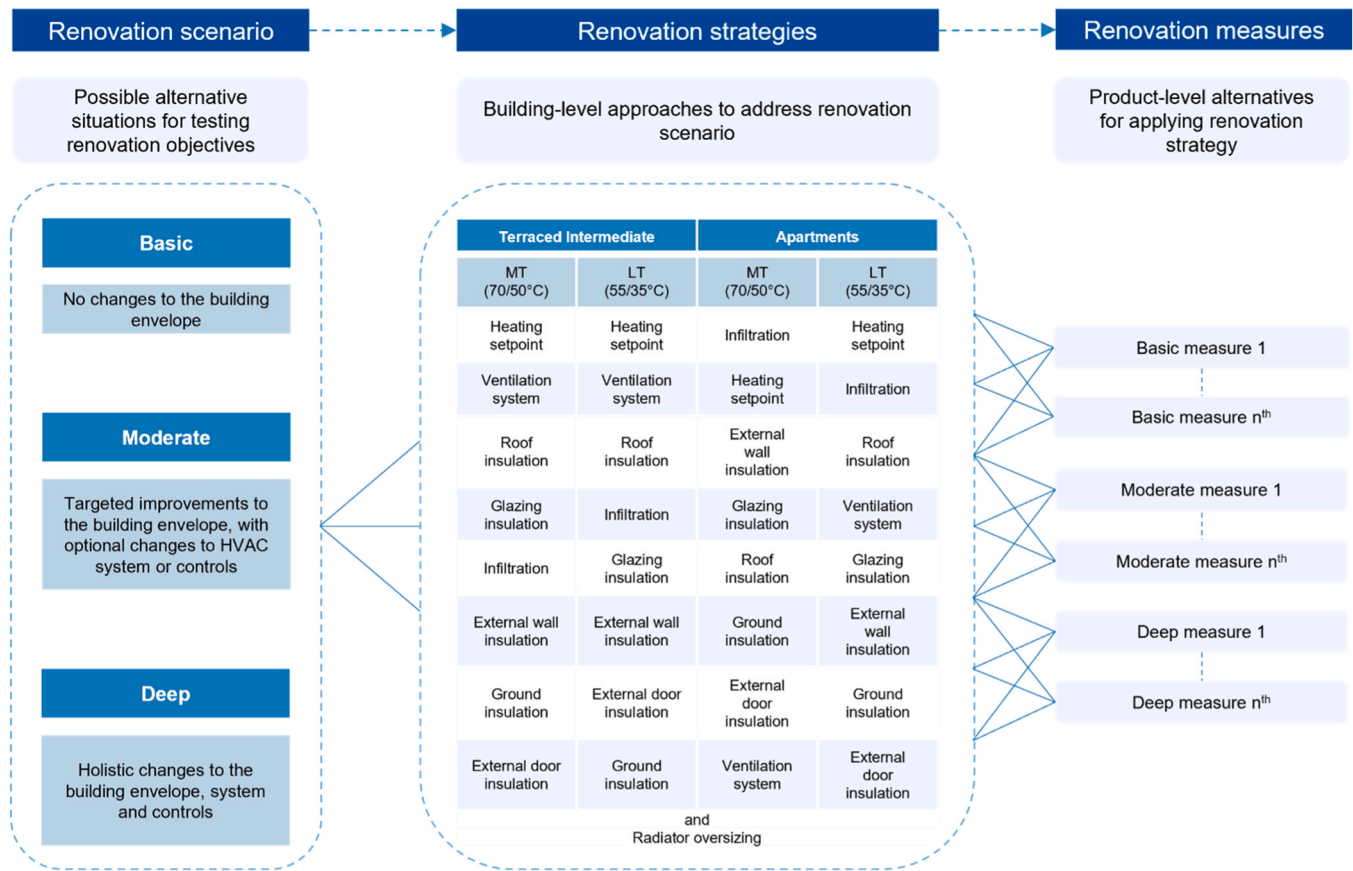


Fig. 3. Sub-Framework for Generating and Organising the Renovation Solution Space. The feature importance list is used to examine the dwelling, identify areas of improvement, and develop targeted strategies according to the required level of intervention. These strategies are then translated into specific product-level measures (Wahi et al., 2024b, 2023b). The feature importance was determined in our previous study (Wahi et al., 2024a).

building-level features. This list is currently specific to terraced-intermediate and apartment dwellings for evaluating the lower temperature supply level of medium temperature (MT:70/50°C) and low temperature (LT: 55/35°C).

3.5. Step 4: Filtering LTH-ready solutions

Numerous renovation options could be developed in Step 3b, although evaluating all of these against every decision criterion would be time-consuming. Consequently, this step involves filtering out those solutions that do not enable the dwelling to be heated with the lower supply transition goal established in Step 1. The renovation solutions are dynamically simulated using the parametric simulation workflow to quantify their performance against the two LTH-ready criteria: space heating demand and thermal comfort. The performance of these solutions under lower supply temperatures is compared with the benchmarks set in Step 1.

According to the LTH-ready definition (Section 3.2), solutions that fail to maintain or improve the dwelling’s performance at lower temperatures compared to the benchmark HT supply are not considered to be LTH-ready. These solutions are, therefore, filtered out. If no solutions meet the LTH-ready criteria, then the processes in Step 3b must be revisited to develop new alternatives. This iterative approach ensures that only feasible solutions that can make a dwelling LTH-ready are carried forward for further evaluation.

3.6. Step 5: Performance quantification

The filtered solutions represent the feasible options for making a dwelling LTH-ready. These solutions will undergo a multi-criteria

assessment as outlined in Step 6. Additionally, the filtered solutions must be quantified against the other decision-making criteria established in Step 3a. Performance quantification can be supported by simulation or calculation tools, or by consulting relevant experts to make accurate estimations. If necessary, another round of filtering may be conducted to eliminate solutions that do not meet the benchmarks established for other criteria in Step 3a.

3.7. Step 6: Rank alternatives

The quantified performance of the alternatives, along with the criteria weights, are subjected to the TOPSIS method for multi-criteria assessment and ranking of the solutions. The TOPSIS method was selected for this study due to its comprehensible logic of calculations, ease of obtaining and interpreting results and its transparent ranking process (Siksneelyte-Butkiene et al., 2021). This method, proposed by Hwang and Yoon (Hwang and Yoon, 1981), evaluates alternatives based on their distance from the negative ideal solutions and proximity to the positive ideal solutions. As discussed in Section 2.4, various authors (Amarocho and Hartmann, 2022; Hwang and Yoon, 1981; Kamari et al., 2018; Lu et al., 2007; Moghtadernejad et al., 2018; Sen and Yang, 1998) have employed the method, following these typical steps:

1. Establish a decision matrix with the alternatives and their performance for each decision criterion.
2. Normalise the decision matrix to convert varying criteria into dimensionless values.
3. Construct the weighted normalised decision matrix using the weights for each criterion obtained in Step 3a.

4. Determine the Positive Ideal Solutions (PIS) and Negative Ideal Solutions (NIS).
5. Calculate the Euclidean distance of alternatives from both negative and positive ideal solutions.
6. Calculate the relative closeness index for each alternative to the positive ideal solution.
7. Rank the alternatives based on the magnitude of the relative closeness index.

These rankings inherently reflect the conflicting criteria and preferences that arise from diverse stakeholder interests. Nevertheless, stakeholders must evaluate these rankings to determine if they align with their expectations and are deemed desirable. If the rankings do not meet satisfaction, the framework should be iterated to reassess the criteria, goals, preferences, or renovation measures. Conversely, if the rankings are satisfactory, the process can advance to the execution phase.

4. Application: case study

The proposed framework builds upon previous literature on MCDM and the assessment of renovation needs for LTH. However, its theoretical nature necessitates empirical testing on a specific case to evaluate its usability. This step is essential for gathering crucial observations in order to refine and further develop the framework. Therefore, this section demonstrates the application of the framework using a case example to assess its usability in a real-world context.

For this purpose, an apartment complex constructed between 1979 and 1980 was selected. This case represents the MFH type, which comprises about one-third of the residential stock in the Netherlands (Cornelisse et al., 2021; Rijksdienst voor Ondernemend, 2023). Moreover, dwellings built prior to the 1980s generally have an energy label of C or lower, reflecting their high energy consumption (Stuart-Fox et al., 2019). Consequently, it could present potential challenges when connecting these houses to DH systems utilising LTH (Harrestrup and Svendsen, 2015). Additionally, renovating a multi-family residential building at once facilitates the energy transition for multiple households, thereby accelerating the process. Fig. 4 illustrates the apartment complex located in the Noord-Holland province of the Netherlands.

The case study was accessed through an energy transition consultant specialising in residential energy renovations. The company provided essential data, including technical inspection documents (such as building photos, floor plans, and installation details), social inquiries (such as occupants' complaints and wishes), and financial estimates for the renovation measures. Furthermore, insights for the decision-making process were gathered through the project plan report and consultations with the project manager. Thus, the information provided formed the

basis for applying the framework and comparing the results. The remainder of this section will demonstrate the practical application of the proposed framework.

4.1. Identification and diagnosis

4.1.1. Case study description

4.1.1.1. General description. The apartment complex is a social housing rental property consisting of 99 one-bedroom apartments and nine two-bedroom apartments, each with 63 m² and 76 m² floor area, respectively. The typical floor plans of the apartments can be found in Appendix A.2. The complex varies from two to four stories, with most apartments primarily oriented east-west, as depicted in Fig. 4 (right). In 2023, the apartments underwent significant renovations, including enhancements to the building envelope, installation of photovoltaic (PV) panels, and replacement of the old gas boiler with a collective air-water heat pump for space heating. The apartments now benefit from an LT supply between 55 and 45°C, supplemented by a gas boiler for peak loads. Even though the framework was developed for LTH supplied by DH systems, it can be adapted for other systems supplying LTH, such as heat pumps. This case, therefore, provides a relevant context to demonstrate the proposed framework. The pre-renovation condition of the complex is used as a benchmark to compare against the actual renovation decisions implemented.

4.1.1.2. Building fabric. The exterior façade is a cavity wall featuring a 6 cm cavity filled with 4 cm of mineral wool. In 2007, all windows were upgraded to HR++ glazing. The complex has a flat concrete roof, insulated with 4 cm of PUR-like material and finished with a mix of cement and EPS granules for sloping. The ground floor remains uninsulated. Table 2 displays the insulation values of the building fabric prior to renovations.

4.1.1.3. Building installations and user profile. The building features a central mechanical exhaust ventilation system, installed in 2009, and a block heating system serviced by an HR100 gas boiler installed in 1997. For hot water, there are two separate HR107 gas boilers, one of which was replaced in 2019. Each apartment is equipped with radiators and individual heat metering for billing purposes. The complex predominantly houses senior residents, with most apartments occupied by a single individual.

4.1.1.4. Energy performance. In 2020, the energy transition consultants calculated the Energy Index (EI) of the complex prior to renovations. Using simulation, six distinct apartment configurations based on their position were analysed: corner-roof, corner-intermediate, corner-

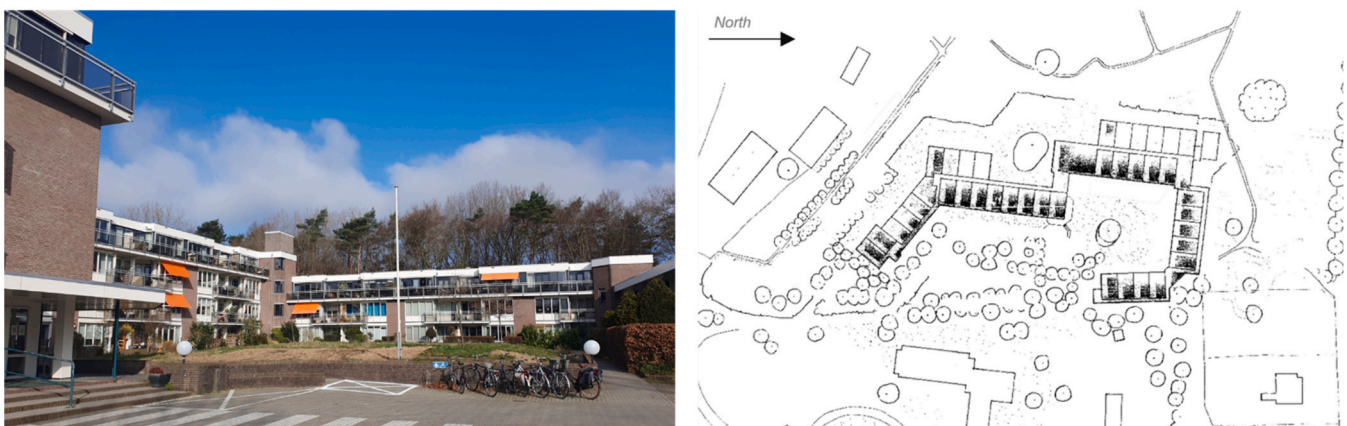


Fig. 4. The apartment complex, built in the 1980s, selected to demonstrate the application of the proposed framework.

Table 2

Input parameters that were used for benchmarking the existing condition of the apartments in HT supply.

Input Parameter	Properties	Units
Orientation	East, North-East, South-East	°
Compactness-Ratio ¹	Intermediate	0.55
	Intermediate-Corner	0.95
	Intermediate-Ground	1.25
	Intermediate-Roof	1.55
	Corner-Ground	1.65
	Corner-Roof	1.95
Ground Insulation ^{2, R}	0.15	m ² ·K/W
External Wall Insulation ^{2, R}	0.69	m ² ·K/W
Roof Insulation ^{2, R}	2.5	m ² ·K/W
Glazing Insulation ^{2, U}	1.8	W/m ² ·K
External Door Insulation ^{2, U}	3.4	W/m ² ·K
Infiltration ^{3,4}	1.95	dm ³ /s.m ²
Ventilation system ²	System C: Natural supply, mechanical exhaust	-
Heating setpoint ²	21	°C
Number of occupants ²	1	Person
Lighting and equipment density	4	W/m ²

¹ Calculated to incorporate the effect of different apartment positions.

² From project report.

³ Calculated based on NTA8800 (Nederlandse technische afspraak NTA, 8800:2023, 2023).

⁴ Adjusted during calibration.

ground, intermediate-roof, intermediate-intermediate, and intermediate-ground. This analysis yielded an average EI of 1.70, equivalent to an energy label of C.

4.1.2. Benchmarking

The parametric simulation workflow was utilised to establish the benchmark performance of the apartments under HT supply. The study was streamlined by focusing on 18 representative apartments rather than all 108 apartments. These were the one-bedroom apartments in the six typical positions across the three most common orientations (East, North-East and South-East). Before the benchmarking phase, the simulated outputs were compared with actual space heating demand data for verification and to estimate the differences between measured and simulated performance (Appendix A.3).

Once verified, the models were subjected to annual simulations using the Test Reference Year (TRY) specified by NEN 5060 (Stichting Koninklijk Nederlands Normalisatie Instituut, 2021). The annual space heating demand under HT supply was calculated for the entire apartment. For the assessment of thermal discomfort, the occupied underheated hours were calculated only for the living rooms. Based on our prior study (Wahi et al., 2023b), the living room can be considered a proxy for evaluating the overall thermal comfort of the dwelling under LTH. To calculate the underheated hours, the living room was assumed to be occupied from 8:00–23:00, totalling 5840 h annually. Table 2 presents the input data used to simulate the benchmark performance of the selected apartments parametrically. Additionally, Table 3 showcases the benchmark performance results under HT supply, highlighting both the space heating demand and thermal discomfort hours.

Table 3

Benchmark performance of the apartments in HT supply compared to that under LT supply. The performances are based on the average of the 18 representative apartments.

Supply Temperature	Annual space heating demand [kWh/m ²]	Occupied underheated hours
HT supply (90/70°C)	215	330
LT supply (55/35°C)	165	1397

4.2. Evaluate LTH readiness

The apartment complex has been renovated with a collective air-to-water heat pump that provides an LT supply of 55–45°C. Consequently, it is essential to assess the readiness of the apartments for LT supply and determine if additional renovations are needed. Therefore, the representative 18 apartments were re-simulated under the adjusted LT supply of 55/35°C. Table 3 compares their performance under this LT supply to the benchmark performance established in Step 1 (Section 4.1). The comparison indicates that as the supply temperature is reduced, the heating system is unable to provide sufficient heat, resulting in an increase in discomfort hours to about four times the benchmark performance. In other words, compared to the benchmark where 5% of total occupied hours were underheated, this increased to 24% under LT supply. Consequently, the apartments are not ready for the LT supply, suggesting that further energy renovations are necessary.

4.3. Establish LTH renovation decision criteria

The decision criteria for evaluating renovation alternatives were derived from the project plan. The primary objective identified was to enhance the energy performance of the apartments, aiming to upgrade from an average energy label of C to B. This goal emphasises achieving maximum energy efficiency with minimal investment costs. Upon closer examination of the project plan, additional benefits of renovation were identified, though not explicitly stated as the primary goal. For instance, the renovations were also expected to increase the property's value, thereby enabling the housing corporation to charge higher rents after tenant turnover. Additionally, the financial impact of the renovations on tenants was considered, with goals to reduce their energy costs and prevent an increase in housing expenses.

Following the identification of these criteria, the corresponding KPIs and benchmarks were sourced from the project plan report. Table 4 presents these decision parameters alongside their respective KPIs, benchmarks and indication of optimal value (maximal or minimal). The renovation objectives O1, O4, O5, O6, and O7 are directly mentioned in the project plan, along with their associated criteria, C2-C7 and C11-C13. Additionally, criteria C1 and C10 are non-negotiable for assessing LTH readiness. Moreover, criteria C8 and C9, sourced from the literature, were included to evaluate the economic performance of the renovation measures.

The decision criteria must ultimately be weighted through pairwise comparison with stakeholders to reflect their preferences. A validation workshop was planned for this purpose; however, it had not yet been conducted at the time of this study. Consequently, a methodological assumption was made to assign equal weights to all criteria, ensuring comparability within the case study. This approach allows for an objective evaluation of the alternatives based solely on their performance across all criteria. Future research will incorporate stakeholder preferences through the planned validation workshop to assess their influence on the ranking of alternatives.

4.4. Generation and filtering of renovation alternatives

Possible renovation alternatives to prepare the apartment complex for LT supply were developed and assessed against LTH-ready criteria. Solutions that failed to meet these criteria were discarded. As outlined in Section 3.4, the level of renovation intervention and the relative importance of building features guide the generation and organisation of these solutions. According to the feature importance list illustrated in Fig. 3, the heating setpoint significantly influences the LT (55/35°C) readiness of the apartment dwelling type. Consequently, adjusting the heating setpoint could be beneficial in lowering energy consumption. This strategy, combined with replacing radiators with higher heating power to ensure thermal comfort, represents the basic level of renovation intervention involving no changes to the building envelope.

Table 4
Decision criteria for the case study extracted from the project report and literature.

Sustainability Pillars	Objectives	Criteria	KPI	Benchmark	Optimal	
Environmental	O1 To upgrade the apartment complex to energy label B ¹	C1 Space heating demand ²	Average kWh/m ² per year	Lower than the existing HT supply	Minimum	
		C2 Energy Label ¹	A+ + to G	Label B or better	Minimum	
	O2 To reduce environmental impact	C3 Energy Index ¹	[-]	≤ 1.4	Minimum	
		C4 Share of renewable energy generation ¹	%	> 0	Maximum	
Economic	O3 To reduce investment costs	C5 Energy savings (gas) ¹	Average m ³ per year	> 0	Maximum	
		C6 Investment costs ¹	€	-	Minimum	
		C7 Investment per label step per unit ¹	€	< €7000	Minimum	
	O4 To optimise cost-benefits ¹	C8 Life cycle costs (30 years) ³	€	-	Maximum	
Social	O5 To improve indoor comfort ¹	C9 Payback period ³	Years	< 20 years	Minimum	
		C10 Thermal Comfort ²	Average occupied cold hours (underheated hours)	Lower than the existing HT supply	Minimum	
	O6 To minimise inconvenience for tenants ¹	C11 Renovation nuisance ¹	Subjective rating		-	Minimum
			1 (minimum) to 5 (maximum)		-	Minimum
	O7 To optimise living costs for tenants ¹	C12 Energy cost savings ¹	Average €/month		-	Maximum
C13 Rent increment ¹			€/month		< € 26.50	Minimum

¹ From the project report.

² Space heating demand and thermal comfort as non-negotiable criteria for evaluating LTH readiness.

³ From literature.

However, the apartments primarily house elderly residents who require higher levels of comfort; therefore, lowering the setpoint temperature might compromise their thermal comfort. Additionally, upgrading radiators does not enhance the energy performance of the apartments, contradicting the primary goal of the project. Hence, a basic intervention level is insufficient, prompting the need for either moderate or deep levels of intervention.

A moderate level of intervention involves targeted improvements to the building envelope, with optional changes to the HVAC system or controls. The analysis based on feature importance indicated that the

airtightness of the apartment needs significant improvement. A further consideration is the existing ventilation system, an exhaust ventilation system installed in 2009, which may have a few more operational years. However, upgrading the system could be beneficial. The insulation of the building envelope (Table 2) was compared with the standards suggested by the Dutch building decree for partial renovations (Bouwbesluit, 2021). The roof and windows are nearly compliant with the minimum suggested insulation for partial renovations (roof R_c: 2.1 m²K/W, windows U: 2.2 W/m²K), although they could benefit from further upgrades. In contrast, walls (R_c: 1.4 m²K/W) and ground

Table 5
Renovation alternatives generated for the case study: Alternatives A1-A4 are sourced from the project report, while A5-A12 represent additional options explicitly prepared for this study. "R" denotes alternatives with upgraded radiators.

Scenario	Building Envelope						System				
	Roof	Wall	Floor	Infiltration	Glazing	Door	Ventilation system	Heat generation	Heat distribution	Other	
	m ² K/W	m ² K/W	m ² K/W	dm ³ /s.m ²	W/ m ² K	W/ m ² K					
Existing	2.5	0.69	0.15	1.95	1.8	3.4	Mechanical	HR107	Existing radiators	FL-lighting LED	
Moderate	A1	-	1.69	-	1.5	-	-	-	New HR107	-	lighting LED
	A2	5.84	1.69	-	1.2	-	-	-	New HR107	-	lighting PV panel
	A3	5.84	1.69	-	1.2	-	-	-	Heat pump PV	-	LED lighting
	A4	5.84	1.69	-	1.2	-	-	-	Heat pump PVT	-	lighting
Deep	A5, A5R	-	6.3	-	1.2	-	-	-	Heat pump PVT	Existing radiators	PV panel LED
	A6, A6R	-	6.3	-	1.2	-	-	Balanced ventilation with heat recovery (MVHR)	Replaced with a radiator with a higher heating power	lighting	lighting
	A7, A7R	-	6.3	-	1	1	-	-	-	-	-
	A8, A8R	-	6.3	-	1	1	-	Balanced ventilation with heat recovery (MVHR)	-	-	-
	A9	5.84	1.69	-	0.7	1	-	-	Heat pump PVT	Replaced with a radiator with a higher heating power	PV panel LED
	A10	5.84	1.69	-	0.7	1	-	Balanced ventilation with heat recovery (MVHR)	-	-	lighting
	A11	5.84	1.69	2.6	0.4	1	-	-	-	-	-
	A12	5.84	1.69	2.6	0.4	1	-	Balanced ventilation with heat recovery (MVHR)	-	-	-
Deep	A13	5.84	1.69	2.6	0.4	1	1.4	-	-	-	-
	A14	5.84	1.69	2.6	0.4	1	1.4	Balanced ventilation with heat recovery (MVHR)	-	-	-

insulation ($R_c:2.6 \text{ m}^2\text{K/W}$) require significant improvements. As per the project plan, improving ground insulation would cause inconvenience to the occupants and is therefore considered under deep renovation alongside door insulation.

The project plan proposes four renovation alternatives that align with the rationale behind choosing moderate intervention solutions, as depicted in Table 5. These solutions focused on cavity wall insulation with roof improvements. Solutions A1 and A2 involve replacing the original gas boiler with a new HR-107 boiler providing a HT supply, while A3 and A4 proposed replacing it with a collective air-water heat pump with an LT supply. Solutions A2 through A4 did not vary in terms of envelope insulation but included the addition of PV panels or photovoltaic thermal (PVT) collectors, indicating a focus on improving the energy label rather than preparing for LTH. This was confirmed when these solutions were evaluated for LT (55/35°C) readiness, revealing that A3 and A4 are not LT-ready solutions (Fig. 5). Consequently, additional solutions with moderate and deep intervention levels were developed.

Eight solutions were developed and simulated for the moderate intervention level, considering options both with and without replacing existing radiators with those of higher heating power. In contrast, for the deep intervention level, an additional six alternatives were developed, encompassing comprehensive improvements across fabric, system, and controls. Consequently, 18 solutions (including A1-A4) were evaluated across 18 representative apartments, culminating in 324 simulations. The simulated space heating demand and thermal discomfort hours were averaged for all 14 solutions. Fig. 5 illustrates the performance of these 18 solutions, highlighting those that are not LT-ready. The simulated results for each alternative can be found in the data repository (Wahi et al., 2024c).

It is crucial to note that although alternatives A1 and A2 reduce space heating demand and thermal discomfort hours compared to the benchmark, they utilise HT supply from the new HR-107 gas boiler. Therefore, they are included only for comparison with other alternatives. While A3 and A4 use LT supply and can reduce space heating demand, they still have a high number of underheated hours compared to the benchmark. From the remaining solutions, moderate measures A6R-A8R, with improved radiator power, and all alternatives associated with deep intervention levels are LT-ready solutions. Additionally, A13 and A14

showed similar performance to A11 and A12 and, thus, were excluded from further analysis. Consequently, seven alternatives were selected for performance quantification: A6R, A7R and A8R with upgraded radiators and A9 to A12.

4.5. Performance quantification of filtered alternatives

The seven renovation solutions (A6R, A7R, A8R, A9, A10, A11, A12), along with the initially proposed solutions (A1-A4), were quantified based on multiple criteria identified in Step 3a (Section 4.3), as illustrated in Table 6. The LTH-ready criteria, including space heating demand (C1) and thermal comfort (C10), are sourced from the simulation results. The dwelling's energy performance is expressed as the Energy Index (C3), which determines the Energy label (C2). Additionally, the renewable energy share (C4) for all seven alternatives was assumed to match that of A4, as detailed in the project report. This assumption ensures consistent comparison across all renovation options. Further, the energy savings (C5) reflect the reduction in energy consumption (in gas) expected due to the renovation alternatives.

The financial aspects of the renovations are captured using several criteria. The energy investment cost (C6) represents the initial costs of the renovation alternatives. They were sourced from the cost database (Kostenkatalogen) provided by the Netherlands Enterprise Agency (RVO) (RVO, n.d.; RVO, n.d). This database provides investment costs for energy efficiency measures, including components, labour and installation costs. Criterion C7 evaluates the cost-effectiveness of each renovation in terms of the investment required per energy label step improvement per house. Global costs were calculated for 30 years using the net present value method to assess the long-term financial impact, classified under life cycle costs (C8). Furthermore, a simple payback period (C9) was calculated to estimate the time required to recover the investment through energy savings.

Moreover, the renovation nuisance (C11) indicates the inconvenience during the construction or renovation process, measured on a scale of 1–5, as described in the project report for alternatives A1-A4. The same rating logic was applied to other alternatives. Additionally, the energy cost savings (C12) represents the reduction in utility bills due to renovation measures. Finally, the rent increment (C13) reflects the possible rise in rental costs attributed to improvements in energy

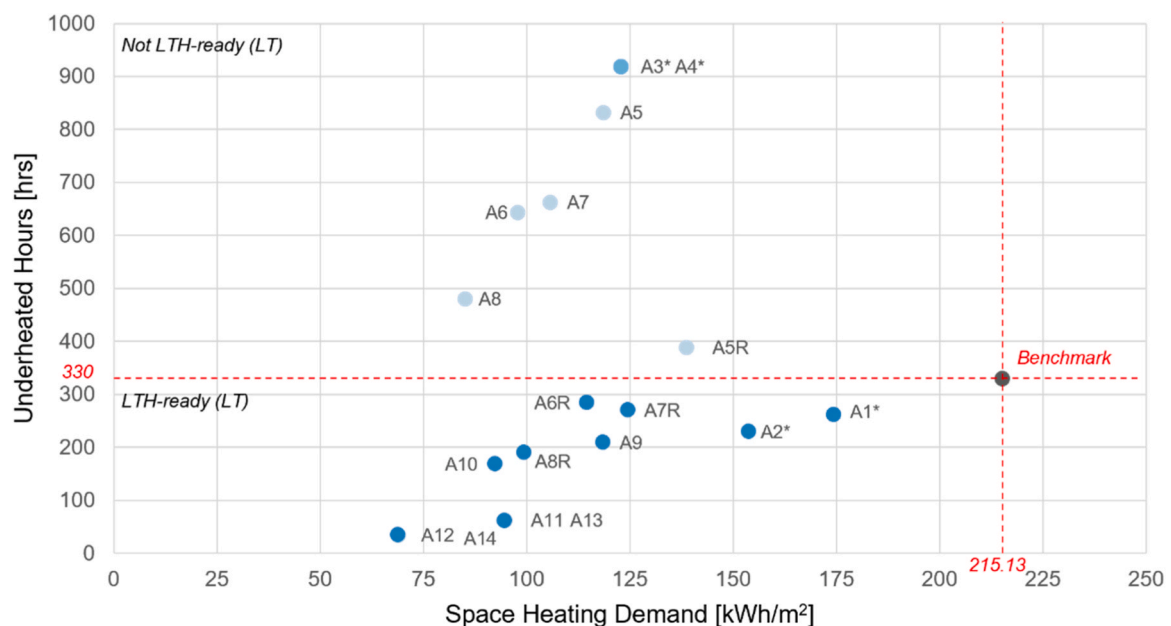


Fig. 5. Filtered Solutions for LTH Readiness. Of 14 solutions, nine could prepare the apartment complex for heating with LT supply (55/35°C). An asterisk (*) indicates alternatives proposed in the project plan, while "R" denotes alternatives with upgraded radiators.

Table 6 Performance Quantification of Renovation Alternatives. A1-A4 are the proposed alternatives for the case study. A6R, A7R and A8R represent moderate measures with improved radiator capacity, while A9, A10, A11, and A12 are measures from the deep intervention level. Ranking alternatives using TOPSIS.

	Environmental			Economic			Social						
	O1	O2	O3	O4	O5	O6	O7	O6	O7				
	To upgrade the apartment energy label B	To reduce environmental impact	To reduce investment costs	To optimise cost-benefits	To improve indoor comfort	To minimise inconvenience for tenants	To optimise living costs for tenants						
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Space heating demand	Energy label	Energy Index	Share of renewable energy generation	Energy savings (gas)	Investment costs	Investment per label step per unit	Life cycle costs	Payback period	Thermal comfort	Renovation nuisance	Energy costs savings	Rent increment
	Average kWh/m ² per year	A+++ to G	[–]	%	Average m ³ per year	€ (thousands) for all 108 apartments	€ (thousands)	€ (thousands)	Years	Average occupied cold hours	1 (minimum) to 5 (maximum)	Average €/month	€/month
A0*	215.13	C	1.71	0	0	0	131.00k	0	0	330	0	0	0
A1	174.34	C	1.46	0	331	1285.78k	12.36k	123.69k	18	263	1	5.13	7
A2	153.76	A	1.18	15	498	1832.01k	8.64k	119.05k	17	230	1	20.83	9
A3	122.8	A	1.01	25	750	1970.16k	7.75k	118.19k	12	919	1	20.83	19
A4	122.8	A++	0.49	38.2	750	2279.30k	4.80k	121.05k	14	919	1	26.53	22
A6R	114.42	A++	0.45	38.2	818	3468.69k	7.40k	137.67k	20	285	4	26.53	22
A7R	124.5	A++	0.49	38.2	736	2933.43k	6.24k	127.96k	18	271	3	26.53	22
A8R	99.21	A++	0.38	38.2	941	3487.88k	7.42k	130.22k	17	191	3	26.53	22
A9	118.45	A++	0.47	38.2	785	2607.01k	5.50k	121.90k	15	210	2	26.53	22
A10	92.32	A++	0.35	38.2	997	3161.46k	6.72k	123.73k	15	169	4	26.53	22
A11	94.62	A++	0.37	38.2	979	2807.77k	5.97k	111.80k	13	63	3	26.53	22
A12	68.8	A++	0.25	38.2	1188	3362.23k	7.15k	113.78k	13	35	4	26.53	22

*Performance of the case study before renovations as the benchmark.

efficiency and occupant comfort. These criteria were extracted from the project plan and remained the same as A4 for other alternatives. Appendix 4 describes the calculation method used for criteria C2, C3, C5, C7, C8, C9.

Once quantified the performance of these LTH-ready solutions were again compared with the benchmarks described in Table 4. It was observed that the investment per label step per unit (C7) for alternatives A6R, A8R, and A12 exceeded the set benchmark of 7k. Considering these results, it was decided to remove alternatives A6R and A8R from the rank evaluations. However, A12 remained a consideration as it only exceeded the investment per label step per unit by 100 euros compared to A6R and A8R and provided a comparatively superior payback period.

All the renovation alternatives are ranked based on multi-criteria assessment using the TOPSIS method. According to the project plan, renovation alternative A4 was the consultant’s and client’s preferred option, followed by A2. This solution offers the most significant improvement in energy labels at relatively lower investment costs. Additionally, replacing the existing gas boiler with a heat pump and installing PVT collectors aligns with the sustainability wishes of the tenants. Therefore, renovation measure A4 was considered to be the optimal solution in order to achieve the primary renovation objective established for the case study.

Considering other decision criteria, it is also essential to evaluate how these proposed solutions (A1-A4) rank. As described in Section 4.3, equal weights were assigned to the decision criteria, making the evaluation based on the alternatives’ performance rather than stakeholder preferences. Fig. 6 illustrates the ranking of the four proposed scenarios. The TOPSIS method also identified A4 as the top solution, with A2 as the second. This indicates the technical validity of the framework, indicating its usability in representing the real-world context and assisting in the decision-making process.

Nevertheless, as detailed in Section 4.4, none of the originally proposed alternatives (A1-A4) can prepare the apartment complex for heating with LT supply. Fig. 6 illustrates the ranking of additional alternatives developed that could make the complex LT ready. When extending the comparison to include A7R, A9, A10, A11, and A12, it evident that A9 stands out as the optimal solution according to the evaluation of the decision criteria, followed by A11 as the next most suitable alternative. The previous best-performing solution, A4, is now ranked seventh.

5. Discussion

This study introduces a comprehensive decision-support framework for selecting energy renovation solutions to prepare existing Dutch dwellings for LTH. Utilising the MCDM approach, the framework offers a structured method to evaluate various renovation options against multiple criteria. Thus, supporting the decision-making process in a holistic manner. This section discusses the framework’s application to the case study, highlighting its utility and revealing key findings, implications, and areas for improvement.

5.1. Insights from case study application

The framework was applied to a MFH dwelling type, providing a real-world context to demonstrate its practical applicability and effectiveness in supporting the decision-making process for selecting renovation solutions. Using the TOPSIS method, the initially proposed solutions (A1-A4) were evaluated against various criteria identified from the project report. Through this framework, solution A4 was identified as the most optimal, aligning with the original conclusion arrived at by the decision-makers. Discussions with project managers highlighted the complexity of decision-making, which often relies on implicit knowledge and policy-driven approaches. The framework’s suggestion of the same solution as the original decision reflects its capability to represent real-world relationships and support decision-

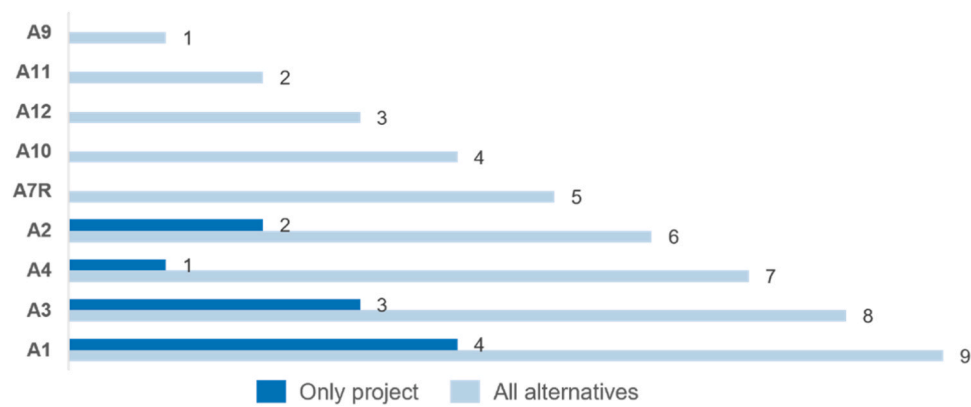


Fig. 6. TOPSIS Ranking of Renovation Alternatives. This graph displays the rankings for the four initially proposed alternatives and their rankings alongside five additional proposed solutions.

making. However, a broader application to additional case studies is necessary to generalise these findings.

As indicated in Table 6, both solutions A4 and A9, reduce space heating demand and enhance energy performance, although A9 reduces thermal discomfort hours below the original benchmark, indicating improved thermal comfort. Even though the initial investment costs are 15% higher than A4, the life cycle costs over 30 years are comparable, with a difference of under 1%. Thus, compared to A4, the additional measures of A9 outweigh the initial investment and provide long-term economic benefits. Nevertheless, A9 would take one more year than A4 for payback. It is also important to note that the second-best solution, A11, performed energetically better than A9. However, it requires higher initial investments and causes significant inconvenience due to ground floor insulation, which is considered inconvenient for tenants, according to the project report.

These rankings are based solely on the performance of the alternatives against individual criteria. However, in practice, the choice of a renovation alternative would depend on stakeholders and their preferences. In the selected case study, criteria weighting, and stakeholder preferences were not explicitly elicited; therefore, all criteria were considered equally important in this study. Nevertheless, as part of a further validation of the framework, stakeholder preferences will be incorporated using pairwise comparison.

5.2. Implication for solving decision-making problems

The framework was developed to address the challenges of selecting renovations to prepare dwellings for LTH. As described in Section 1, one of the significant challenges in this process is the absence of standardised criteria for evaluating LTH readiness. To address this gap, the framework integrates the LTH readiness definition based on non-negotiable criteria, space heating demand and thermal comfort, derived from our previous study (Wahi et al., 2023b). In the case study, these criteria were crucial for evaluating the need for renovations for LTH system. Additionally, these criteria help filter possible renovation solutions to reduce the number of feasible options, streamlining subsequent analyses and reducing analysis paralysis.

Furthermore, decision-makers often struggle to evaluate numerous feasible solutions comprehensively. By employing the TOPSIS method, the framework facilitates a systematic comparison and ranking of alternatives based on predefined decision criteria. This method effectively identified the optimal solutions, such as A9 and A11, from the set of potential options, demonstrating its utility in simplifying complex decision-making scenarios. Nevertheless, there are limitations in using TOPSIS.

The method exhibits sensitivity to the PIS and NIS, which can impact the ranking of the results. For instance, when evaluating only the

provided project alternatives (A1-A4), A4 is ranked higher than A2. In contrast, when evaluating all alternatives (A1-A4, A7R, A9-A12), A4 is ranked lower than A2. The introduction of additional alternatives altered the point of reference (PIS and NIS), thereby changing the ranking of the alternatives. Therefore, to enhance the reliability and robustness of the ranking results, this study suggests cross-validation with another MCDM method, such as ÉLECTRE and/or PROMETHEE.

Moreover, balancing the interests of various stakeholders is a critical challenge in MFH renovations. Even though the criteria weighting was not performed in this study, the framework is designed to accommodate such participation in future applications. In the case study application, this was partially addressed by identifying renovation objectives, relevant decision criteria, KPIs, and quantification methods, which were then structured into a decision tree. This decision tree could be used during the criteria weighting process using pairwise comparisons. Thus, ensuring that renovation solutions meet the actual needs and expectations of the stakeholders involved.

Lastly, the framework includes a sub-framework to generate and organise renovation solution spaces. This involves defining scenarios based on intervention levels, building-level strategies, and product-level measures. The sub-framework lists influential building-level characteristics that impact LTH readiness. This relative importance of the building-level characteristics was used to pinpoint areas for improvement and assist in generating renovation solutions. The feature importance list, derived from our previous study (Wahi et al., 2024a), was developed by analysing representative samples of terraced intermediate and apartment dwelling types. It reflects possible variations in geometry, fabric, systems, and control-level parameters. This approach addresses and incorporates the effect of heterogeneity into the proposed framework.

6. Conclusions

This study introduces a comprehensive framework developed to support the decision-making process in selecting appropriate solutions for preparing existing Dutch dwellings for LTH. The framework utilises six essential decision-making steps, identified and generalised from existing literature on MCDM methods in renovation projects. These steps serve as the foundation for developing and tailoring the framework specifically for preparing dwellings for LTH systems. The framework provides a clear and methodical approach by:

- 1) Collecting relevant data and benchmarking the existing condition.
- 2) Evaluating LTH readiness and determining the need for renovations.
- 3) Establishing decision-making preferences using decision trees and pairwise comparison tools, and generating possible solutions based on the dwelling's context.

- 4) Filtering feasible solutions that can specifically make the dwelling LTH ready.
- 5) Quantifying these solutions against the decision criteria and further filter out non-feasible solutions.
- 6) Ranking and selecting the most desirable solutions through a multi-criteria assessment using the TOPSIS method.

In this study, the practical applicability of the framework was validated through a case study involving a multi-family housing complex built in the 1980s. The complex had previously undergone renovations and currently utilises an LT supply (55–45°C) from a collective air-water heat pump. The framework was applied to the pre-renovation condition and identified the same optimal solution (A4) as originally decided by the stakeholders. Thus, indicating the ability of the framework to incorporate real-world context and assist in decision-making.

The initially proposed solution (A4) focused on enhancing roof and cavity wall insulation, improving airtightness, replacing the gas boiler with a heat pump, and installing PVT panels. While this solution aimed to maximise energy efficiency with minimal investment, it was not deemed LTH-ready. Consequently, alternative solutions were developed. The optimal solution identified through the framework (A9) differed from A4 by upgrading windows, airtightness, and radiators. Compared to the originally proposed solution, this approach enhances thermal comfort although it results in a higher initial investment and an additional year to reach the payback point. Nevertheless, the additional investment proved beneficial in the long-term considering the life cycle costs.

The application of the framework on a case study demonstrated a holistic decision-making approach involving the comparison of various criteria, including trade-offs, thereby supporting decision-makers in evaluating solutions comprehensively. However, in this study, all decision criteria were considered equally important, and thus, the ranking evaluation was based on the performance of the solutions rather than stakeholder preferences. Consequently, further studies will conduct stakeholder validation to incorporate their preferences and compare the ranking of the solutions based on both performance-focused and preference-focused evaluations. Further, each step inherits various uncertainties due to assumptions in calculation methods, and subjective evaluations that can affect the reliability of the results. Therefore, this study suggests conducting a sensitivity analysis as part of the framework in order to enhance the robustness in selecting appropriate solutions. Furthermore, even though the current case study validated the framework's applicability, multiple cases with different context are needed to further finetune the framework.

Appendices

A.1: Checklist for collecting data

Table A. 1

A one-page datasheet was developed as a checklist to gather information about the dwelling(s) for LTH renovation

Parameters	Availability	Description	Remarks
General Data			
Dwelling type		Residential type (Detached, Semi-detached, Terraced, Apartment, etc)	
Construction year		Year of construction	
Number of floors		Number of floors, including basement, crawl space and attic	
Total Dwellings		Total Apartments/houses	
Number of rooms		Number of rooms per dwelling unit	Please indicate the designated floor as well.
Orientation		Building orientation of the longer side	
Renovation year		Last renovation or maintenance.	If the building is renovated, please specify the renovation year and description of the renovation measures.
Architectural and Technical drawings		Floor plans and detail drawings	If the building is renovated, before and after drawings

(continued on next page)

The framework was developed to support the renovations required for preparing dwelling to be heated with LTH supplied from DH systems. However, the case study used for demonstrating the application of the framework utilised LTH from a heat pump. This suggests that the framework is adaptable enough to support transitions to LTH, whether supplied through DH or heat pump systems. By offering a structured approach, the framework alleviates decision-making challenges and supports informed decision-making. This, in turn, accelerates the rate of energy renovations, which is essential for achieving the Netherlands' goal of a decarbonised built environment.

CRedit authorship contribution statement

Henk Visscher: Writing – review & editing, Funding acquisition, Conceptualization. **Martin J. Tenpierik:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Vera Koster:** Writing – review & editing, Visualization, Software, Investigation, Conceptualization. **Prateek Wahi:** Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Thaleia Konstantinou:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT and Grammarly to improve the clarity and cohesion of the text. After using this tool/service, the authors reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table A. 1 (continued)

Parameters	Availability	Description	Remarks
Building Fabric			
Insulation properties		The thermal insulation level of opaque and transparent parts, including the exterior and interior of the dwelling.	If renovated, both original and renovated specifications.
Airtightness		Infiltration rate or airtightness of the dwelling.	Indicate the airtightness or crack seal value at 10 Pa or 50 Pa. If the building is renovated, before and after values
Heating and ventilation			
Ventilation system		Type of ventilation system (natural, mechanical, balanced) and capacity	
Heat supply source (primary)		Source of heating (gas boiler, DH, heat pump)	
Heat distribution system		Heat distribution/release application (e.g. radiators, convectors, underfloor heating)	
Location and type of Heat emission system		Location of the radiator (for example, directly under the window, the wall next to the window, etc.)	
Design Heating capacity		Heating capacities at design conditions as per manufacturers	If determined through on-site monitoring
Heat supply temperature		Existing supply and return temperature for space heating and hot tap water	
Hot water supply		Type of hot water system	
User profile			
Number of residents			
Heating schedule and setpoints		Heating schedule and setpoints preferred by occupants.	
Energy Consumption			
Energy Label / EI index		Indicate the current energy label or index of the dwelling.	If the building is renovated, before and after the energy label / EI index
Annual energy consumption		Indicate if annual energy consumption data is available. If available, the distribution of energy usage due to gas, electricity and others.	
Indoor air temperature		Indicate if the indoor air temperature is monitored.	

A.2: Typical floor plans

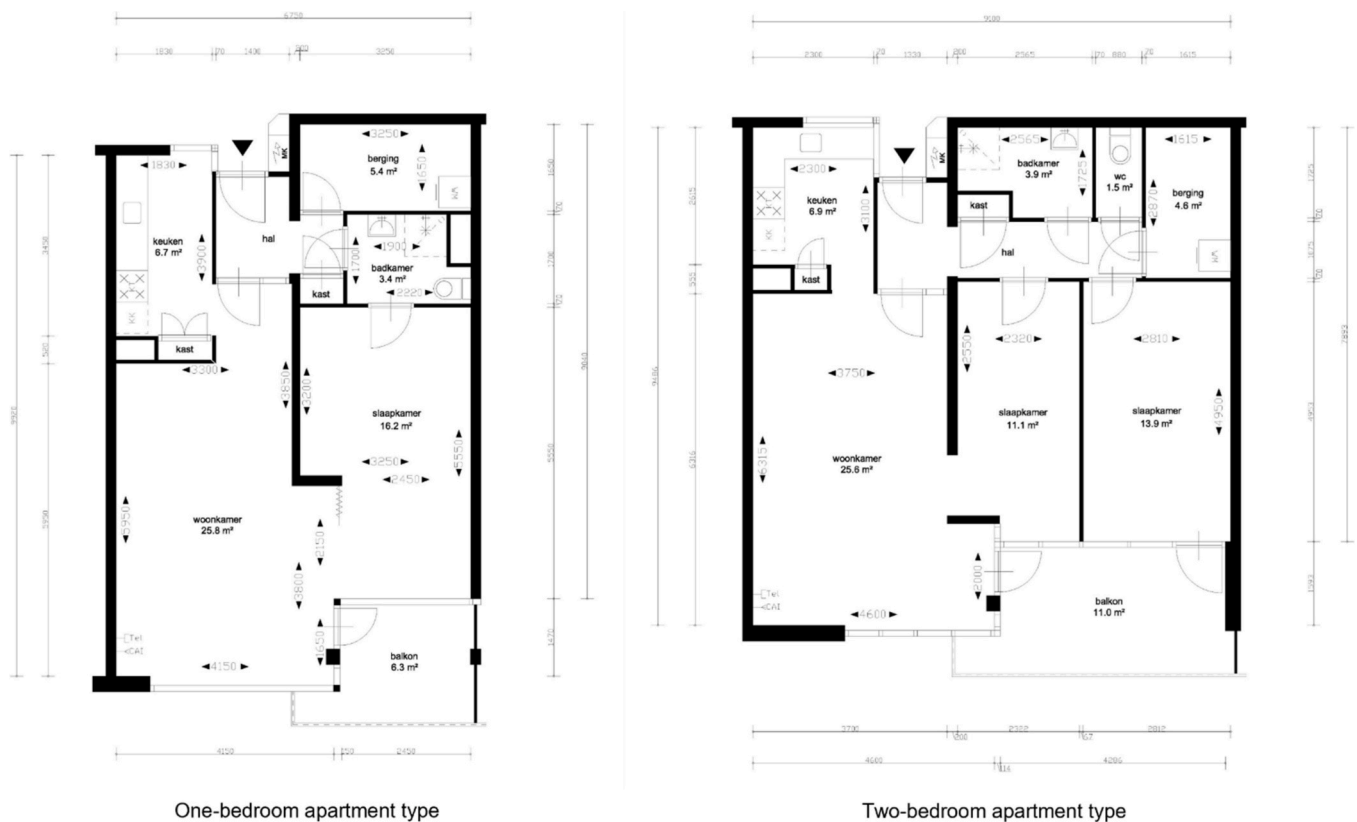


Fig. A. 1. Typical one-bedroom and two-bedroom apartment type

A.3: Model calibration

To ensure the accuracy of the simulation results, the parametric simulation workflow was calibrated against the available energy performance data. Several simplifications and assumptions were made to streamline the simulation process. As outlined in Section 4.1.2, two-bedroom apartments were omitted from the simulations. Furthermore, it was assumed that the layouts of all remaining one-bedroom apartments were comparable. These layouts were simplified to ensure compatibility with the simulation script. The model disregards the thickness of interior walls, resulting in a slightly larger calculated surface area for the apartment (67 m²) compared to the original floorplan dimensions (63 m²).

The average results from the 18 models (comprising six unique positions and three orientations) were compared with the average of 108 apartments. A performance deviation within 10% was considered reasonable due to the simplifications and assumptions made. Table A.2 compares the heating demand extracted from the project report and the simulated data. As shown, the simulated average space heating demand of six apartments is within a 10% deviation from the reported values.

Table A. 2
Case study performance compared to simulated performance for calibration

	Heating Demand (kWh/m ²)
Case Study: Average of 108 units	217.05
Case Study: Average of 6 positions	238
Simulated average of 6 positions	215.13

A.4: Performance quantification

A.4.1: Calculation of Energy Index (C2) and Energy Label (C3)

The Energy Index (EI) indicates the energy efficiency of buildings in the Netherlands, often translated into Energy Labels ranging from A+ + to G (Filippidou et al., 2016; Maghsoudi Nia et al., 2024). The EI is calculated according to Eq. 1 suggested by Majcen et al. (Majcen et al., 2013). Here, *Qtotal* represents the total theoretical primary energy consumption in MJ, *Afloor* is the total usable floor of the dwelling, and *Aloss* is external heat loss surface area in m². The total primary energy consumption includes the energy required for space heating (SHD), domestic hot water (DHW), lighting, and auxiliary (AUX) functions, minus the total energy generated from other sources, such as photovoltaics (PV), as detailed in Eq. 2. Table A.3 provides the sources for the data used to calculate the EI. Once the EI is calculated, it is correlated with the energy label, as shown in Table A.4, to determine the corresponding energy label (RVO, 2024, RVO, n.d; RVO, n.d).

$$EI = \frac{Q_{total}}{(155 * Afloor) + (106 * Aloss) + 9560} \tag{1}$$

$$Q_{total} = Q_{SHD} + Q_{DHW} + Q_{lighting} + Q_{AUX} - Q_{PV} \tag{2}$$

Table A. 3
Data source used for calculating EI

Parameters	Source	Units	Remarks
<i>Q_{SHD}</i>	Dynamic simulation	kWh/m ²	Different for each apartment and each alternative.
<i>Q_{DHW}</i>	Project report	kWh/year	3049.081 kWh/year fixed
<i>Q_{lighting}</i>	Project report	kWh/year	836 kWh/year fixed
<i>Q_{PV}</i>	Project report	kWh/year	1258 kWh/year fixed
<i>A_{floor}</i>	Simulations	m ²	67 m ² fixed
<i>A_{loss}</i>	Calculated	m ²	Intermediate: 38.92 m ² Intermediate - corner: 67.92 m ² Intermediate - ground: 89.32 m ² Intermediate - roof: 110.92 m ² Corner - ground: 118.32 m ² Corner - roof: 139.93 m ²

Table A. 4
Relationship between energy label and energy index (RVO, 2024, RVO, n.d; RVO, n.d).

Label	EI range
A+ +	EI ≤ 0.6
A+	0.6 < EI ≤ 0.8
A	0.8 < EI ≤ 1.2
B	1.2 < EI ≤ 1.4

(continued on next page)

Table A. 4 (continued)

Label	EI range
C	1.4 < EI ≤ 1.8
D	1.8 < EI ≤ 2.1
E	2.1 < EI ≤ 2.4
F	2.4 < EI ≤ 2.7
G	2.7 < EI

A.4.2: Calculation of Energy savings in gas (C5)

The gas energy savings in m^3 can be calculated using Eq. 3. In this equation, the reduction in space heating demand from the benchmark is calculated in kWh/m^2 . The floor area of the dwelling is represented by A_{floor} , the efficiency (η) of the boiler is assumed to be 85%, and CV_{gas} denotes the calorific value of natural gas, $35.2 \text{ MJ}/\text{m}^3$. The change in energy demand (ΔQ_{shd}) is calculated in kWh/m^2 from simulations, and a conversion factor of 3.6 is used to convert kWh to MJ.

$$\text{savings}(\text{gas}) = \frac{\Delta Q_{\text{shd}} * A_{\text{floor}} * 3.6}{\eta * CV_{\text{gas}}} \quad (3)$$

A.4.2: Calculation of Investment per label step per unit (C7)

First, the label step factor (LSF) was calculated by summing the total label step changes for the complex, compared to the benchmark, across all six positions of the units. This factor is then divided by the total investment cost per alternative to determine the investment required per label step change. The LSF and the investment per label step per unit can be calculated using Eqs. 4 and 5, respectively. In Eq. 4, i corresponds to the apartment position number, illustrated in Table A.5, along with the distribution of 108 apartments across the six positions.

$$\text{Label step factor}(\text{LSF}) = \frac{\sum_{i=1}^6 \text{label step change}_i * \text{number of units}_i}{108} \quad (4)$$

$$\text{Investment per label step per unit} = \frac{\text{Investment cost per alternative}}{\text{LSF}} \quad (5)$$

Table A. 5
Distribution of all apartments among the six positions

Position		No. of units
1	Intermediate	34
2	Intermediate-Corner	4
3	Intermediate-ground	27
4	Intermediate-roof	31
5	Corner-ground	5
6	Corner-roof	7
		108 units

A.4.3: Calculation of Life cycle costs (C8)

The life cycle costs (LCC) were calculated using the global costs (GC) methodology described in EN15459:2017 to evaluate the long-term economic effects of selected renovation measures (NEN, 2017). As illustrated in Eq. 6, the calculation is the sum of the present values of investment, operation, replacement, maintenance, and disposal costs. In this study, disposal costs are excluded. Investment costs (IC) are typically considered as the present value at the beginning of the project. However, other recurring costs such as operating costs (OC), maintenance costs (MC), and replacement costs (RC) must be discounted to reflect their future costs in today's value, often termed as Net Present Value (NPV). The following section describes all the components involved in calculating GC to determine LCC.

$$\text{global costs} = IC + OC + RC + MC \quad (6)$$

A.4.3.1 Investment costs (C6)

The initial investment costs (in €) encompass all the components installed in each renovation alternative. In this study, the investment costs are sourced from the online cost databases provided by the Netherlands Enterprise Agency (RVO) (RVO, n.d; RVO, n.d). These databases include common energy-efficient measures and associated costs, covering components, labour, and installation expenses. Table A.6 illustrates the costs extracted from the database used in this study.

Table A. 6
Investment costs for different components extracted from the cost database. (RVO, n.d; RVO, n.d)

Component	Description	Code from database	Insulation Value		Total Investment costs (€)
			RC [m ² K/W]	U [W/m ² K]	
Radiator	Panel Radiator for LT	WB064	-	-	1882.68
Ventilation System	Balanced ventilation with heat recovery	WB156	-	-	5133.82
Improved infiltration	Medium improvement	WB092	-	-	421.04
	High improvement	WB226	-	-	1395
External Wall	Cavity insulation EPS beads	WB009b	1.6	0.625	869.85
	External EPS solutions	WB224	6.3	0.158	9923.31
Windows	Triple glazing unit with wooden frames	WB161a	-	1	9641.036
Roof	-	From project	5.84	0.171	5057.62
Ground floor	Underside concrete floor mineral wool	WB002b	2.6	0.38	1858.95
Boiler	High-efficiency collective boiler	WB052	-	-	1151.24
Heat pump	Heat pump	WB107	-	-	16897.93
	Heat pump with solar boiler	From project	-	-	5292.80

A.4.3.2 Operating costs

The operating costs correspond to the annual recurring energy expenses, which must be discounted for future years to calculate NPV, as described in Eq. 7. In this equation, OC_a represents the annual recurring costs, and df is the discount factor used to calculate the NPV of the OC.

$$OC_{NPV} = df * OC_a \quad (7)$$

Annual recurring operating costs (OC_a)

The annual recurring costs can be calculated using Eq. 8. The *Total annual energy demand* includes the sum of SHD, DHW, lighting and other energy used. In contrast, depending on the system used (e.g. gas boiler, heat pump, district heating) a *performance factor* is used to convert this energy to total delivered energy (Hamdy et al., 2013). In this study, the gas boiler is assumed to have an efficiency of 0.85 while a collective heat pump is assigned a COP of 1.82, according to the project report. Depending on the fuel type used to meet the energy demand, variable and fixed costs are applied, with tax benefits adjusted accordingly. Table 7 details the average variable and fixed costs from 2022, excluding VAT, used in this study (Centraal Bureau voor de Statistiek, 2023).

$$OC_a = \left[\left(\frac{\text{Total annual energy demand}}{\text{performance factor}} \right) * cost_{var} \right] + cost_{fixed} - tax\ reduction \quad (8)$$

Table A. 7
Average Variable and fixed costs from 2022 (Centraal Bureau voor de Statistiek, 2023)

Fuel Type	Variable Costs ($cost_{var}$)	Fixed Costs ($cost_{fixed}$)	Tax reduction
Natural Gas	2.02 €/m ³	218.24 €/year	-
Electricity	0.470 €/kWh	280.72 €/year	681.63 €/year

Discount Factor (df)

The discount factor (df) used to calculate the NPV can be determined using Eq. 9 (Fuller and Petersen, 1995; Hamdy et al., 2013). In this equation, r_e represents the real interest rate, which accounts for the inflation rate, and n is the calculation period, set at 30 years for this study.

$$df = \frac{1 - (1 + r_e)^{-n}}{r_e} \quad (9)$$

The real interest rate (r_e) can be calculated using Eq. 10 (Hamdy et al., 2013), where r is the market interest rate taken as 2.8% (Kotireddy, 2018), and e is the inflation rate. According to Fabrycky and Blanchard (Fabrycky and Blanchard, 1991), an economic analysis requires an average annual inflation rate representing a composite of individual yearly rates. Therefore, the average inflation rate was calculated from 2012 to 2021 over ten years. This average annual inflation rate (e) can be determined using Eq. 11, where CPI_{2021} and CPI_{2012} represent the price development of goods and services an average Dutch household pays. These CPI (consumer price index) values were taken from the energy group, including indices related to gas, electricity, and other energy sources (Centraal Bureau voor de Statistiek, n.d). The term t corresponds to 10 years. The calculation yielded an average inflation rate of 2.00%.

$$r_e = \frac{r - e}{1 + e} \quad (10)$$

$$e = \left(\frac{CPI_{2021}}{CPI_{2012}} \right)^{-t} - 1 \quad (11)$$

A.4.3.3 Maintenance costs

The annual recurring maintenance costs (MC) are calculated using Eq. 12 (Fabrycky and Blanchard, 1991), where the MC are a fraction ($Mrate$) of the IC. The $Mrate$ values were determined according to Annex D of EN15459-1:2017 (NEN, 2017) and are discounted to account for future costs.

$$MC = IC * Mrate * df \quad (12)$$

A.4.3.4 Replacement costs

The replacement costs are calculated using Eq. 13, as suggested by Hamdy et al. (Hamdy et al., 2013). The replacement costs are determined for components k that will reach the end of their service life before the 30-year study period. The service life of the components is provided in Annex D of EN15459-1:2017 (NEN, 2017). Here, IC_k is the investment cost of the components that need to be replaced, r_e is the real interest rate calculated from Eq. 10, and c is the life span of the component.

$$RC_k = IC_k * (1 + r_e)^{\frac{-c}{2}} \quad (13)$$

A.4.4: Simple Payback period (C9)

The simple payback period is calculated without discounting future costs, using Eq. 14. In this equation, the investment costs (€) represent the initial investment costs for the alternatives, and the annual savings (€ per year) are the savings achieved each year due to the renovation measures. The annual savings can be calculated by determining the energy saved, as per Eq. 3, and then multiplying this amount by the variable energy price, as specified in Table A.7.

$$SPB = \frac{\text{Investment costs}}{\text{Annual savings}} \quad (14)$$

Data Availability

Decision-support framework for Lower-Temperature Heating Renovation Solutions: Simulation results of the case study application (4TU. ResearchData)

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