Preparing Dutch Homes for Energy Transition

A Decision Support Framework for Renovating Existing Dutch Dwellings for Lower Temperature District Heating

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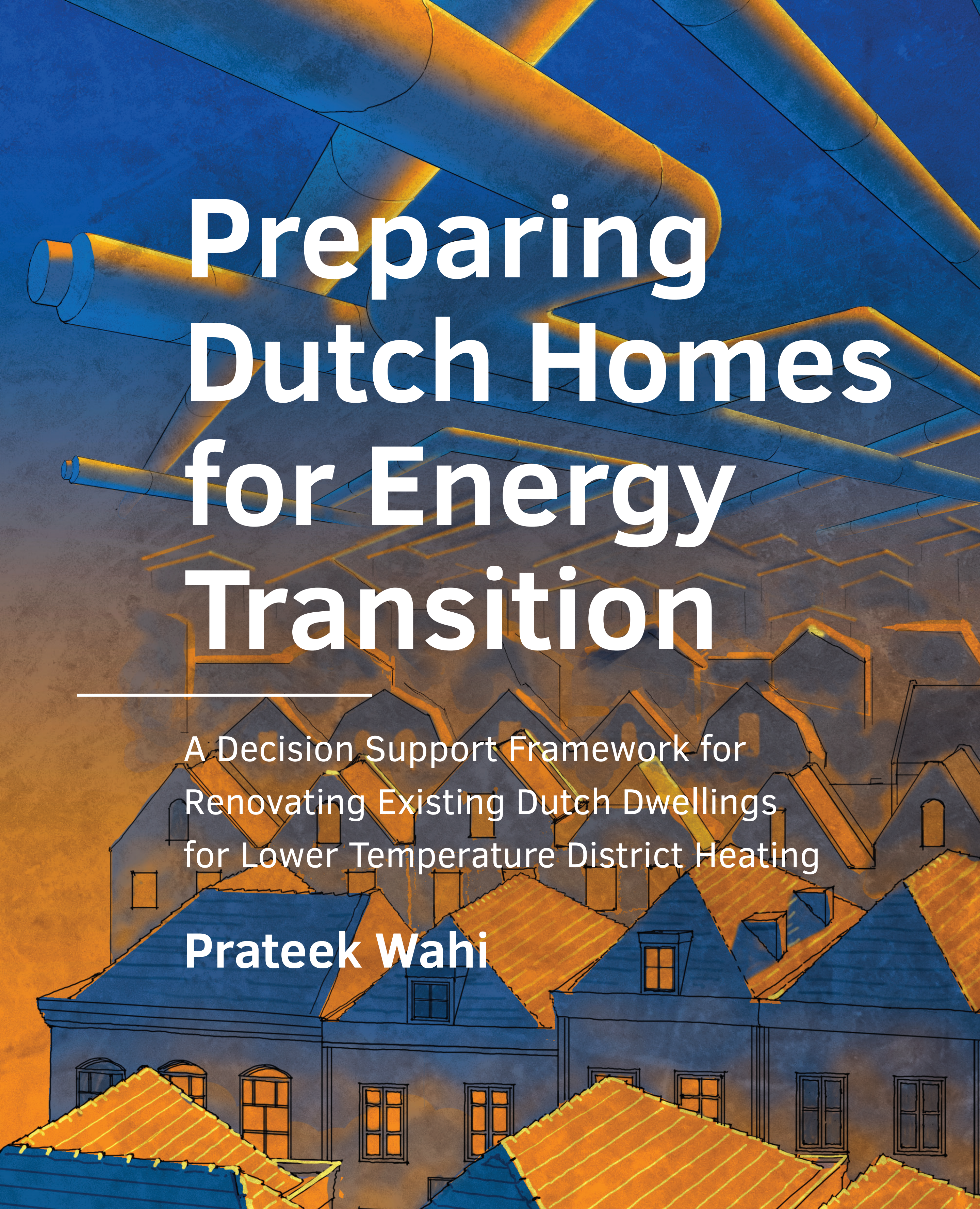
DOI
10.71690/abe.2025.10

Publication date
2025

Document Version
Final published version

Citation (APA)
Wahi, P. (2025). *Preparing Dutch Homes for Energy Transition: A Decision Support Framework for Renovating Existing Dutch Dwellings for Lower Temperature District Heating*. [Dissertation (TU Delft), Delft University of Technology]. A+BE | Architecture and the Built Environment. https://doi.org/10.71690/abe.2025.10



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TOC

A+BE | Architecture and the Built Environment | TU Delft BK

25#10

Design | Sirene Ontwerpers, Véro Crickx

Cover photo | Prateek Wahi, Pavan Kumar Sathyamurthy, Vipul Anand Sahu

Keywords | Heating Decarbonisation, Mixed-Method Research, LTH Readiness, Multi-Criteria Decision-Making

ISBN 978-94-6384-767-4
ISSN 2212-3202

This dissertation is open access at https://doi.org/10.71690/abe.2025.10

Preparing Dutch Homes for Energy Transition

A Decision Support Framework for Renovating Existing Dutch Dwellings for Lower Temperature District Heating

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus, prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Monday 28th April 2025 at 17:30 o'clock

by

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This dissertation has been approved by the promotors.

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This research was supported by the MMIP 3&4 scheme of the Dutch Ministry of Economic Affairs & Climate and the Ministry of the Interior & Kingdom Relations

Acknowledgements

It was the 8th of June 2020, the night before my second and final interview with Thaleia, Martin, and Henk. I was anxious, wide awake until 3 a.m., my mind a whirlwind of thoughts—my graduation thesis, honours programme research, and the peak of COVID leaving me deeply worried for my family in India and friends in the Netherlands. Unable to focus, I took a long walk with my then-girlfriend (now my wonderful wife), Anagha. In near silence, we wandered around Aan het Verlaat in Delft, and my thoughts were fixated on the big interview ahead.

"What are you thinking about?" she finally asked.

I told her about my father's advice—to mentally visualise what I wanted to achieve.

"Then what are you visualising now?" she pressed.

I replied, *"I see myself defending my dissertation, holding that red degree holder in front of my family and friends, and celebrating together."*

As I write this acknowledgement today, I see that same vision again. Only now, it's in high definition, refined by years of experience, effort, and resilience. The journey to this moment has been long, filled with challenges and triumphs, and reaching this milestone fills me with immense joy. Words can barely capture the emotions of this journey. Still, this acknowledgement is my humble attempt to express my deepest gratitude to those who have been a part of it.

First and foremost, I would like to extend my sincere gratitude to the Dutch Ministry of Economic Affairs and Climate and the Ministry of Interior and Kingdom Relations for supporting this research through the MMIP 3&4 scheme. Receiving a fully funded PhD opportunity removed much of the uncertainty often accompanying a doctoral trajectory, allowing me to focus entirely on my work rather than financial constraints. I remain deeply grateful for this chance to immerse myself wholeheartedly in research.

I also extend my most profound appreciation to my supervisory committee. Their unwavering support and expert guidance have been instrumental in shaping both my research and my academic growth.

TOC

Associate Professor Dr. Thaleia Konstantinou— Dear Thaleia, thank you for being an incredible mentor. Over the years, you have not only guided me in research management but also instilled in me the importance of structure, adaptability, and, above all, resilience. You showed me how to pick myself up when challenges seemed insurmountable, and confidence wavered. You helped me realise that failure, too, is a result—a lesson in disguise. Despite your demanding schedule, you always made time for me, quickly grasped my concerns, and provided solutions that were not only effective but often transformative. Working with you has never felt like mere supervision; it has been a collaboration—driven by shared curiosity, problem-solving enthusiasm, and a mutual commitment to excellence. I truly hope we have the opportunity to work together again in the future.

Professor Dr. Martin Tenpierik—Dear Martin, if still water in a pond could be personified, it would be you. The calmness and clarity you bring have always given me peace and focus. I deeply admire your sharp intellect and the depth of your feedback. Your ability to simplify complex ideas and break them down into clear, manageable steps has been invaluable, not just in research but also in shaping how I approach challenges. I will deeply miss our tri-weekly meetings at the Espresso Bar, where our conversations seamlessly drifted from academia to broader philosophies. Those moments were more than just discussions; they played a crucial role in shaping my research and problem-solving approach. I am genuinely grateful to have had you as a supervisor.

Professor Dr. Henk Visscher— Dear Henk, your ability to take a bird's-eye view of a problem and bring the focus back to its core has been immensely valuable throughout this journey. I vividly remember moments of doubt, questioning the "impact" of my research—worries that many PhD candidates face. Your advice—"In these times, novelty is often not in the problem itself, but in its context, and context changes everything"—was a revelation that completely transformed my perspective. It gave me clarity and reaffirmed the significance of my work. Your precise feedback, sharp observations, and welcoming nature, especially during the annual Christmas gatherings, have meant much to me. I hope to continue attending if you still have me!

Thaleia, Martin, and Henk—thank you for the incredible support, guidance, and encouragement you have given me from the beginning, when everything was locked down due to COVID, until now. I will truly cherish the memories we have shared, and I sincerely hope we will have the opportunity to collaborate again.

I am also profoundly grateful to my independent committee members, including **Prof. Shady Attia, Prof. Vincent Gruis, Prof. Per Heiselberg, and Prof. Laure Itard**. Thank you for taking the time to review my work. Your insightful feedback and thorough

TOC

evaluations have meant a great deal to me. The knowledge and perspectives you shared have refined my research, and I am honoured that such esteemed experts in the field have reviewed my work.

Starting my PhD in the midst of a global pandemic was an experience unlike any other. The first two years, marked by limited in-person interactions, made it challenging to engage in the spontaneous knowledge exchange that is so valuable in academia. In this regard, I owe particular thanks to **Prof. Shady Attia** and his YouTube channel, which became an unexpected but invaluable resource. His in-depth videos on research structuring and methodology clarified many nuances and helped me organise my research plan. I am truly grateful that he is part of my defence committee.

Academic writing is the foundation of any PhD journey, and I would like to express my gratitude to **Dr. Marek Kiczkowiak** and **Dr. Lynn Nicks-McCaleb** from Academic English Now and **Dr. Karin van Nispen** from TU Delft Writing Centre for their exceptional guidance. They not only helped me refine my writing but also showed me how language itself can be an instrument of research. Their patient mentorship allowed me to articulate my thoughts more effectively, shaping the clarity and precision of my work.

A heartfelt thank you to my MSc. graduation thesis mentor, **Ir. Eric van den Ham** and **Dr. ing. Marcel Bilow**, who recognised my research potential early on and encouraged me to pursue a PhD. Without your support and belief in me, I may not have had the confidence to embark on this academic journey. Your encouragement played a crucial role in setting me on this path, and for that, I am forever grateful.

I would also like to extend my appreciation to my colleagues at Building Physics and Services Group—**Ir. Christien Janssen** (who is dearly missed), **Dr. Eleonora Brembilla, Ir. Eric van den Ham, Juan Carlos Prazmowski, Prof. Dr. Martin Tenpierik, Nima Forouzandeh, Dr. Regina Bökel, Dr. Willem van der Spoel,** and **Dr. Zhikai Peng**. Thank you for the thought-provoking discussions, the enlightening lunch meetings, and for helping shape a vision of how education and research can contribute to tackling future challenges.

Additionally, I want to acknowledge the Architectural Façade and Product Research Group—**Adam Pajonk, Ahmed Felimban, Dr. Alejandro Prieto, Dr. Alessandra Luna Navarro, Alvaro Balderrama, Hamza Hamida, Dr. Magdalena Zabek, Dr. ing. Marcel Bilow, Max Salzberger, Dr. Olga Ioannou, Pablo Martinez Alcaraz, Pedro Barra Luegmayer, Dr. Tatiana Armijos Moya, Dr.-ing. Thaleia Konstantinou, and Prof. dr.-ing. Ulrich Knaack** and everyone else who made the PhD colloquium days so engaging and motivating. These sessions challenged me to refine my arguments and prepare rigorously for my defence. Beyond the academic rigour, I will always cherish the dinners, trips, and strong camaraderie that made this journey even more special.

Behind every successful research project are the people who ensure its smooth operation through logistical and administrative support. I am incredibly grateful to section head **Dr. Craig Martin** and department manager **Dr. Onno de Wit** for their leadership and for making our PhD trajectories seamless. A special thanks to our department head, **Prof. dr. ir. Michiel Kreutze**r, whose open-door policy and in-depth discussions helped me understand the structural (re)organisations within the department. I particularly enjoyed our conversations about enhancing PhD education and using doctoral feedback to improve the experience for future candidates.

Equally deserving of appreciation is our secretariat team, whose day-to-day support made all the difference. **Bo Song**, thank you for your warmth, for introducing international students to cultural traditions (and delicious dishes!), and for making us feel at home. **Annelies Friesser**, your tireless coordination and ability to handle the logistical hurdles of my defence saved me countless hours and made the final weeks far less stressful—I am truly grateful for your help.

A special mention goes to **Prethvi Raj**, my mentor in building physics and simulation since my master's days. Your guidance has been invaluable—you patiently answered my (often highly detailed) questions, dived into EnergyPlus documentation with me at odd hours, and troubleshot every simulation hiccup. A significant portion of my research stands on the foundation of your support—thank you for always being there. Additionally, my heartfelt thanks to **Maéva Dang**, with whom I've spent countless hours brainstorming and discussing our shared interest in decarbonising the built environment.

The PhD journey can sometimes feel solitary, but it never indeed did, thanks to the incredible community in BK.01.West.250—our PhD room. You ensured I never felt alone in this process. **Zoheir Haghighi**, thank you for introducing me to the PhD Council and for your invaluable advice. **Nick ten Caat**, thank you for your lessons on productivity and for organising the "boys' nights" that helped clear our minds. **Prateek Bhustali**, for being my unofficial machine-learning oracle and for demonstrating the importance of humility. **Nima Firozandeh**, my library buddy and walking partner, whose philosophical talks enriched my perspective. **Pedro Barra Luegmayer**, for showing me what resilience truly looks like—juggling parenting, home renovations, and academic responsibilities with unwavering calm. **Hamza Hamida**, for helping me navigate the complexities of ethics in interviewing, for sharing your culture, and for reminding me that consistency is key to mastery.

To my other amazing colleagues—Aga Kuś, Dr. Ahmed Felimban, Alessio Pelagalli, Amin Jalilzadeh, Amneh Hamida, Dr. Adriana Ciardiello, Anna Maria Koniari, Dr. Anna Yerza, Dr. Ameya Kamat, Dr. Berk Ekici, Diletta Ricci, Dr. Emeline Lin, Dr. Fatemeh Hedieh, Fatemeh Mostafavi, Dr. Federica Marulo, Dr. Federica Romagnoli, Dr. Fillipo Molaioni, Han Zhang, Juan Carlos Prazmowski, Komal Potdar, Kyujin Kim, Lourdes Beneito, Dr. Lia Tramontini, Michiel Fremouw, Dr. Nan Bai, Pablo Martinez Alcaraz, Dr. Pooyan Kazemisangedehi, Ruben van der Plas, Tamara Egger, Dr. Tess Blom, Ziead Metwally and everyone else who brightened my PhD journey—thank you for your support, insights, and friendship. I trust that our paths will cross again in the future.

A special acknowledgement goes to my PhD Council teammates— Abhijeet Chandel, C. Koray Bingöl, Lukas Höller, Mar Muñoz Aparici, Mônica Veras Morais, and Stefanie Horian. —for working together to rebuild the council after two challenging COVID years. I am incredibly proud of what we achieved, particularly our PhD Council Day, which brought everyone together in a much-needed moment of connection and celebration. None of this would have been possible without the steadfast support of our Faculty Graduate School—Inge Meulenberg-Ammerlaan, Nouzha Chamkh, and Prof. ir. Paul W. Chan—whose guidance and encouragement were invaluable.

During my research, I had the privilege of working with some of the brightest graduate students. A special thanks to Saskia Ruttens, Naeem Kantawala, and Vera Koster for their fresh perspectives, valuable contributions, and passion for innovation. Your curiosity and dedication were inspiring.

My sincere gratitude also goes to the Integrated Approaches for the Energy Transition in Existing Buildings (IEBB) programme and my colleagues at the Urban Energy Institute (UEI) consortium—Andrea Iris Joseph Thaddeus, Evert van Beek, Dr. Luyi Xu, Dr. Paula van den Bom, Dr. Stella Boess, and many others—for their shared commitment towards a sustainable and decarbonised future. I would like to extend a special mention to my project partners from Project 1.5, including Martijn Matijssen from Vattenfall, as well as Ellemieke Henquet, Charlotte Lelieveld, and Andries Wijhe from TNO, whose insights and collaboration have been invaluable. Special thanks to Alizé Hall and Sarah Marchionda, whose exceptional organisational skills helped smooth the complexities of our project deliverables.

I am deeply grateful to my current manager, Gertjan Verbaan, and my mentor, Jesse Plas, for their continuous support and understanding as I balanced the final stages of my PhD with the full-time role at DGMR. Your flexibility and encouragement have been invaluable. A special thanks to Brenda Dietz and Jesse Plas for reviewing the Dutch version of the summary on such short notice.

I also want to extend my heartfelt thanks to Pavan Kumar Sathyamurthy and Vipul Anand Sahu for their outstanding work on the thesis cover. Inspired by M.C. Escher's 'Metamorphosis,' the design effectively illustrates the energy transition, showing lower-temperature district heating pipes entering typical Dutch homes. Their thoughtful colour palette, representing the temperature shift and evoking the Dutch dawn, was truly remarkable. Thank you both for capturing and realising my vision. Additionally, my sincere appreciation goes to Véro Crickx for her invaluable support in preparing and publishing this dissertation.

Beyond academia, I have been incredibly fortunate to have a remarkable group of friends—Aditya Parulekar, Ajay Kumar Tiwari, Akanksha Singhal, Angel Sharma, Anubhuti Chandana, Arabhi Balasubramanian, Asmeeta Sharma Soni, Barsha Amarendra, Deepti Adlakha, Divya Desai, Divyae Mittal, Harsh Soni, Ivneet Singh Bhatia, Kiana Mousavi, Kritika Tiwari, Nikhil Saldana, Noor ten Harmsen van der Beek, Pavan Kumar Sathyamurthy, Pragya Tiwari, Pranay Khanchandani, Pratul Nema, Rahul Grover, Rajat Tiwari, Ranjan Gaur, Reddhi Bhatt, Rhea Ishani, Sagar Oke, Samanwita Ghosh, Sanjana Shettigar, Shasan Chokshi, Shivangee Rathi, Shubhonil Chatterjee, Solco Reijnders, Sonal Takkar, Soumik Guha, Sreejit Bakshi, Tanvi Gupta, Tapasya Mukkamala, Tarang Gupta, Tushar Desai, Ujwal Dawar, Vedya Soni, Yeshika Bakathavatsalam, Yeshwanth N., and so many others—who created a sense of home far away from home. Your humour, warmth, and constant support kept me grounded throughout this journey. Thank you for celebrating my victories, providing much-needed distractions, and patiently listening to me ramble about research, often at great length!

Reaching this point in life would have been impossible without the selfless sacrifices and immense love of my parents. To my mother, Sonia Wahi, whose dream of becoming a doctor found fulfilment through me: your countless sacrifices, unwavering devotion, and boundless love gave me the courage and opportunity to pursue my passion. Your steadfast belief in me guided my every step, helping me face challenges head-on. Thank you for being my greatest supporter and helping me fulfil our cherished dream. Every milestone of this journey reflects your strength and aspirations, and today, I proudly share this moment with you.

To my father, Bipin Wahi—your consistent encouragement, infectious positivity, and perceptive lessons underscored the importance of optimism and perseverance. Your confidence in my potential, patient willingness to listen, and thoughtful guidance consistently offered the clarity and motivation I needed. Your calm resolve showed me how to approach adversity with composure in difficult moments. Thank you for being my guiding light, instilling in me the values of integrity, and continually reminding me to meet life's challenges with bravery and hope.

To my wonderful sister, **Ishita Wahi Takyar**, thank you for making me feel deeply loved and cared for each time I returned home. Your kindness, compassion, and consistent support have made every return a comforting and rejuvenating experience. To my fantastic brother-in-law, **Ashish Takyar**, your joyful presence has continuously lifted my spirits and kept me moving forward.

To my parents-in-law, **Uma Yoganand** and **Ashok Yoganand**, and my sister-in-law, **Aradhana Yoganand**, your trust, warmth, and constant encouragement have enriched my journey immeasurably. Your kindness and unconditional support have made my path brighter and easier.

Though words can never fully capture the depth of my appreciation for all the love, sacrifices, and continuous support I have received, I dedicate this achievement to each of you today. Thank you all for being my foundation, strength, and greatest inspiration.

And finally, this entire journey would not have been the same without the person who has shared every moment of it with me—my friend, partner, and wife, **Anagha Yoganand**. Thank you for your endless patience, for standing by me through the highs and lows, and for pulling me back up during the toughest moments. You gave me the strength to fulfil the dream we envisioned together on the 8th of June, 2020. This PhD is as much your achievement as it is mine.

Thank you, **TU Delft**, for these past six years. They have been among the most thrilling, challenging, and enlightening years of my life.

And to anyone reading this thesis, thank you for joining me on this journey. I now invite you to explore how we can prepare existing Dutch homes to transition to lower-temperature heating solutions for a more sustainable and decarbonised built environment.

Prateek Wahi
Delfgauw, 13th March 2025

TOC

Contents

List of Tables

List of Figures

List of abbreviations and symbols

Abbreviations	Description
AB	Apartment Block
AHP	Analytical Hierarchy Process
ANP	Analytical Network Process
ATL	Adaptive Thermal Limit
CHP	Combined Heat and Power
CI	Consistency Index
CR	Consistency Ratio
DEMATEL	Decision Making Trial and Evaluation Laboratory
DGU	Double Glazing Unit
DH	District Heating
3GDH	3rd Generation District Heating
4GDH	4th Generation District Heating
DHW	Domestic Hot Water
DSS	Decision Support System
EI	Energy Index
ELECTRE	ÉLimination Et Choix Traduisant la Realité
EU	European Union
GC	Global Costs
GHG	Greenhouse Gas
GSA	Global Sensitivity Analysis
GWP	Global Warming Potential
HBjson	HoneyBee Json
HP	Heat Pumps
HREC	Human Ethics Research Committee
HT	High-Temperature
HVAC	Heating, Ventilation and Air Conditioning
IC	Investment Costs
KPI	Key Performance Indicators
LCC	Life Cycle Costs
LCCA	Life Cycle Cost Analysis

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Abbreviations	Description
LHS	Latin Hypercube Sampling
LMTD	Logarithmic Mean Temperature Difference
LT	Low-Temperature
LTH	Lower Temperature Heating
LSF	Label Step Factor
MADM	Multi-Attribute Decision Making
MC	Maintenance Costs
MCDM	Multi-Criteria Decision Making
MODM	Multi-Objective Decision Making
MFH	Multi-Family House
MT	Medium-Temperature
NIS	Negative Ideal Solution
NPV	Net Present Value
OC	Operating Costs
PD	Percentage of Dissatisfaction
PDFs	Probability Density Functions
PIS	Positive Ideal Solution
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PROMETHEE	Preference Ranking Organisation METHod for Enrichment
PV	Photovoltaic Panels
PVT	Photovoltaic Thermal Collectors
RC	Replacement Costs
RCI	Randomly Generated Consistency Index
RF	Random Forest
RH	Relative Humidity
SALSA	Search, Appraisal, Synthesis and Analysis
SFH	Single-Family House
SH	Space Heating
SHD	Space Heating Demand
SPB	Simple Payback Period
SSM	Soft System Methodology
SRRC	Standardised Rank Regression Coefficient
TH	Terraced Houses
TGU	Triple Glazing Unit
TOPSIS	Technique of Order of Preference by Similarity to Ideal Solutions
TRY	Test Reference Year
UBEM	Urban Building Energy Modelling
ULT	Ultra-Low Temperature
VFT	Value-Focused Thinking

Symbols	Description	Units
Als / A_{loss}	External Heat Loss Area	m^2
Ag / A_{floor}	Total Usable Heated Area	m^2
c	Life span of a component	years
CPI_{2012}	Consumer price index in 2012	% difference from 2015
CPI_{2021}	Consumer Price Index in 2021	% difference from 2015
$cost_{fixed}$	Fixed energy costs	€
$cost_{\mathrm{var}}$	Variable energy costs	€
CV_{gas}	Calorific value of natural gas: 35.2	MJ/m^3
df	Discount factor	-
e	Average annual inflation rate	%
f_{type}	Dimensionless correction factor for building type	-
f_y	Dimensionless correction factor for construction year	-
i	Apartment position number	-
IC_k	Investment costs of component k	€
M_{rate}	Maintenance rate	%
n	Radiator exponent	-
n_y	Calculation period for LCC	years
OC_a	Annual recurring operating costs	€
OC_{NPV}	Net present value of operating costs	€
r_e	Real interest rate accounting for inflation	%
r	Market interest rate	%
T_s	Radiator supply temperature	°C
T_r	Radiator return temperature	°C
T_i	Design indoor temperature	°C
Q_{v10}	Air infiltration rate at 10 PA	$dm^3/s.m^2$
$Q_{v10;spec}$	Specific air infilteration rate for a building type at 10PA	$dm^3/s.m^2$

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Symbols	Description	Units
Q_{total}	Total annual theoretical primary energy consumption	MJ
Q_{SHD}	Annual primary energy consumption due to space heating	kWh/m^2
Q_{DHW}	Annual primary energy consumption due to domestic hot water	kWh
$Q_{lighting}$	Annual primary energy consumption due to lighting	kWh
Q_{PV}	Annual energy generated from PV panels	kWh
R^2	Coefficient of Determination	-
$\varnothing$	Radiator heating power at new temperature set	W
$\varnothing_0$	Radiator heating power at original design temperature set	W
ΔQ_{SHD}	Change in energy demand for space heating	kWh/m^2
ΔT	Logarithmic mean temperature difference at new temperature set	°C
ΔT_0	Logarithmic mean temperature difference at original design temperature set	°C
η	System efficiency	-

Summary

The Netherlands faces a critical challenge in transitioning its existing housing stock to sustainable heating systems as part of its broader strategy to decarbonise the built environment and achieve climate neutrality by 2050. This transition involves phasing out natural gas for heating in 1.5 million housing equivalents by 2030 and 7.7 million by 2050. It is essential for reducing greenhouse gas emissions (GHG), mitigating seismic risks associated with natural gas extraction, enhancing energy security, and tackling energy poverty. Lower-temperature heating (LTH) systems, particularly through district heating (DH), are central to these efforts. At the supply side, reducing the supply temperature improves heat generation and distribution efficiencies while enhancing thermal comfort and indoor environmental quality at the building demand level. Alternative LTH-based systems, such as heat pumps or hybrid systems, will also contribute, depending on local resources and infrastructure availability. Nonetheless, by 2050, DH systems are projected to supply half of the sustainable heat in the Netherlands.

The success of this energy transition depends significantly on preparing existing dwellings for LTH from DH systems. These dwellings with high heating demands can experience thermal discomfort when supply temperatures are lowered. This creates barriers to reducing supply temperatures at the neighbourhood level, as they continue to require high-temperature (HT) supply to maintain thermal comfort. Consequently, it is imperative to renovate the existing housing stock to enable the adoption of LTH. However, several challenges complicate this process. The absence of standardised LTH readiness criteria to determine renovation needs, the overwhelming range of potential renovation options leading to decision paralysis, the heterogeneity of the housing stock requiring tailored solutions, and the involvement of diverse stakeholders with conflicting preferences, coupled with insufficient decision-support insights for LTH, collectively impede the decision-making process. These challenges hinder progress toward achieving energy transition goals.

To tackle the challenges discussed, this research aims to develop a systematic approach to guide the selection of renovation solutions for making Dutch dwellings LTH-ready. In doing so, it seeks to support and accelerate the transition of the existing housing stock towards sustainable energy solutions. It addresses the main research question:

- How can the selection of renovation solutions that prepare diverse dwellings in the Netherlands to utilise lower temperature heat from district heating systems be systematically supported?

To comprehensively answer this central question, the following sub-questions were formulated:

- *What factors must be considered when **selecting renovation solutions** to prepare dwellings for adopting lower-temperature heating?*
- *How can the **readiness** of dwellings to utilise **lower temperature heat from district heating** be defined and assessed to identify the necessary renovations?*
- *How can variations in building-level parameters that contribute to **diversity within the dwelling stock** be incorporated into assessing readiness for lower-temperature heating?*
- *How can the multi-criteria decision-making approach be utilised to **systematically support** the selection of renovation solutions for using lower-temperature heating?*

Research Methodology

This study employed a mixed-methods approach to comprehensively address the complexities of preparing Dutch dwellings for LTH. Combining qualitative and quantitative methods, the research was structured around four interconnected activities, each addressing a specific sub-research question.

The first research activity involved a systematic literature review to identify critical factors influencing LTH readiness, such as building-level characteristics, renovation options, and performance indicators. This review established the foundation for defining LTH readiness and organising renovation solutions into structured categories.

The second activity involved developing a two-step assessment approach to evaluate the readiness of dwellings for LTH and determine the renovation measures needed to achieve readiness. This approach was applied to a case study, using dynamic simulations to test its applicability and refine the methodology.

Recognising the heterogeneity of the Dutch housing stock and the limitations of archetype-based analyses, the third activity involved employing a probabilistic sampling approach to capture variations within terraced and apartment dwelling types. These dwelling types were selected as they represent approximately 60% of the Dutch housing stock. Machine learning techniques were used to analyse the influence of building-level parameters on LTH readiness. This activity provided a nuanced understanding of the factors affecting readiness and informed the development of tailored renovation strategies.

The final research activity synthesised insights from the earlier activities into a decision-support framework. The framework was applied to a multi-family housing (MFH) case study to demonstrate its practical utility, and it was validated through a workshop involving the stakeholders involved in the case study. The validation workshop provided critical feedback on the framework's applicability, usability, and potential for refinement.

Results

— What factors must be considered when selecting renovation solutions to prepare dwellings for adopting lower-temperature heating?

The systematic literature review revealed building level characteristics, including insulation levels, airtightness, ventilation systems, radiator heating capacities and level of lower temperature supplied, play a significant role in determining the LTH readiness of a dwelling. The review also categorised renovation options using a structured approach involving objectives (functional, feasible, and accountable), scenarios (base-case, basic, moderate and deep), strategies (envelope, system, control), and measures. Despite focusing on "low-hanging fruit" strategies like insulation and airtightness, the literature highlights gaps in product-level data and qualitative accountability renovation objectives. Key performance indicators (KPIs) related to energy efficiency and thermal comfort criteria are critical for assessing the possibility of renovation solutions for LTH. At the same time, those related to environmental and economic criteria are necessary to assess the feasibility of renovation solutions. Nevertheless, the absence of standardised criteria for assessing the LTH readiness of a dwelling was noted.

- **How can the readiness of dwellings to utilise lower temperature heat from district heating be defined and assessed to identify the necessary renovations?**

  The study introduced a definition of LTH readiness based on two non-compensatory criteria: energy efficiency and thermal comfort. A dwelling is considered LTH-ready if it can maintain or improve these criteria under lower supply temperatures compared to its existing condition under HT supply. A two-step assessment approach was developed to evaluate readiness and identify necessary interventions, focusing on annual space heating demand and occupied underheated hours as KPIs. First, a dwelling's performance under HT supply was benchmarked to establish baseline metrics. Second, the dwelling's performance under medium-temperature (MT: 70/50°C) and low-temperature (LT: 55/35°C) supply was simulated and compared to the benchmark. Applying this approach to a pre-1945 terraced intermediate dwelling revealed that reducing supply temperature increased thermal discomfort. The basic level of intervention, including strategies such as upgrading radiators, was insufficient to prepare the dwelling for LTH, thus necessitating building envelope upgrades for LTH readiness. Moderate interventions, such as window insulation, improved airtightness, and radiator upgrades, were sufficient for MT supply but inadequate for LT supply, which required additional airtightness, comprehensive insulation measures to the building envelope, and upgrades to ventilation systems and radiators. Comparisons with Dutch insulation standards highlighted the need to integrate thermal comfort metrics alongside heating demand benchmarks for a comprehensive LTH-readiness evaluation. The two-step approach not only establishes clear LTH readiness criteria but also streamlines the selection of renovation options. While effective, scaling the approach to diverse dwelling types is essential to account for variations and broaden its applicability.

- **How can variations in building-level parameters that contribute to diversity within the dwelling stock be incorporated into assessing readiness for lower-temperature heating**?

  While archetype-based generalisations offer valuable insights at the policy level, they often overlook dwelling-level variations, leading to performance gaps when applied to specific cases. To address this limitation, a probabilistic sampling-based approach was employed to capture the diversity within terraced-intermediate and apartment dwellings. This approach had two key objectives: determining an adequate sample size to represent variations and identifying the relative influence of building-level parameters on LTH readiness. Using Latin hypercube sampling, parametric simulation, and global sensitivity analysis, a sample size of 1,300 per dwelling type was deemed sufficient. This sample effectively captured variations due to geometric, fabric, HVAC, and occupant and control-related factors that characterise a dwelling and influence its LTH readiness. Supervised machine learning techniques were subsequently used to assess the relative importance of these parameters. The findings indicated that, for both dwelling types, the heating setpoint had the highest influence on LTH readiness. This was followed by ventilation-related parameters and then the thermal properties of the building envelope. Geometric factors, in contrast, played a relatively minor role. Notably, the study revealed that radiator oversizing significantly affects LTH readiness. However, the degree of oversizing varies depending on the dwelling type and lower supply temperature. The insights from this study serve as a tool for prioritising renovations and tailoring solutions to specific dwelling types, enabling stakeholders to make informed decisions and effectively address challenges in preparing buildings for LTH.

– **How can the multi-criteria decision-making approach be utilised to support the selection of renovation solutions for using lower-temperature heating?**

This study developed and validated a structured decision-making framework based on Multi-Criteria Decision-Making (MCDM) methods to support the selection of renovation solutions for preparing dwellings for LTH. The framework integrates LTH readiness criteria, performance evaluation, and stakeholder preferences into a systematic six-step process to address the complexity of balancing conflicting stakeholder priorities and provide decision-support insights. These steps include diagnosing renovation needs, evaluating LTH-readiness, defining and prioritising decision criteria using a *pairwise-comparison* method, developing and filtering renovation alternatives, quantifying performance, and ranking alternatives using the *Technique for Order of Preference by Similarity to Ideal Solution* (TOPSIS) method. The framework was applied to a case study involving an MFH apartment complex in the Netherlands. It successfully identified optimal renovation solutions, incorporating real-world conditions and stakeholder inputs. While the stakeholders initially preferred a cost-efficient option, it was found to be not LT-ready. The framework revealed an alternative that enhanced thermal comfort under LT supply with higher long-term benefits despite increased initial investment. A validation workshop with stakeholders confirmed the framework's structured, analytical approach as a valuable improvement over intuition-based decision-making. However, participants emphasised incorporating social factors, iterative feedback loops, and risk assessments for greater practical applicability. Overall, the framework provides a comprehensive, structured approach to renovation decision-making for LTH, with significant potential for further refinement and broader applications.

Conclusions

The main research question — **How can the selection of renovation solutions that prepare diverse dwellings in the Netherlands to utilise lower temperature heat from district heating systems be systematically supported?** — is addressed through the development, application, and validation of a decision-support framework. This framework integrates insights from previous sections while addressing the decision-making challenges involved in selecting technically appropriate solutions to prepare dwellings for LTH. Central to the framework is the definition of LTH readiness, based on energy efficiency and thermal comfort criteria, employing a non-compensatory model to determine whether a dwelling requires renovations to achieve LTH readiness. The framework also provides a structured process for identifying and filtering renovation options, streamlining decision-making by reducing complexity and effort. To account for the diversity of the Dutch housing stock, a sampling-based analysis of 1,300 dwellings was conducted. This analysis captured variations in building-level parameters and identified the relative importance of these features in predicting the LTH readiness of different dwelling types, serving as a tool for developing tailored renovation solutions. Specific MCDM methods, including pairwise comparison and TOPSIS, were employed to incorporate stakeholder preferences, effectively balancing priorities and evaluating renovation solutions. The framework's adaptability extends its relevance beyond DH systems to other LTH supply systems, such as heat pumps. By offering a systematic approach to navigating the complexities of selecting suitable renovation solutions it facilitates the transition to sustainable heating systems and significantly contributes to the Netherlands' energy transition goals.

Samenvatting

Nederland staat voor een cruciale uitdaging bij de overgang naar duurzame verwarmingssystemen in bestaande woningen. Deze overgang is onderdeel van een bredere transitie om de gebouwde omgeving klimaatneutraal te maken in 2050. Deze transitie omvat het uitfaseren van aardgas voor verwarming in 1,5 miljoen woningequivalenten in 2030 en 7,7 miljoen woningequivalenten in 2050. De transitie is essentieel voor het verminderen van de uitstoot van broeikasgassen, het beperken van seismische risico's in verband met aardgaswinning, het verbeteren van de energiezekerheid en het aanpakken van energiearmoede. Systemen voor verwarming op lagere temperatuur (LTV), met name door middel van stadsverwarming (SV), staan centraal bij deze inspanningen. Op leveringszijde verbetert het verlagen van de aanvoertemperatuur de efficiëntie van warmteopwekking en -distributie , terwijl het thermisch comfort en de kwaliteit van het binnenmilieu op gebouwvraagzijde worden verbeterd. Alternatieve LTV-gebaseerde systemen, zoals warmtepompen of hybride systemen, zullen ook een bijdrage leveren, afhankelijk van de lokale middelen en de beschikbaarheid van infrastructuur. Er wordt verwacht dat SV-systemen in 2050 de helft van de duurzame warmte in Nederland zullen leveren.

Het succes van deze transitie naar LTV uit SV-systemen hangt in belangrijke mate af van het voorbereiden van bestaande woningen. In deze woningen, met een hoge warmtebehoefte, kan men thermisch ongemak ervaren wanneer de aanvoertemperaturen worden verlaagd. Dit werpt barrières op, omdat de woningen een hoge temperatuur (HT) nodig hebben om het thermische comfort te behouden. Daarom is het absoluut noodzakelijk om de bestaande woningvoorraad te renoveren om de invoering van LTH mogelijk te maken. Dit proces wordt echter bemoeilijkt door verschillende uitdagingen. Het ontbreken van gestandaardiseerde ‘LTV-gereedheidscriteria’ om de renovatiebehoeften van bestaande woningen te bepalen, het overweldigende scala aan potentiële renovatie opties dat leidt tot besluiteloosheid, de verschillen tussen bestaande woningen heterogeniteit van het woningbestand dat oplossingen op maat vereist, en de betrokkenheid van diverse belanghebbenden met tegenstrijdige voorkeuren in combinatie met onvoldoende beslissingsondersteunende inzichten voor LTV. Deze uitdagingen belemmeren de voortgang in de richting van het behalen van de energietransitiedoelstellingen.

Om de besproken uitdagingen aan te pakken, heeft dit onderzoek tot doel een systematische aanpak te ontwikkelen voor het selecteren van renovatieoplossingen voor het gereed maken van Nederlandse woningen voor LTV. Hiermee wil dit onderzoek de transitie van de bestaande woningvoorraad naar duurzame energieoplossingen ondersteunen en versnellen. Het gaat in op de belangrijkste onderzoeksvraag:

- **Hoe kan de selectie van renovatieoplossingen die diverse woningen in Nederland voorbereiden op het gebruik van lagere temperatuur warmte uit stadsverwarmingssystemen systematisch worden ondersteund?**

Om deze centrale vraag volledig te beantwoorden, zijn de volgende deelvragen geformuleerd:

- *Met welke factoren moet rekening worden gehouden bij **het kiezen van renovatieoplossingen** om woningen geschikt te maken voor verwarming met een lagere temperatuur?*
- *Hoe kan de **geschiktheid** van woningen, om warmte met een **lagere temperatuur uit stadsverwarming** te benutten, worden gedefinieerd en beoordeeld om de benodigde renovaties te identificeren?*
- *Hoe kunnen **variaties in gebouweigenschappen binnen de woningvoorraad** worden meegenomen bij het beoordelen van de gereedheid voor verwarming op lagere temperatuur?*
- *Hoe kan de multi-criteria besluitvormingsaanpak worden gebruikt om de selectie van renovatieoplossingen voor het gebruik van lagetemperatuurverwarming **systematisch te ondersteunen**?*

Onderzoeksmethodologie

In dit onderzoek werd gebruikgemaakt van een ‘mixed-methods’ benadering om de complexiteit van de transitie, namelijk het voorbereiden van Nederlandse woningen op LTV, in kaart te brengen. Door kwalitatieve en kwantitatieve methoden te combineren, werd het onderzoek gestructureerd rond vier onderling verbonden activiteiten, elk gericht waren op een specifieke deelonderzoeksvraag.

De eerste onderzoeksactiviteit betrof een systematisch literatuuronderzoek om kritieke factoren te identificeren die invloed hebben op de gereedheid voor LTV, zoals kenmerken van gebouwen, renovatieopties en prestatie-indicatoren. Deze beoordeling legde de basis voor het definiëren van LTV-gereedheid en het organiseren van renovatieoplossingen in gestructureerde categorieën.

De tweede activiteit betrof het ontwikkelen van een twee-stappen aanpak om de gereedheid van woningen voor LTV te beoordelen en te bepalen welke renovatiemaatregelen daarvoor nodig zijn. Deze aanpak werd toegepast op een casestudy, waarbij dynamische simulaties werden ingezet om de toepasbaarheid ervan te testen en de methodologie verder te verfijnen.

Om rekening te houden met de verscheidenheid in de Nederlandse woningvoorraad en de beperkingen van archetypen, betrof de derde activiteit het gebruik van een probabilistische steekproefbenadering om variaties binnen rijtjes- en appartementswoningtypen vast te leggen. Deze woningtypen zijn gekozen omdat ze ongeveer 60% van de Nederlandse woningvoorraad vertegenwoordigen. Machine learning-technieken werden toegepast om de invloed van parameters op gebouwniveau op de LTV-gereedheid te onderzoeken. Deze activiteit bood inzicht in de factoren die de paraatheid beïnvloeden en vormde de basis voor de ontwikkeling van op maat gemaakte renovatiestrategieën.

De laatste onderzoeksactiviteit integreerde de inzichten van de voorgaande activiteiten in een beslissingsondersteunend raamwerk. Dit raamwerk werd toegepast op een casestudy betreffende meergezinswoningen (MGW) om het praktische nut ervan te demonstreren. Vervolgens werd het raamwerk gevalideerd door middel van een workshop met belanghebbenden die betrokken waren bij de case study. De validatieworkshop leverde essentiële feedback over de toepasbaarheid, bruikbaarheid en het potentieel voor verdere verfijning van het raamwerk.

Resultaten

— **Met welke factoren moet rekening worden gehouden bij het kiezen van renovatieoplossingen om woningen geschikt te maken voor verwarming met een lagere temperatuur?**

Uit het systematische literatuuronderzoek bleek dat gebouwkenmerken zoals de isolatiewaarde, luchtdichtheid, het type ventilatiesysteem, verwarmingsvermogen van radiatoren en het niveau van de lagere temperatuur een belangrijke rol spelen bij de LTV-gereedheid van woningen. Renovatieopties werden gecategoriseerd op basis van doelstelling (functionaliteit, haalbaarheid en verantwoording), scenario's (basisscenario, basis, gemiddeld en diepgaand), strategieën (gebouwschil, systeem, controle) en maatregelen. Ondanks de nadruk op 'laaghangend fruit', zoals isolatie en luchtdichtheid, wijst de literatuur op hiaten in gegevens op productniveau en kwalitatieve renovatiedoelstellingen. Key performance indicators (KPI's) met betrekking tot energie-efficiëntie en thermisch comfort zijn van cruciaal belang bij de beoordeling van renovatieoplossingen, terwijl milieu- en economische criteria nodig zijn om de haalbaarheid te beoordelen. Niettemin werd opgemerkt dat er geen gestandaardiseerde criteria waren voor de beoordeling van de LTV-gereedheid.

— **Hoe kan de geschiktheid van woningen, om warmte met een lagere temperatuur uit stadsverwarming te benutten, worden gedefinieerd en beoordeeld om de benodigde renovaties te identificeren?**

De studie definieerde LTV-gereedheid op basis van twee niet-compenserende criteria: energie-efficiëntie en thermisch comfort. Een woning wordt als LTV-gereed beschouwd als zij deze criteria kan handhaven of verbeteren bij lagere aanvoertemperaturen in vergelijking met de bestaande toestand onder HT-levering. Er is een beoordelingsaanpak in twee stappen evalueert de gereedheid en identificeert de noodzakelijke interventies, waarbij de nadruk ligt op de jaarlijkse vraag naar ruimteverwarming en de onderschrijdingsuren tijdens de gebruikstijd als KPI's. Eerst werd een woning onder HT-aanbod 'gebenchmarkt'. Vervolgens werden de prestaties van diezelfde woning bij gemiddelde (MT: 70/50°C) en lage temperatuur (LT: 55/35°C) gesimuleerd en vergeleken met de benchmark. Bij een tussenwoning van vóór 1945 steeg het thermisch discomfort bij het verlagen van de aanvoertemperatuur. Basisinterventies, zoals het upgraden van radiatoren, waren onvoldoende om de woning voor te bereiden op LTV, waardoor verbeteringen in de gebouwschil nodig waren. Raamisolatie, verbeterde luchtdichtheid en radiatorupgrades waren voldoende voor MT-levering, maar ontoereikend voor LT-levering, die extra maatregelen vereiste zoals een betere luchtdichtheid, uitgebreide isolatiemaatregelen en upgrades van het ventilatiesysteem en radiatoren. Vergelijkingen met Nederlandse isolatienormen benadrukten dat zowel het thermisch comfort als de warmtevraag moeten worden meegenomen in de evaluatie van de LTV-gereedheid. De tweefasenaanpak stelt duidelijke criteria vast en vereenvoudigd de keuze voor renovatiemaatrelgeen, maar moet nog worden opgeschaald om toepasbaar te zijn voor diverse woningtypen.

- **Hoe kunnen variaties in gebouweigenschappen binnen de woningvoorraad worden meegenomen bij het beoordelen van de gereedheid voor verwarming op lagere temperatuur?**

  Archetypische generalisaties bieden waardevolle inzichten op beleidsniveau, maar missen vaak de aanwezige variaties op woningniveau, wat prestatiekloven kan veroorzaken in specifieke gevallen. Een probabilistische steekproefbenadering werd gebruikt om de diversiteit binnen rijtjeshuizen en appartementswoningen vast te leggen. Deze aanpak had twee hoofddoelstellingen: (1) het bepalen van een geschikte steekproefomvang om variaties weer te geven en (2) het identificeren van de relatieve invloed van gebouweigenschappen op de LTV-gereedheid. Met behulp van Latijnse hypercube-steekproeven, parametrische simulatie en globale gevoeligheidsanalyse werd een steekproefomvang van 1.300 per woningtype vastgesteld. Deze steekproef identificeerde variaties in geometrie, bouwkundige eigenschappen, HVAC en bewoners gerelateerde factoren die LTV-gereedheid beïnvloeden. Gesuperviseerde machine learning wees uit dat het instelpunt -technieken werden vervolgens gebruikt om het relatieve belang van deze parameters te beoordelen. De bevindingen gaven aan dat voor beide woningtypen het instelpunt voor verwarming de grootste invloed had op de LTH-gereedheid. Daarna volgden de ventilatiegerelateerde parameters en vervolgens de thermische eigenschappen van de gebouwschil. Geometrische factoren speelden daarentegen een relatief ondergeschikte rol. Uit het onderzoek bleek met name dat overdimensionering van de radiator een aanzienlijke invloed heeft op de LTV-gereedheid. De mate van overdimensionering varieert echter afhankelijk van het type woning en de lagere aanvoertemperatuur. De inzichten uit deze studie dienen als een hulpmiddel voor het prioriteren van renovaties en het afstemmen van oplossingen op specifieke woningtypes, waardoor belanghebbenden weloverwogen beslissingen kunnen nemen en uitdagingen bij het voorbereiden van gebouwen op LTH effectief kunnen aanpakken.

- **Hoe kan de multi-criteria besluitvormingsaanpak worden gebruikt om de selectie van renovatieoplossingen voor het gebruik van lagetemperatuurverwarming systematisch te ondersteunen?**

  Deze studie ontwikkelde en valideerde een gestructureerd besluitvormingskader, gebaseerd op Multi-Criteria Decision-Making (MCDM)-methoden, ter ondersteuning van de selectie van renovatieoplossingen die woningen geschikt maken voor Lage Temperatuur Verwarming (LTV). Het raamwerk integreert LTH-gereedheidscriteria, prestatie-evaluatie en voorkeuren van belanghebbenden in een systematisch proces van zes stappen: (1) renovatiebehoeften diagnosticeren, (2) LTV-gereedheid evalueren, (3) beslissingscriteria definiëren en prioriteren met behulp van een *pairwise-comparison* methode, (4) renovatiealternatieven ontwikkelen en filteren, (5) prestaties kwantificeren, en (6) alternatieven rangschikken met behulp van de *Technique for Order of Preference by Similarity to Ideal Solution* (TOPSIS) methode. Het raamwerk werd toegepast op een case study met betrekking tot een MGW-appartementencomplex in Nederland. Het identificeerde met succes optimale renovatieoplossingen, waarbij rekening werd gehouden met de omstandigheden in de praktijk en de inbreng van belanghebbenden. Hoewel de belanghebbenden aanvankelijk de voorkeur gaven aan een kostenefficiënte optie, bleek deze niet LT-gereed te zijn. Het raamwerk onthulde een alternatief dat het thermisch comfort onder LT-levering verbeterde met hogere voordelen op lange termijn. Daartegenover stonden echter verhoogde investeringskosten. Validatie door belanghebbenden bevestigde de waarde van deze gestructureerde aanpak en suggereerde verdere toevoegingen voor het verbeteren van de praktische toepasbaarheid. Denk hierbij aan het opnemen van sociale factoren, iteratieve terugkoppelingseffecten en risicobeoordelingen. Het kader biedt een uitgebreide en gestructureerde aanpak voor LTV-renovatiebesluiten met potentieel voor verfijning en bredere toepassingen.

Conclusies

De centrale onderzoeksvraag: Hoe kan de selectie van renovatieoplossingen die diverse woningen in Nederland voorbereiden op het gebruik van lagere temperatuur warmte uit stadsverwarmingssystemen systematisch worden ondersteund?
— wordt beantwoord door de ontwikkeling, toepassing en validatie van een beslissingsondersteunend kader. Dit raamwerk verenigt inzichten uit eerdere paragrafen en behandelt de besluitvormingsaspecten die komen kijken bij het kiezen van technisch geschikte oplossingen voor het voorbereiden van woningen op LTV. Centraal in het kader staat de definitie van LTV-gereedheid, gebaseerd op criteria die betrekking hebben op energie-efficiëntie en thermisch comfort. Hierbij wordt een niet-compenserend model gehanteerd om te beoordelen of een woning gerenoveerd moet worden om LTV-gereedheid te bereiken. Het raamwerk biedt tevens een gestructureerd proces voor het identificeren en selecteren van renovatieopties, waardoor de besluitvorming wordt vereenvoudigd door de complexiteit en inspanning te reduceren. Er is een steekproefsgewijze analyse uitgevoerd van 1.300 woningen om de diversiteit van de Nederlandse woningvoorraad in kaart te brengen. Deze analyse registreerde variaties in parameters op gebouwniveau en identificeerde het relatieve belang van deze kenmerken bij het voorspellen van de LTV-gereedheid van verschillende woningtypes. Daarnaast diende de analyse als hulpmiddel voor het ontwikkelen van op maat gemaakte renovatieoplossingen. Specifieke MCDM-

methoden, waaronder paarsgewijze vergelijking en TOPSIS, werden gebruikt om de voorkeuren van belanghebbenden te verzamelen, prioriteiten effectief af te wegen en renovatieoplossingen te evalueren. Het aanpassingsvermogen van het raamwerk breidt zijn relevantie uit van SV-systemen naar andere LTV-systemen, zoals warmtepompen. Door een systematische aanpak te bieden voor het kiezen van geschikte renovatieoplossingen, vergemakkelijkt het de overgang naar duurzame verwarmingssystemen en draagt het aanzienlijk bij aan de energietransitiedoelstellingen van Nederland.

1 Introduction

1.1 Background

1.1.1 Energy Transition in the Built Environment

The increase in global surface temperature by 1.1°C between 2011 - 2020, compared to the baseline levels of 1850-1990, quantifies the detrimental impact of climate change (IPCC, 2023), threatening both the natural and the built environment. With current policies, it is no longer feasible to limit global warming to 1.5°C; in fact, there is a 66% probability that the global temperatures will rise between 1.9°C to 3.8°C by the end of the century (United Nations Environment Programme, 2023). This upward trend in global temperature, driven by greenhouse gas (GHG) emissions from fossil fuel consumption, is the leading cause of climate change. Significantly, the building sector plays a substantial role in these emissions, underscoring its critical impact. In the European Union (EU), the built environment is responsible for 40% of final energy consumption and approximately 35% of CO_2 emissions (Mandel et al., 2023; Rousselot et al., 2021), making it a major contributor compared to the transport, industry, and agricultural sectors (ODYSSEE-MURE, 2023)[1].

In the Netherlands, the built environment accounted for 29% (596 PJ) of the total final energy consumption in 2022, with approximately 68% (408 PJ) of this energy used for heating purposes (Energie Beheer Nederland, n.d.). In the same year, it contributed around 12% (19.6 Mton $CO_{2;\ eq}$) of the total GHG emissions, with 72% of these emissions resulting from household heating demands (Centraal Bureau voor de Stastiek, 2022b). Notably, about 90% of residential buildings

1 In 2021, the final energy consumption of the EU amounted to 932.4 Mton. Of this, the built environment accounted for 41.72%, transport 29.7%, industry 25.42% and agriculture 3.15%. Households alone are responsible for 27.67% of the final energy consumption.

primarily rely on natural gas for heating and cooking (Centraal Bureau voor de Stastiek, 2021; Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022). Given the detrimental impact of the burning of natural gas on GHG emissions, coupled with the earthquakes resulting from its extraction in the Groningen region, the Dutch government has re-evaluated its reliance on natural gas. Additionally, the recent geopolitical events have further accelerated the urgency of transitioning towards fossil-free energy systems. To address this challenge, the Netherlands has initially established targets to cease gas extraction by 2030 and decarbonise the built environment by 2050, as outlined in its climate agreement (Dutch Ministry of Economic Affairs and Climate, 2019). Nevertheless, the Netherlands has since expedited this plan and passed a law to stop gas extraction from the Groningen field as of May 1, 2024 (NOS Nieuws, 2024; Rijksoverheid, 2023).

As part of the decarbonising strategy, the Dutch climate agreement focuses on the energy transition towards sustainable heating sources, with a goal of making 1.5 million homes gas-free and achieving a $CO_{2;\,eq}$ reduction of 3.4 Mton by 2030 (Dutch Ministry of Economic Affairs and Climate, 2019). Consequently, the energy transition goals revolve around adapting both the supply and demand sides. On the supply side, this involves generating and distributing natural gas-free sustainable heat. Meanwhile, the demand side focuses on improving the energy efficiency of the building stock and promoting energy-conscious behaviour to ensure the effective integration of sustainable heat sources (Degelin et al., 2024; Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2022).

The phasing out of natural gas for heating primarily entails exploring heating systems powered by renewable energy sources, such as collective (district heating), individual (heat pumps) or hybrid (heat pumps and sustainable gas) systems (Beckman & van den Beukel, 2019; van Vliet et al., 2016). Among these options, district heating (DH) systems, which can supply heat at lower temperatures (belonging to the fourth generation of DH systems), offer a pathway for integrating sustainable energy sources and delivering sustainable heat to the housing stock, thereby advancing towards achieving the energy transition goals.

1.1.2 Role of District Heating Systems with Lower Temperature Supply

Collective heating systems or DH systems are a combined technology of heat production at a centralised location and distribution of hot water through an underground network of insulated pipes or heat network (Klip, 2017; Lund et al., 2014; Niessink, 2019; Østergaard, 2018). The adoption of sustainable heating systems depends on various factors, such as the availability of sustainable heat resources, building density, building profiles and types, and the requirements of end-users at the district level (Østergaard, 2018; Schmidt et al., 2017). A DH grid would be advantageous in densely populated areas, while less-dense districts would benefit from an all-electric solution such as heat pumps (Dutch Ministry of Economic Affairs and Climate, 2019). In areas where neither of these systems is feasible due to monumental guidelines or satellite towns, the existing gas network can be supplied with sustainably produced gases such as hydrogen, biomethane and biogas (Beckman & van den Beukel, 2019; Dutch Ministry of Economic Affairs and Climate, 2019). Nevertheless, compared to other heating systems, it is estimated that by 2050, DH systems will provide 50% of sustainable heat, compared to 5% in 2019 (Beckman & van den Beukel, 2019)[2]. However, achieving this depends on addressing challenges such as regulatory complexities, high infrastructure costs, and ensuring affordable heat for end-users (Gürsan et al., 2024; Herreras Martínez et al., 2022). Despite these hurdles, DH systems are expected to play a crucial role in the energy transition, making it essential to study their impact and integration into the built environment.

The Netherlands has different DH systems, primarily based on the temperature they supply. These systems can be categorised as “High Temperature” (HT), “Medium or Middle Temperature” (MT), “Low Temperature” (LT) and “Ultra Low Temperature” (ULT) (Averfalk et al., 2017; Kruit & Schepers, 2019), where the supply regime varies from region to region (Østergaard, 2018). Table 1.1 illustrates the DH temperature levels accepted in the Netherlands and the corresponding heat sources.

2 By 2050, district heating systems are projected to supply 50% of the heat. The remaining half will come from heat pumps, split equally between all-electric heat pumps and hybrid heat pumps that combine electric and gas heating for peak loads.

TOC

TABLE 1.1 District heating types based on system supply temperature, where Ta is the supply temperature delivered to buildings. Source: (Kruit & Schepers, 2019; TKI Urban Energy, 2019)

Supply Temperature	Heat Source
High Temperature Ta > 70°C	– Combined heat and power (CHP) fired with coal, natural gas, solid waste, or biomass. – Heat plants fired with biomass and natural gas. – Ultra-deep geothermal energy. – Residual heat from industry, power plants, and waste incineration.
Medium/Middle Temperature 55°C ≤Ta≤ 70°C	– Geothermal Energy – Biomass Boilers – Residual heat from industry, power plants, and waste incineration. – Solar Thermal Plants with Heat pumps
Low Temperature 25°C ≤Ta≤ 55°C	– Shallow Geothermal Energy – Low-temperature Residual Heat from the cooling process of data centres, ice rinks, and cold storage. – Solar Thermal Plants and heat pumps with ULT sources.
Very Low temperature Ta≤ 25°C	– Aquathermal from sewage and surface water. – ULT residual heat from the cooling process of data centres and supermarkets. – Solar thermal systems.

The predominant DH systems in the Netherlands still rely on HT networks that supply heat between 70-90˚C (Koster et al., 2022a). These HT DH systems use natural gas, coal, waste incineration, biomass, industrial waste heat and geothermal energy for heat generation (DNE Research, 2020; Kruit & Schepers, 2019; Niessink, 2019; van Vliet et al., 2016). This high-grade energy is used to meet the low-exergy demands of dwellings, such as supplying water at 90˚C to maintain an indoor air temperature of 20˚C (Eijdems et al., 1999; Sakulpipatsin et al., 2010; Tolga Balta et al., 2008). However, there is a shift towards reducing supply temperatures in existing networks to provide lower-temperature heat (LTH) and developing new lower-temperature networks or fourth-generation DH systems. The fourth-generation systems use heat from shallow geothermal, low-temperature residual heat from industry or data centres, solar heat and gasses such as hydrogen, biogas and biomethane. Compared to traditional gas-fired DH systems, fourth-generation systems can supply low-temperature heat between 30-55 °C depending on the heating sources (DNE Research, 2020; Jansen et al., 2020; Kruit & Schepers, 2019; Niessink, 2019; van Egmond, 2020; van Vliet et al., 2016). In this study, the temperature levels “Medium”, “Low”, and “Very/Ultra Low” are collectively referred to as lower-temperature levels. Consequently, lower-temperature DH systems refer to those that supply heat at temperatures below 70 °C to meet residential heating demands.

Lowering the supply temperature in the heat network offers advantages for both the supply and demand sides. On the supply side (i.e., *heat networks*), reducing the supply temperature enables the integration of fossil-free heating sources such as geothermal, solar, ambient, and residual heat from industrial processes

(Averfalk & Werner, 2018; Harrestrup & Svendsen, 2015). Additionally, this decreases the heat losses in the network and enhances production and distribution efficiency within the DH system (Harrestrup & Svendsen, 2015; Østergaard & Svendsen, 2018; Prando et al., 2015). On the demand side (i.e. *buildings*), employing LTH for space heating improves indoor thermal comfort and air quality (Eijdems et al., 1999; Ovchinnikov, Borodiņecs, & Millers, 2017). The large-scale implementation of DH systems would have a significant impact on their integration in residential dwellings, as currently, only 6.4% of the houses are connected to the DH systems (Centraal Bureau voor de Stastiek, 2022a; Koster et al., 2022b). With a focus on making buildings gas-free, many houses will be connected to these lower-temperature DH systems to achieve the energy transition goals. Therefore, it is essential to investigate the impact of a DH system with a lower-temperature supply and its incorporation in the built environment for an effective energy transition.

1.1.3 Challenges in the existing residential stock

The potential for reducing the supply temperature of DH systems depends on the building heating demands for space heating and hot water (Østergaard, 2018; Østergaard et al., 2022). The space heating demands correspond to the energy efficiency of the existing dwelling and the heat delivery systems. According to the Gas Act (Gaswet) revised in 2018 and the Nearly Energy Neutral Buildings (BENG) regulations, any new construction from 2021 onwards is mandated to have natural gas-free heating (Koster et al., 2022a). The improved energy efficiency of new buildings, resulting in lower heating demands, has made it feasible to use reduced supply temperatures for heating purposes (Kruit & Schepers, 2019; van Egmond, 2020; van Vliet et al., 2016). However, effectively integrating lower-temperature DH systems into the existing housing stock poses a challenge in ensuring a smooth energy transition (Roca et al., 2024).

The existing dwelling stock in the Netherlands is associated with higher heating demands, which presents a barrier to connecting these dwellings to lower-temperature DH systems. Specifically, a recent housing survey revealed that Dutch dwellings built before the 1980s have an energy label of C or worse (Stuart-Fox et al., 2019). Since existing heat emission systems (such as radiators) are designed for HT supply, reducing the supply temperature in these houses leads to decreased heating output (Ovchinnikov, Borodiņecs, & Strelets, 2017; Roca et al., 2024; Tunzi et al., 2016). Consequently, the heating system might not compensate for the heat losses, resulting in thermal discomfort for occupants. Therefore, these houses require an HT supply to maintain the desired thermal comfort of residents, limiting the potential to reduce the supply temperature on the DH network side.

Moreover, this issue creates bottlenecks in designing future lower-temperature DH systems based on sustainable sources (Harrestrup & Svendsen, 2015). Thus, undertaking energy renovations of the existing dwelling stock is crucial to facilitate the integration of lower-temperature DH systems for the energy transition. In this study, energy renovations refer to building-level modifications that reduce heating demands, making dwellings suitable for connecting to DH systems using sustainable sources (Asdrubali & Desideri, 2018; TKI Urban Energy, 2019).

Renovating existing dwellings as part of the energy transition presents a wide range of challenges, including governance and policy constraints (Herreras Martínez et al., 2022), construction and installation complexities, market-related barriers such as labour shortages, material availability, and the development of viable business models (D'Oca et al., 2018), as well as participatory challenges requiring the engagement of occupants and stakeholders (van der Schoor & Sanders, 2022). However, this study focuses on the challenges of selecting appropriate renovation solutions to integrate LTH systems into existing dwellings.

Recent studies in the Netherlands indicate a growing interest in integrating LTH from DH systems into existing dwellings. However, these studies primarily focused on LTH network design (Kneppera et al., 2021), sustainable energy concepts at the neighbourhood level (Jansen et al., 2021), and the maximum reduction in supply temperatures in existing heating systems under design conditions (Pothof et al., 2022). Notably, limited attention has been given to assessing the readiness of existing dwellings for LTH from DH systems, primarily due to the absence of standardised criteria for testing lower-temperature readiness (Pehnt et al., 2023).

Furthermore, the extent of renovation interventions needed to integrate LTH into existing dwellings remains largely unexplored. According to Wu et al. (2017), the difficulty in choosing appropriate renovation options arises from the numerous building-level renovation options. Multiple authors have researched renovation options for the building envelope, space heating, hot water, and ventilation systems to adapt existing dwellings for lower temperature supply from the DH system (Brand & Svendsen, 2013; Gustafsson et al., 2016; Østergaard & Svendsen, 2018; Wang et al., 2015). However, selecting suitable renovation options for integrating LTH into a specific dwelling is a complex challenge that requires further investigation. Another related issue, as discussed by Wang et al. (2015, 2016), is the need to balance the trade-offs associated with different renovation options. For instance, while changing existing radiator systems to use LTH may improve space demand at a low cost, it does not contribute to reducing overall energy demands (Brand & Svendsen, 2013). Conversely, insulating the building envelope can reduce energy demands, but it may be an expensive solution with a lengthy installation time and potential occupant inconveniences (Brand & Svendsen, 2013; Wang et al., 2016).

Moreover, the challenge is compounded by the heterogeneity of the existing dwelling stock, which causes the renovation requirements to vary widely. Previous studies investigating renovations for LTH in existing dwellings (Prando et al., 2015; Wang et al., 2015, 2016; Wu et al., 2017) have often considered archetypes or specific dwellings to determine renovation solutions. Analysing the building stock using archetype dwellings is a bottom-up approach that can offer insights into the energy-saving potential and cost-effectiveness of certain renovation options at a policy level (Mauro et al., 2015). However, variations within a particular dwelling type are averaged out in these archetypes. Consequently, uncertainties stemming from the diversity of the dwelling stock are not accounted for when assessing dwellings for LTH implementation and identifying suitable renovation options.

These challenges are significant for private individual, homeowners and professional entities, such as developers or housing associations, who face complex decisions when selecting applicable renovation solutions. The involvement of multiple stakeholders, each with varying preferences and needs, further complicates the process, making it difficult to reach consensus and establish shared objectives (Husiev et al., 2023; Jensen et al., 2013). Additionally, factors such as limited knowledge of available renovation options, high costs, restricted customisation possibilities (D'Oca et al., 2018) and lack of time and expertise to thoroughly assess the options (Mjörnell et al., 2014) contribute to informational barriers that hinder decision-making in selecting suitable renovations. The scarcity of decision support that aligns with individual preferences (TKI Urban Energy, 2019) further intensifies these challenges, ultimately impeding the scalability of the energy transition.

These gaps underscore the need for a systematic decision-making process. In this context, the literature highlights the Multi-Criteria Decision-Making (MCDM) approach and methods as a potential solution to navigate the complexities of renovation decision-making. However, further exploration is necessary to determine how it can be utilised to facilitate the selection of suitable renovations specifically for LTH, thereby contributing to the energy transition of the existing Dutch housing stock.

1.2 Research Framework

1.2.1 Problem Statement

Despite the expectation that DH systems will supply 50% of the sustainable heat by 2050, the readiness of existing Dutch dwellings to utilise these systems with LTH remains uncertain. These dwellings with high heating demand may require energy renovations to accommodate LTH from DH systems. As discussed in section 1.1.3, several challenges hinder the decision-making process of selecting suitable renovation solutions, including:

- **Lack of standardised criteria.** The absence of established standards for assessing the LTH readiness makes it difficult to identify the necessity of renovations and determine which dwellings require interventions.

- **Abundance of renovation options.** The wide range of renovation solutions at the building level can lead to decision paralysis, making it challenging to select the most suitable option for integrating LTH.

- **Heterogenous dwelling stock.** The diversity within the housing stock complicates the selection of renovation solutions. Archetype-based approaches that generalise dwelling types fail to account for variations within the stock, making it difficult to assess lower temperature readiness for specific dwellings.

- **Lack of decision support insights.** Diverse stakeholders with conflicting preferences make it difficult to reach consensus and establish shared goals. This complexity leaves decision-makers without adequate time, expertise, or a comprehensive overview to generate meaningful insights, leading to informational barriers that hinder effective decision-making.

Collectively, these challenges impede the decision-making process and complicate the selection of appropriate renovation solutions. Ultimately, they contribute to the low rate of energy renovations, representing a critical bottleneck in achieving the energy transition goals of the Netherlands.

1.2.2 Aim and Questions

The aim of this study is to aid in selecting suitable renovation solutions for integrating LTH from DH systems into existing dwellings in the Netherlands. By providing systematic decision-making support, this study hypothesises to alleviate the challenges faced in renovating dwellings for LTH. In the end, this research contributes to the broader objective of achieving a scalable and sustainable energy transition in the Netherlands.

Consequently, to effectively address the research aim, the following central question is developed:

- **How can the selection of renovation solutions that prepare diverse dwellings in the Netherlands to utilise lower temperature heat from district heating systems be systematically supported?**

The main research question is further segmented into four sub-questions designed to address the specific gaps identified in section 1.2.1 and inform the study's methodological steps.

- What factors must be considered when **selecting renovation solutions** to prepare dwellings for adopting lower-temperature heating?
- How can the **readiness** of dwellings to **utilise lower-temperature heat from district heating** be defined and assessed to identify necessary renovations?
- How can variations in building-level parameters that contribute to **diversity within the dwelling stock** be incorporated into assessing readiness for lower-temperature heating?
- How can the multi-criteria decision-making approach be utilised to **systematically support** the selection of renovation solutions for using lower-temperature heating?

1.3 Approach and Methodology

Selecting renovation solutions to prepare dwellings for LTH-based systems requires a nuanced process that considers various factors unique to each context. Accordingly, this study advocates for a systematic and adaptable approach that can be practically applied or tailored to identify suitable solutions. This approach aligns with a pragmatic philosophical worldview, which emphasises generating actionable insights to address real-world problems (Kaushik & Walsh, 2019).

Pragmatism provides both a foundation and the flexibility to incorporate diverse methodologies, methods, and data types (Creswell, 2009; Tashakkori & Teddlie, 2003), which is essential for navigating the complexities of decision-making in selecting renovation solutions. Consequently, this study employs a mixed-methods approach, combining qualitative and quantitative research methods to investigate the research problem comprehensively. Four distinct research activities were designed, each corresponding to a specific sub-research question. These activities were conducted sequentially and resulted in academic articles included as chapters in this manuscript. Figure 1.1 illustrates the relationship between research activities, methods, and chapters.

Activity 1: Identifying Factors Influencing Renovation Selection

The first activity aims to identify essential building-level parameters that influence the selection of renovation options for incorporating LTH in existing dwellings. A systematic literature review synthesises insights from previous research on LTH renovations. This review identifies key parameters, including building characteristics, applicable renovation options, and key performance indicators (KPIs), establishing a foundation for the subsequent activities.

Activity 2: Defining and Assessing Lower-Temperature Heating Readiness

The second activity focuses on defining and assessing LTH readiness in existing dwellings. Building on the findings of Activity 1, an LTH readiness definition is developed and integrated into an assessment approach to evaluate a dwelling's readiness for LTH and filter applicable renovation options. This activity employs case studies and dynamic simulation methods to test the LTH readiness assessment approach. The results from this activity are then used to label data for machine learning applications in the following activity.

Activity 3: Analysing Variations in the Dwelling Types

The third activity captures the diversity within the Dutch dwelling stock by incorporating variations among dwelling types. This activity utilises probabilistic sampling, dynamic simulations, and sensitivity analysis to generate a representative sample of dwelling types. Additionally, supervised machine learning is employed to identify the influence of dwelling characteristics on predicting LTH readiness.

Activity 4: Development of Decision-Support Framework

The fourth and final activity develops the decision-support framework using the MCDM approach and methods. It synthesises findings from the previous activities to assist in selecting the necessary renovations for preparing a dwelling for LTH-based systems. A case study is used to demonstrate the framework's application, and validation workshop with stakeholders provide essential feedback.

1.4 Research Relevance

1.4.1 Scientific Relevance

This study contributes to the current knowledge on decarbonising residential buildings by transitioning towards sustainable heating sources in the Netherlands. While Scandinavian countries such as Denmark and Sweden have extensively researched the utilisation of LTH through DH systems, the Netherlands is still at an early stage of widespread adoption. However, this shift underscores the necessity for the dwellings to prepare for an effective transition alongside the changes on the supply side (generation, distribution and delivery).

In this context, the present study offers valuable insights into the potential challenges of preparing the dwellings for heating with DH systems with lower temperature supply and the necessity of renovations. Moreover, the study introduces a comprehensive framework for selecting appropriate renovation solutions for transitioning towards sustainable heating sources. The development of the framework presents a methodological advancement by employing a mixed-methods approach integrating qualitative methods, systematic literature review and stakeholder workshops with quantitative methods, including case studies, dynamic simulations and machine learning techniques.

Additionally, the framework's novelty lies in exploring the variations within the dwelling stock. Compared to the previous studies that focused on single dwelling types or archetype dwellings, this study broadens the scope by incorporating the variations within dwelling types and investigating the solutions by addressing the heterogeneity in the residential stock. This approach allows a more nuanced understanding of adapting different dwelling types in the Netherlands for LTH-based systems.

1.4.2 Societal Relevance

The Netherlands' ambitious energy transition goals, aiming to transform 1.5 million homes by 2030, form the foundation of this study. Aligned with these national objectives, the study investigates utilising LTH supplied through DH systems as a gas-free alternative. A significant challenge lies in determining whether a dwelling is ready for this transition and, if not, identifying the necessary renovations. This challenge is particularly complex for stakeholders with extensive portfolios, such as housing associations or municipalities. Consequently, the study introduces a comprehensive framework developed to empower stakeholders in this context. The framework guides the assessment and preparation of dwellings for LTH from DH systems, enabling informed decision-making. By applying the framework, decision-making challenges could be lowered, substantially contributing to achieving the energy transition goals.

1.5 Thesis Outline

This thesis is structured into seven chapters, beginning with the current introductory chapter (Chapter 1) and concluding with a synthesis of findings and future research recommendations in Chapter 7. Chapters 2 through 6 address specific sub-research questions, as outlined in Section 1.2, with each chapter building upon the insights from the previous ones. Chapters 2–5 have either been published or are currently under review as scientific articles. The following sections briefly introduce each chapter, outlining their core objectives and connection with other chapters.

— **Chapter 2:**
Lower temperature heating integration in the residential building stock: A review of decision-making parameters for lower-temperature-ready energy renovations

The introduction chapter established the critical need to support the decision-making process in selecting suitable renovation solutions for preparing existing Dutch dwellings for LTH systems. This energy transition is essential for eliminating natural gas usage and decarbonising the built environment. Building on this foundation, chapter 2 aims to identify the factors affecting the selection of renovation solutions for using LTH in dwellings. To achieve this, a comprehensive review of the scientific literature on LTH renovations in residential buildings is conducted.

The chapter begins by introducing the decision-making challenges associated with selecting renovations for LTH implementation and outlines the objectives of the systematic literature review. Section 2.2 describes the stages and protocols employed to conduct the review systematically. Section 2.3 presents the thematic analysis results, discussing different building characteristics, organising various renovation possibilities, and summarising the key performance indicators and evaluation criteria used to assess renovation choices. Finally, Section 2.4 summarises the findings for addressing the decision-making challenges in preparing the existing dwelling stock for LTH adoption.

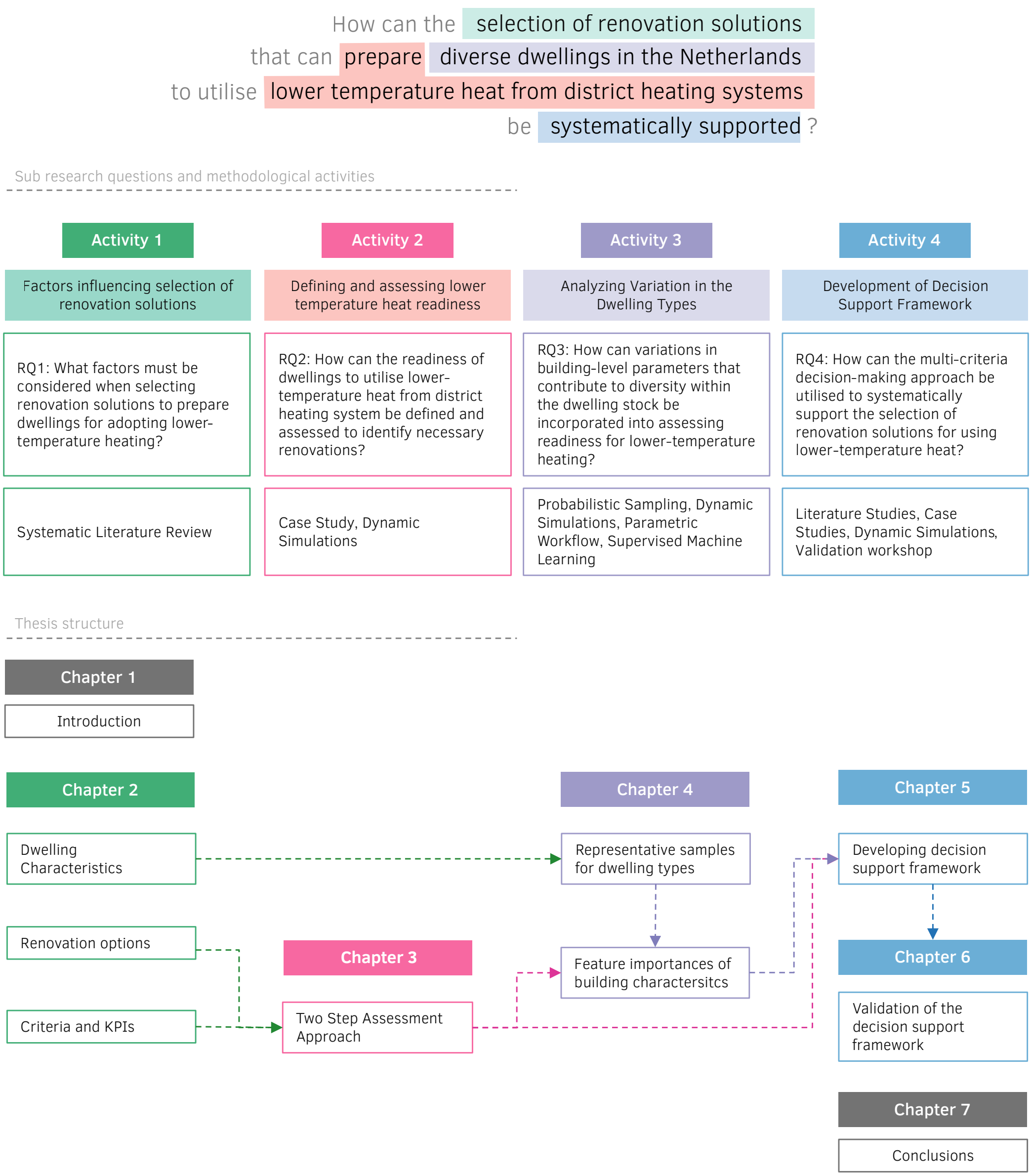

FIG. 1.1 Relationship between research questions, activities and thesis outline.

- **Chapter 3:**
  Lower-temperature-ready renovation: An approach to identify the extent of renovation interventions for lower-temperature district heating in existing Dutch homes

  In Chapter 2, the dwelling characteristics influencing the use of LTH were outlined, possible renovation options were organised, and KPIs used for evaluating these options were summarised. Collectively, these factors impact the decision-making process for selecting renovations to implement LTH. Notably, a significant gap identified was the lack of standardised criteria for assessing a dwelling's readiness for LTH. Understanding a dwelling's readiness is crucial for identifying necessary renovations. It is also essential to refine the selection of suitable solutions, given the variety of available renovation options, each with its own effects.

  To address this gap, Chapter 3 establishes criteria for assessing a dwelling's lower-temperature readiness and applies these criteria to narrow the renovation solution space. Building on insights from Chapter 2, this chapter presents a two-step approach for assessing the readiness of Dutch dwellings and determining the level of renovation intervention required to prepare them for LTH, mainly when supplied by DH systems.

  The chapter first introduces the necessity of the two-step approach.
  Section 3.2 elaborates on this approach and details the dynamic simulation method, including a case study of a terraced-intermediate dwelling built before 1945 to demonstrate the developed approach. Section 3.3 presents the results of applying the approach to the case study. Section 3.4 discusses the necessary renovations identified and explores the broader implications of the proposed approach. Finally, Section 3.5 summarises the main findings, acknowledges limitations, and suggests directions for future research.

- **Chapter 4:**
  Evaluating building-level parameters for lower-temperature heating readiness: A sampling-based approach to addressing the heterogeneity of Dutch housing stock.

  In Chapter 3, the criteria for LTH readiness were established and applied through an assessment approach to evaluate the suitability of dwellings for LTH supplied by DH systems. This approach also served to identify the extent of renovation needed and narrow down potential renovation options. By applying it to a case study dwelling, the usefulness of the approach was demonstrated in addressing two key decision-making challenges in selecting LTH renovations: the lack of a clear LTH-ready definition and the abundance of renovation options. Additionally, the approach was qualitatively extended to archetypes for the terraced intermediate type, offering generalised insights into LTH readiness. However, these generalised suggestions cannot be universally applied because variations within dwelling types lead to diverse renovation needs that demand tailored solutions. Consequently, the heterogeneity of the dwelling stock contributes to challenges in selecting suitable LTH renovation solutions.

To address these challenges, Chapter 4 focuses on incorporating variations due to building-level parameters into assessing LTH readiness. It begins by highlighting the need to account for building stock variability when determining LTH renovation solutions. Section 4.2 focuses on terraced intermediate houses and apartments, representing single-family (SFH) and multi-family housing (MFH) types, respectively. These dwelling types together make up 60% of the Dutch housing stock. Next, Section 4.3 introduces a probabilistic sampling framework. This framework generates samples based on the dwellings' characteristics identified in Chapter 2 as crucial for LTH renovation. The section explains the workflow for parametric simulation and the two-step approach from Chapter 3 for data processing and labelling. It also outlines using a machine learning algorithm to identify the importance of different features in the sample. Sections 4.4 and 4.5 present the findings from this approach and discuss their implications for assessing LTH readiness. Finally, Section 4.6 summarises the chapter with key findings, acknowledges limitations, and suggests future research directions.

— **Chapter 5: Preparing for Lower-Temperature Heating: A multi-criteria decision-making framework for energy renovations of existing Dutch dwellings.**

Previous chapters addressed the decision-making challenges in selecting suitable renovations to prepare existing Dutch dwellings to transition to LTH systems. However, renovation decision-making involves multiple stakeholders with their preferences and needs, complicating the process. While the previous chapters provided insights into the need for LTH renovations and helped narrow down solutions from various possibilities, the actual decision-making involves multiple criteria that are often conflicting in nature. Balancing these trade-offs is necessary to arrive at appropriate solutions. A potential approach to address this complexity is through MCDM methods. Consequently, the primary purpose of this chapter is to explore the utilisation of the MCDM approach to support the selection of appropriate solutions required for making dwellings ready to use LTH.

Section 5.1 introduces the decision-making challenges for LTH renovations and the potential of the MCDM approach to address these challenges. The main aim of this study is to develop a decision-support framework using the MCDM approach for selecting LTH renovations. To develop the framework, it is first essential to generalise from existing decision-making frameworks for renovations, described in Section 5.2. Next, the generalised framework is theoretically adapted for the context of LTH in Section 5.3. Once the framework is developed, it is applied to an existing case to evaluate its practical applicability, as detailed in Section 5.4. This section also presents the step-by-step application of the framework and its results. Section 5.5 discusses the insights from the case study application and its implications for solving decision-making challenges. Finally, Section 5.6 concludes the study, describes the limitations, and proposes future recommendations.

Chapter 6: Validation of the Decision-Support Framework

In the previous chapter, a decision-support framework was introduced. This framework was developed based on the MCDM approach and incorporated insights from earlier chapters to address decision-making challenges in selecting renovations for LTH-based systems. Although the framework was applied to an existing case of MFH to demonstrate its application, further validation with actual decision-makers is necessary to assess its usability in a real-world context. Therefore, this chapter describes the validation studies conducted through a workshop involving participants engaged in the decision-making process for the case study presented in Chapter 5.

The chapter begins by briefly outlining the need to validate the framework. Section 6.2 details the methodology employed for planning the validation workshop, structured into four specific phases: diagnosis, planning, facilitation, and analysis. These stages of workshop design address various aspects related to the purpose of validation, operationalised through specific questions and logistical considerations. In Section 6.3, the workshop outcomes are presented and discussed, focusing on validating the framework's usability in supporting decision-making. Finally, Sections 6.4 and 6.5 conclude the chapter by summarising the findings, discussing the limitations of the study, and proposing future recommendations.

Data availability

The data pertaining to this doctoral research, including the dataset and accompanying software/code developed to support the analyses and findings presented in the study, is available on 4TU.ResearchData and can be accessed through the following DOI: https://doi.org/10.4121/01cb2a00-3c5c-49e9-838a-900d16ddea47.v2

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2 Lower temperature heating integration in the residential building stock

A review of decision-making parameters for lower-temperature-ready energy renovations

First published as: Wahi, P., Konstantinou, T., Tenpierik, M. J., & Visscher, H. (2023). Lower temperature heating integration in the residential building stock: A review of decision-making parameters for lower-temperature-ready energy renovations. Journal of Building Engineering, 65, 105811. https://doi.org/10.1016/j.jobe.2022.105811

Aside from layout changes and minor textual changes to improve readability, this paper has not been amended for uptake in this dissertation.

ABSTRACT Lower temperature heating (LTH) involves using the lowest possible supply temperatures to meet residential heating demands, thus supporting the integration of sustainable heating sources and decarbonising the existing residential stock. However, choosing appropriate energy renovation options to prepare existing dwellings for LTH presents decision-making challenges due to the heterogeneous dwelling stock with varying building characteristics, numerous renovation options, and various performance indicators for evaluating trade-offs. This study aims to review the scientific literature on integrating LTH into existing dwellings to identify the building characteristics for evaluating the potential of using LTH and the necessity for renovations, presents a systematic method for organising renovation options and summarises key performance indicators. The study employed the SALSA (search, appraisal, synthesis and analysis) framework for systematic review and identified 24 scientific publications. Findings show that dwelling characteristics such as compactness ratio, thermal insulation, thermal bridges, airtightness, ventilation systems, space heating system capacity and supply temperature level are essential for investigating LTH potential and the need for renovations. Most research lacks qualitative renovation criteria and product-level information for selecting renovation options. Key performance indicators related to energy efficiency, thermal comfort and quality-of-services can help indicate the possible solutions, while those related to environmental and economic performance indicate the feasibility of possible solutions. Nevertheless, there is a lack of standard set of criteria for indicating the dwelling's readiness for using LTH. These findings can help address the decision-making challenges of selecting appropriate renovation strategies to enable the use of LTH and contribute to decarbonising the built environment.

KEYWORDS Lower Temperature Supply, Existing Residential Stock, Energy Transition, Sustainable Heating Sources, Decision-Making Process

2.1 Introduction

Globally, fossil fuels continue to be the primary sources of energy, with oil, natural gas and coal accounting for 82.21% of the total primary energy sources, resulting in 34.8 billion tonnes of fossil fuel-related CO_2 emissions in 2020 (BP, n.d.; Karakurt & Aydin, 2023). Comparatively, the European Union (EU27) is responsible for 7% of the total fossil fuel consumption, with households being one of the three dominant final energy consumers (28%) (BP, n.d.; Eurostat, 2020). The majority of this energy is used to meet domestic heating requirements, with around 64% for space heating and 15% for hot water preparation (Eurostat, 2021). Due to the predominance of fossil fuels as the energy source, approximately 20% of the greenhouse gas (GHG) emissions are attributable to the residential sector in the EU (Arregui et al., 2020). To reduce these emissions, a shift towards sustainable energy sources is necessary. One approach for achieving this is by adopting lower temperature heating (LTH) solutions. The term "LTH" represents supply temperature levels comprising medium, low and ultra-low, the definitions of which vary by country.

LTH involves operating heating systems at the lowest supply temperatures while meeting space heating and hot water demands (Q. Wang, 2016). Lower supply temperatures allow heat from sustainable sources such as geothermal, solar,

TOC

ambient and residual heat from industrial processes (Averfalk & Werner, 2018; Eijdems et al., 1999; Harrestrup & Svendsen, 2015; Nagy et al., 2014) to satisfy the low-exergy heating needs of the dwelling. In recent years, studies have investigated the potential of LTH in both newly built (Dalla Rosa & Christensen, 2011; Hasan et al., 2009; Hesaraki et al., 2015; Maivel & Kurnitski, 2014; Thorsen et al., 2011) and existing dwellings (Brand & Svendsen, 2013; Nagy et al., 2014; Østergaard, 2018; Q. Wang, 2016). The former typically have lower space heating demands that can be achieved through LTH solutions (Eijdems et al., 1999; Hesaraki et al., 2015; Maivel & Kurnitski, 2014). Existing dwellings, on the other hand, often require energy renovations to use a lower temperature supply to reach comfortable indoor temperatures through space heating (Harrestrup & Svendsen, 2015; Lidberg et al., 2019; Q. Wang, Ploskic, et al., 2015; Zajacs & Borodiņecs, 2019).

Energy renovations aim to reduce heating demands, thereby making it suitable for LTH supplied by sustainable systems (Asdrubali & Desideri, 2018; BTIC, 2020; TKI Urban energy, 2019). Many authors have further investigated different renovation options for the building envelope, space heating, hot water and ventilation systems to make existing dwellings suitable for LTH (Brand & Svendsen, 2013; Gustafsson et al., 2016; Østergaard & Svendsen, 2018; Q. Wang, Ploskic, et al., 2015). However, selecting appropriate renovation strategies for integrating LTH in a particular dwelling is a complex challenge and requires further studies.

According to Wu et al. (2017), the difficulty in choosing suitable strategies stems from a large number of demand (building level) and supply (heat supply systems) side renovation options. In addition, the challenge is exacerbated by the fact that renovation options vary by context, building type, construction profile, occupant behaviour and decision-makers' goals (Nagy et al., 2014; Wu et al., 2017). Another issue discussed by Wang et al. (2016; 2015) pertains to balancing the trade-offs associated with different renovation options. For instance, while improving only space heating systems could be a low-cost, quick-fix solution for using LTH (Brand & Svendsen, 2013), it has no potential for energy savings. Likewise, although retrofitting the building envelope can reduce the energy demand, it is frequently expensive, has a long installation time, and creates difficulties for occupants (Brand & Svendsen, 2013; Q. Wang et al., 2016). Hence, there is a need for a systematic decision-making approach for selecting renovation strategies for using LTH and eventually contributing to the energy transition of the existing residential stock.

Within the context of renovation, a systematic decision-making process includes various stages such as investigation of the problem, determining objectives and evaluation criteria, generation of alternative solutions, their evaluation and selection of the appropriate solutions (Nielsen et al., 2016; Si et al., 2016; J. J.

Wang et al., 2009). Furthermore, the same process can be extended for planning necessary actions for implementing selected renovations (Nielsen et al., 2016). Henceforth, a literature review is conducted as a first step toward addressing the challenges associated with effective decision-making regarding energy renovations for LTH.

Previous reviews considering the integration of LTH solutions have been conducted by Ovchinnikov et al. (2017), who reviewed the potential of low-temperature hydronic space heating systems and their apparent application in Russia, and Regius et al. (2021), who reviewed studies using LTH and the challenges of its application in the UK. Nevertheless, both studies were limited to the impact of lower temperatures on space heating systems. Ovchinnikov et al. compared various space heating systems and emitters against standardised performance criteria, including energy consumption, thermal performance and environmental impact. Similarly, Regius et al. reviewed the design and performance of existing heating systems with lower temperature supply in the UK. Despite the fact that both reviews ascertain the need for minimal retrofitting, such as increasing airtightness, replacing windows, changing critical radiators, and oversizing the radiators to use LTH comfortably, the studies notably lack discussion about decision-making aspects for selecting appropriate renovation strategies for heating existing dwellings with LTH. Bearing this in mind, the current knowledge base requires expansion from a renovation decision-making standpoint. As a result, the primary objective of this review is to identify essential parameters needed to be considered for selecting appropriate renovation options for LTH use.

The specific decision-making challenges related to the impact of building characteristics, applicable renovation options, selection of performance indicators and evaluation criteria may influence the selection of renovation option/s at the building level for using LTH. Hence, the primary objective could be further compartmentalised into the following sub-objectives:

- To identify the essential building characteristics that determine the requirements of a dwelling to be renovated for using LTH.
- To systematically organise the renovation options from the literature for developing a renovation solution space.
- To identify and summarise the key performance indicators and evaluation criteria that determine the selection of renovation options.

After the introduction, the paper describes the method for assembling relevant studies from scientific databases. Next, the results and discussion section first summarises different building characteristics and discusses their impact on using

LTH in existing dwellings. As previously stated, since the decision-making problem is also related to various renovation possibilities, renovation options mentioned in the selected studies are methodically summarised. Finally, a summary of the key performance indicators and evaluation criteria utilised by the studies to evaluate renovation choices is provided. The conclusion summarises the findings and further steps for addressing the decision-making challenges for selecting renovations to prepare the existing dwelling stock for LTH.

2.2 Materials and Methods

This study used a systematic literature review to identify and evaluate existing scientific articles. According to Booth et al. (2016), a systematic review ensures the review process's clarity, validity, and replicability. As a result, the review was carried out using the SALSA (Search, Appraisal, Synthesis and Analysis) framework as a systematic method (Booth et al., 2016; Toronto & Remington, 2020).
Figure 2.1 illustrates the research framework and the steps followed for conducting the review.

2.2.1 Stage 1: Search

This stage involved searching scientific databases for relevant articles with the help of key concepts and their synonyms, such as lower temperature heating, existing residential buildings, renovation options and decision-making. However, the search queries combined with the decision-making concept returned very few papers, none of which discussed the issue directly. Therefore, keywords related to decision-making were removed from the final iteration of searching databases. Figure 2.2 shows the word combinations used, excluding the decision-making keyword to create search queries, while Table A.2.1 in the appendix illustrates the exact search strings used in the databases.

Prior to stage 2, the articles discovered through the search queries were screened for eligibility. As a result, only review, journal or conference papers, and book chapters published in English before 2022 were included. Figure 2.1 summarises the number of articles identified during the preliminary screening process before stage 2.

2.2.2 Stage 2: Appraisal

After preliminary screening in stage 1, 241 articles were identified and further subjected to a more thorough evaluation. Firstly, 47 identical results were removed from the initial 241 papers during the screening stage of the appraisal. The remaining papers were then analysed for the availability of keywords, relevance of the abstract, and retrievability of papers. Finally, full papers were reviewed to eliminate papers according to the exclusion criteria. Table 2.1 depicts the articles screened, removed, and the exclusion criteria at each stage of the process, resulting in the selection of 24 papers for the synthesis stage.

2.2.3 Stage 3: Synthesis

This stage involved extracting and organising the data from the selected papers. The study employed the thematic synthesis method, where the aggregative themes were derived from the research objectives. According to Booth et al. (2016), thematically organising the extracted data can provide opportunities for consistent analysis across multiple studies. For operationalising the data collection, sub-themes were further identified depending on the maximum availability of the information. However, for organising and comparing renovation options across different studies, the review used the holistic renovation scenario methodology by Kamari et al. (2017; 2017). This methodology allows a common platform to observe different aspects together. Figure 2.1 illustrates the themes and sub-themes used to extract the data from the 24 selected articles.

2.2.4 Stage 4: Analysis

The final stage of the study included evaluating the collected data across all the studies. The analysis drew observations and compared the thematic data for identifying parameters essential for selecting strategies to use LTH. Furthermore, the results from the analysis were discussed from the perspective of decision-making for selecting options for renovating existing dwellings to use LTH.

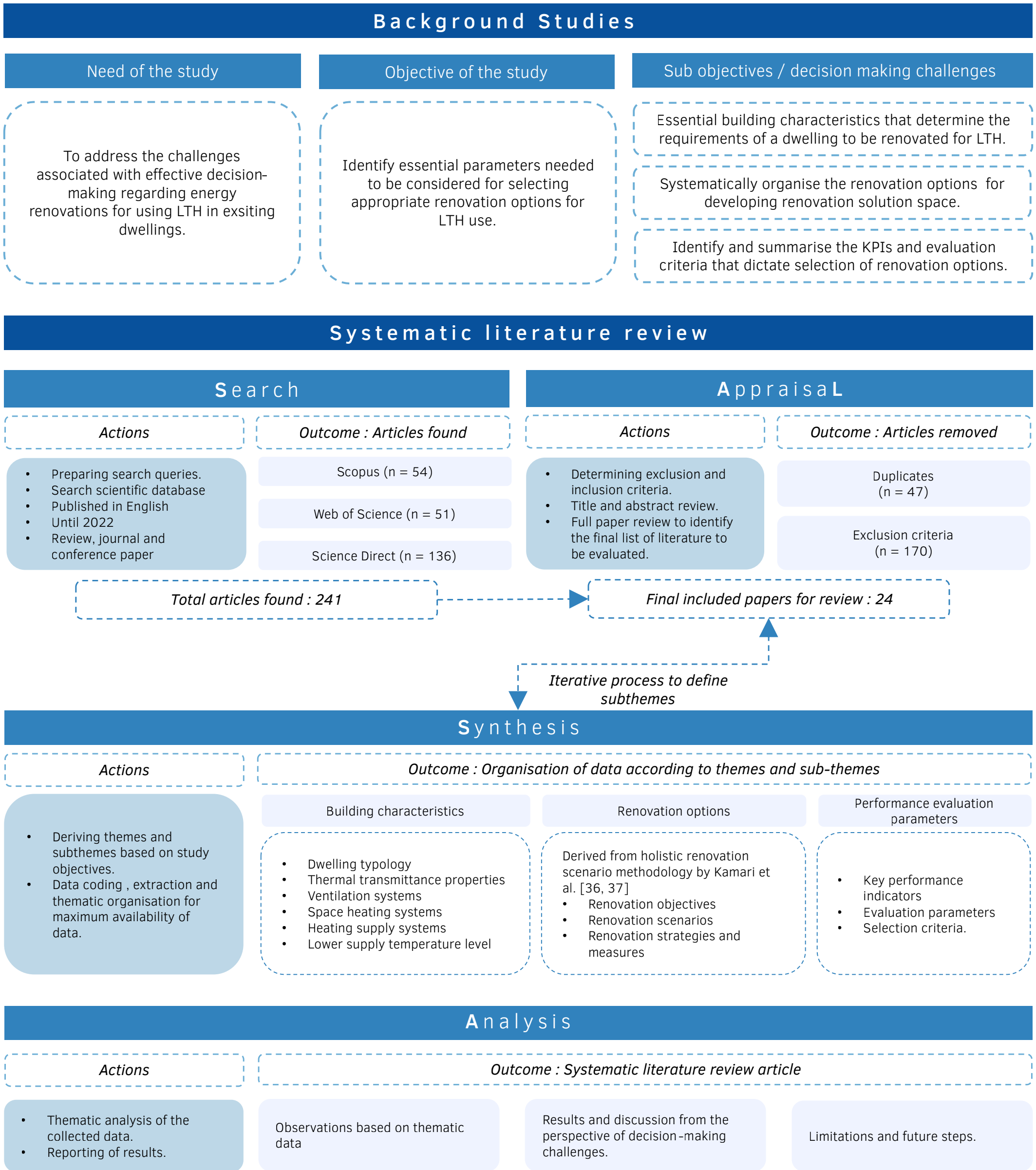

FIG. 2.1 Research framework and different steps for conducting a systematic literature review. SALSA framework adapted from Amo et al. (2018).

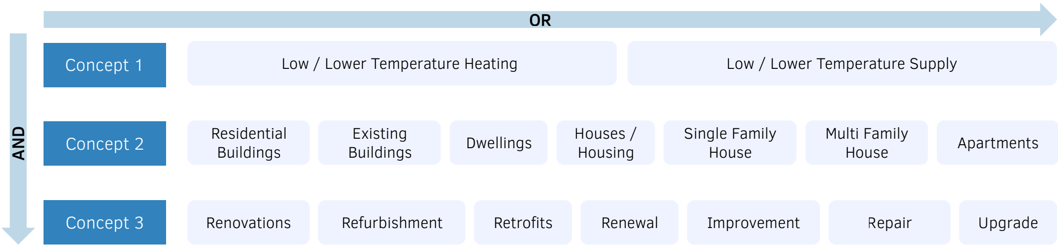

FIG. 2.2 Combination of words used for creating search queries.

TABLE 2.1 Steps used for appraising the search results. The table includes the number of articles screened and removed, along with the exclusion criteria for removing articles.

Steps	Records Screened	Records removed	Exclusion Criteria
Screening	241	47	– Duplicate records
Eligibility	194	137	– Keywords present in the title, list of keywords, and abstract but not related to the research scope – No relevance of abstract – Not retrievable
	57	16	– System design, network typologies
		9	– No relationship between LTH and renovations
		7	– Newly constructed dwellings that do not require renovations for LTH
		1	– Internal duplicity
Final papers to be included for review	**24**		

TOC

2.3 Results and Discussion

In this section, the results of the review are presented and organised according to the themes illustrated in Figure 2.1. These themes are based on the sub-objectives of the research aim discussed in the introduction. Furthermore, the thematic analysis results are discussed concerning their implications on addressing decision-making challenges for selecting appropriate renovation solutions for using LTH.

2.3.1 Overview of building characteristics

In this theme, data were extracted and analysed regarding the characteristics of the dwellings studied by different authors for using LTH. Table 2.2 illustrates the data from the literature organised based on the dwelling typology, thermal transmittance of the envelope, ventilation systems, space heating systems and criteria for selecting them for renovations. Additionally, these parameters reflect the state of the dwelling prior to any renovations considered by individual studies for integrating LTH.

TABLE 2.2 Data collection: Dwelling typologies, thermal insulation values, HVAC system and the criteria for selecting the dwellings for renovation.

Author	Country	Dwelling typology			Insulation values (U-value) [W/m^{2}K]			
		Size	Subtype	Age	Wall	Roof	Floor	Window
Anastaselos et al., 2011	Germany	-	Semi-Detached Low rise (<5 floors)	1970	3.69	1.51	1.59	4.3
				1994	0.49	0.32	0.56	2.8
Brand & Svend-sen, 2013	Denmark	SFH	Detached	1973	-	-	0.48	3.2
Q. Wang, Laurenti, et al., 2015	Sweden	AB, MFH	Low rise (<5 floors)	1946-1960	0.41	0.21	-	2.8-2.9
		AB. MFH	High rise (>5 floors)	1961-1975	0.33	0.17	-	2.3
		SFH	-	Before 1945	0.47	0.30	-	2.5
Q. Wang et al., 2016; Q. Wang, Ploskic, et al., 2015		AB, MFH (2)	Low rise (<5 floors)	1965-1975	0.48	0.26	-	2.85
Prando et al., 2015	Italy	14 typical units representative of building stock		Before 1960	1.03	-	-	5.69
				1960-1991	0.82	-	-	5.69
				After 1991	0.45	-	-	3.44
Harrestrup & Svendsen, 2015	Denmark	AB	High rise (>5 floors)	1910	1.34	0.2	1.5	2.9
		AB	High rise (>5 floors)	1906	1.34	1.2	1.2	4.5
Østergaard & Svendsen, 2016a	Denmark	SFH (4)	-	1930	0.78	0.15-0.37	-	1.5-4.3
Østergaard & Svendsen, 2016b	Denmark	SFH (3)	-	1900-1960	-	-	-	-
		SFH	-	1961-1972	-	-	-	-
		SFH	-	1973-1978	-	-	-	-
		SFH	-	1979-1998	-	-	-	-
Gustafsson et al., 2016	Sweden	AB, MFH	Low rise (<5 floors)	1961-1980	0.6	0.6	-	2.58-2.72
Terés-Zubiaga et al., 2016	Spain	AB, MFH	High rise (>5 floors)	1959-1961	0.74	2.7	2.27	2.76

	HVAC		Criteria for selection
	Ventilation system	Space heating system	
	-	Hydronic Radiators	Built before the thermal regulation of 1992.
	-		Built after the thermal regulations of 1992.
	-	Hydronic Radiators Type 21	Houses built in the 70s were designed for HT supply. Therefore, a reduction in supply temperature may cause thermal discomfort.
	Mechanical Exhaust	HT Hydronic Radiators	Residential boom during 1950-1975. These houses are at least 40 years with high final energy use.
	Mechanical exhaust with Heat recovery	HT Hydronic Radiators	
	Natural Ventilation	Electric heater	
	Decentralised exhaust air ventilation	Hydronic Radiators	During 1965-75 massive amounts of low-rise MFH were constructed. However, these houses are 40-50 years old and cannot meet energy and thermal comfort requirements.
	-	Hydronic radiators	37% of residential buildings were built before 1960.
	-		49% of residential buildings were built before 1960-1991.
	-		14% of residential buildings were built after 1991.
	Natural ventilation	Hydronic Radiators dimensioned for 70/40	Representative of a large portion of buildings in urban areas with energy-saving potential.
	Natural Ventilation	Hydronic Radiators	SFH accounts for 60% of the residential sector.
	-	Hydronic Radiators dimensioned for 90/70	
	-	Hydronic Radiators dimensioned for 80/60	
	-	Hydronic Radiatorsdimensioned for 80/40	
	-	Hydronic Radiators dimensioned for 70/40	
	Mechanical exhaust	Hydronic radiators	2.5 million MFH, out of which 75% are 40 years old. There is a need for renovation for energy-saving potential.
	-	Electric heaters	56% of 2.6 million dwellings were built before the thermal regulations of 1980. These dwellings need to be renovated to achieve a 20% reduction in primary energy.

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TABLE 2.2 Data collection: Dwelling typologies, thermal insulation values, HVAC system and the criteria for selecting the dwellings for renovation.

Author	Country	Dwelling typology			Insulation values (U-value) [W/m²K]			
		Size	Subtype	Age	Wall	Roof	Floor	Window
Wu et al., 2017	Switzerland	Detached Semi-detached Large		Before 1900	1.54	0.79	1.42	2.5
		Detached and Large		1900-59	2.04	1.29	1.18	2.5
		Semi-detached, detached and large		1960-79	1.78	1.38	1.95	2.5
		Semi-detached, detached and large		1980-99	0.53	0.33	0.56	2.5
Jin et al., 2017	Nordic countries	-	-	1975-2000	0.25	-	-	2.1
Safizadeh et al., 2019	Germany	AB, MFH	Low rise (<5 floors)	1958-1968	1.4	0.6	1	2.93
Millar et al., 2019	Scotland	Tenement flats, AB	Low rise (<5 floors)	Typical 20th century	1	2.5	0.78	5.8
Zajacs & Borodiņecs, 2019	Latvia	-	Townhouse	70s	0.85	0.8	0.8	2.21
Lidberg et al., 2019	Sweden	MFH	Low rise (<5 floors)	1965-1974	0.34	0.24	-	3.15

SFH: single-family houses, MFH: Multi-family houses, AB: Apartment Blocks, HT: High-Temperature Supply

2.3.1.1 Dwelling typologies

The dwelling typologies were defined using three subcategories: dwelling size, subtypes, and age. The typical house sizes are based on the typology matrix used by the TABULA project to harmonise national building stock across the EU (Loga et al., 2012). As a result, dwelling size includes single-family houses (SFH), terraced houses (TH), multi-family houses (MFH), and apartment blocks (AB). Additionally, dwelling subtypes such as detached, semi-detached, low-rise, and high-rise were identified. Finally, the dwelling age refers to the year of construction, which indicates the dwelling's typical construction and material properties (Ballarini et al., 2011).

Due to the heterogeneous residential stock, most studies identified typical or archetype dwellings for investigating LTH usability. Some studies selected archetypes representing dwellings that comprise a significant proportion of the existing housing stock. For instance, the high-rise AB represent a large fraction of dwellings in the urban areas of Denmark (Harrestrup & Svendsen, 2015), while the SFH constitutes the most typical dwelling type in Denmark (Østergaard & Svendsen, 2016b).

HVAC		Criteria for selection
Ventilation system	Space heating system	
-	Oil/electric heaters	Eleven representative building typologies from different construction years were selected for optimising retrofits.
-		
-		
-		
Exhaust ventilation	Hydronic Radiators radiators	85% of the buildings were constructed before 1975. A frequent problem with low indoor air temperature.
-	-	
-	-	74% of the housing stock was built pre-1982. These need to be upgraded to EPC C by 2040.
Exhaust ventilation	Convector radiator	Buildings are poorly insulated from the 70s.
Mechanical exhaust	Panel radiators	They were constructed during the million homes programme. After 40-50 years, they need renovations.

However, many studies choose representative dwellings based on typical construction years (Prando et al., 2015; Wu et al., 2017) as it indicates standard constructional styles and thermal properties of most dwellings built during that period. For example, in Sweden, 1.4 million dwellings comprising SFH, MFH, and AB were constructed en masse during the million programme (1950-1975) (Gustafsson et al., 2016; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015). Considering modern standards, these dwellings with similar constructional styles also exhibit higher energy demands, thus, requiring renovations to improve energy efficiency (Gustafsson et al., 2016; Lidberg et al., 2019; Q. Wang, Laurenti, et al., 2015).

Similarly, Table 2.2 shows that most dwellings investigated for using LTH were constructed before or around the 1970s. They are expected to perform poorly in energy efficiency, as they were built before the widespread implementation of the first thermal regulations throughout Europe (European Commission, 2020; Millar et al., 2019; Zajacs & Borodiņecs, 2019). Another important aspect relates to the position of the dwelling. For instance, the corner apartments with higher envelope areas result in higher heat losses, thus causing increased energy demand and lower thermal comfort (Safizadeh et al., 2019; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Zajacs & Borodiņecs, 2019).

From the perspective of renovation decision-making, identifying dwelling types is essential for evaluating their suitability for using LTH and proposing renovation solutions. The findings suggested identifying archetypes representative of the diverse residential stock to investigate LTH usage. For developing such archetypes, the dwelling size subcategory does not provide enough information to indicate if a dwelling can be supplied with LTH.

This could be explained due to differences in the national-level definitions of dwelling sizes subcategories (SFH, TH, MFH, AB). In contrast, the compactness of a dwelling might better suggest the usability of LTH since it indicates the energy losses dictating the heating and cooling requirements of a dwelling (Gratia & Herde, 2003; Pacheco et al., 2012). As a result, dwellings with a higher envelope surface area in relation to their volume or useable (heated) floor area often correspond to higher heat losses. For instance, building subtypes such as detached, semi-detached, and dwelling position in terraced houses and apartment blocks will significantly impact LTH use and the need for renovations. Lastly, the construction year indicates the dwelling's thermal properties and typical constructional style. These parameters are essential to estimate the energy performance of the dwelling and the possibility of renovations to make a dwelling suitable for LTH, respectively.

2.3.1.2 Building envelope characteristics

The utilisation of LTH for comfortably heating homes depends on the space heating demands and the ability of the space heating systems to compensate for it (Østergaard & Svendsen, 2016b). However, with a lower supply temperature, the heating capacity of the space heating systems designed for a higher temperature (HT) supply is often reduced (Østergaard & Svendsen, 2018; Ovchinnikov et al., 2017). As a result, a mismatch between higher space heating demands and reduced heating capacity of the space heating systems could cause thermal discomfort for the occupants (Figure 2.3).

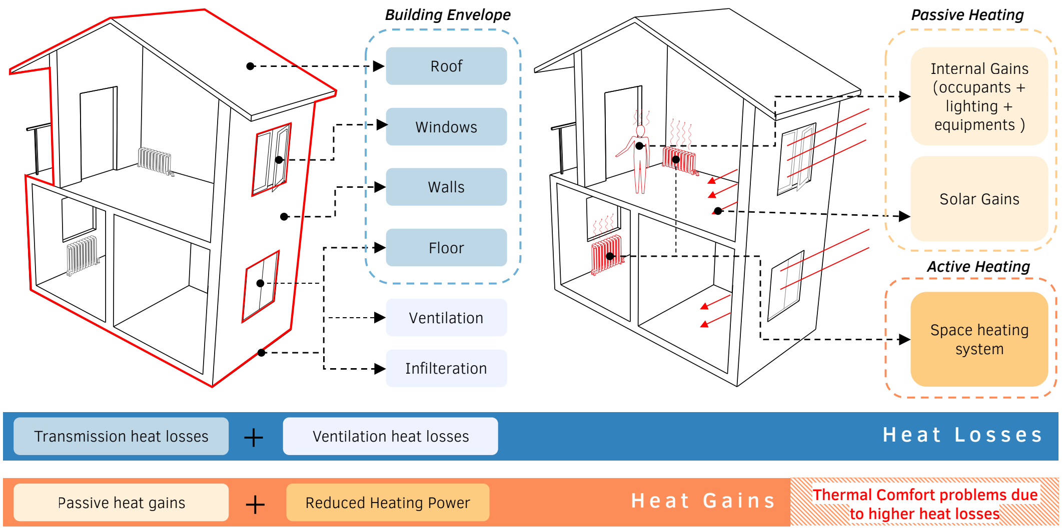

FIG. 2.3 Thermal comfort problems due to higher heat losses and inability to compensate them by heat gains due to reduced heating power of the space heating systems under lower supply temperatures.

Space heating demands are governed by the building envelope's transmission, infiltration and ventilation heat losses, combined with solar and internal gains (Østergaard & Svendsen, 2016b; Q. Wang, Laurenti, et al., 2015), even though solar and internal gains are often ignored for system sizing. The energy loss factors through a building envelope correspond to its orientation, shape, compactness ratio, and thermo-physical properties (Oral & Yilmaz, 2002; Pacheco et al., 2012). However, for existing buildings altering orientation and shape is difficult. Therefore, the building envelope's compactness ratio and its thermal properties are essential factors for determining the usability of LTH.

The impact of the compactness ratio on building heat losses is well documented in the literature (Gratia & Herde, 2003; Hemsath & Bandhosseini, 2015; Pacheco et al., 2012; Parasonis et al., 2012). It is often calculated as the ratio between the building envelope surface area and its usable heated area (Parasonis et al., 2012) or between the envelope surface area and the volume of the building (Omrany & Marsono, 2016; Pacheco et al., 2012). In either definition, a dwelling with a compact form has lower heat losses and eventually lower heating demands (Pacheco et al., 2012; Parasonis et al., 2012). In other words, dwellings such as single-family houses, would experience higher heat losses than multi-story dwellings (Parasonis et al., 2012). As a result, it can be argued that dwellings with a lower compactness ratio would require more renovation interventions on the building envelope to curb heat losses for using LTH. Similarly, in apartment buildings, dwellings located on the corner with higher envelope areas result in higher heat losses, thus impacting the use of LTH for comfortably heating dwellings (Safizadeh et al., 2019; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Zajacs & Borodiņecs, 2019). Therefore, the compactness ratio is an essential parameter to be considered while evaluating the possibility of using LTH, although it is not widely discussed within the selected literature studies.

The thermal transmittance of the building envelope is another essential parameter for determining the space heating demands from the transmission losses. Figure 2.4 illustrates the thermal transmittance values of the building envelope components of the dwellings investigated by different authors. It can be observed that, generally, windows have the lowest insulation values (i.e. highest U-Values), indicating the presence of single glass units (Østergaard & Svendsen, 2016b) or older double-glazing units (Q. Wang, Laurenti, et al., 2015). Next to the windows, the external walls or façade of the opaque part of the building envelope have lower insulation values (higher U-values). Therefore, the thermal insulation of the building envelope acts as a barrier to transmission heat losses, thus, impacting the use of LTH. Combined with the transmission loss, heat is also dissipated through the poor airtightness of the envelope and ventilation requirements of the dwelling.

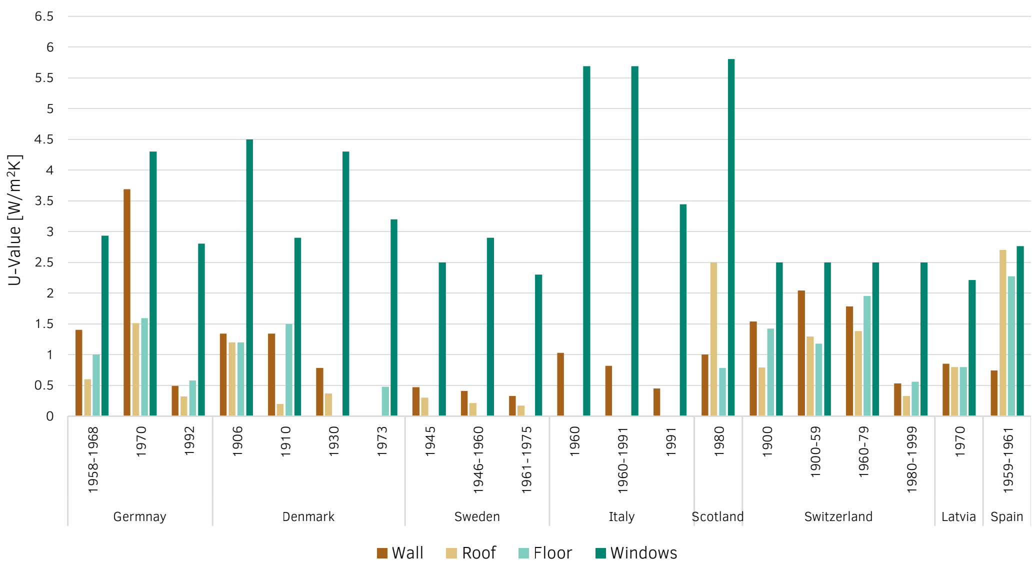

FIG. 2.4 Insulation (U-Value) of building envelope of the dwellings investigated by different authors before renovations. The data belonging to individual studies can be found in Table 2.2.

2.3.1.3 Ventilation systems

The ventilation heat losses caused by air infiltration through cracks and joints of the building envelope and the systems used to introduce fresh air can substantially affect the energy efficiency and indoor air quality of a dwelling (Hesaraki, 2015; Itard, 2012a). The infiltration rate of a dwelling depends on the constructional quality dictating the airtightness of the dwelling. As a result, existing dwellings are expected to have lower airtightness resulting in higher heating demands and local comfort problems such as cold draught (Gillott et al., 2016).

The ventilation systems utilised in a dwelling typically depend on its type (low rise or high rise) and the ventilation needs of the dwelling, as specified by local building standards and guidelines (Linden & Erdtsieck, 2013). Natural, mechanical, balanced and hybrid systems are examples of typical ventilation systems. In natural ventilation systems, fresh air is supplied and exhausted via adjustable grilles and windows (Itard, 2012a; Linden & Erdtsieck, 2013), while in mechanical systems, this is achieved through ventilators or vertical channels (Itard, 2012b; Linden & Erdtsieck, 2013). Another variation of this system is a balanced ventilation system with both mechanical supply and exhaust and a heat recovery unit (Itard, 2012a). Lastly, hybrid systems provide ventilation by switching between natural and mechanical modes based on outdoor conditions (Kostka, 2017).

As observed in Table 2.2, the dwellings constructed before the 1950s are equipped with natural ventilation (Harrestrup & Svendsen, 2015; Østergaard & Svendsen, 2016a; Q. Wang, Laurenti, et al., 2015), whereas those constructed after with mechanical exhaust systems (Gustafsson et al., 2016; Jin et al., 2017; Lidberg et al., 2019; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015; Zajacs & Borodiņecs, 2019). However, only one instance of heat recovery combined with exhaust ventilation was found (Q. Wang, Laurenti, et al., 2015), and no studies utilising hybrid ventilation systems were found. According to Hesaraki (2015), ventilation heat losses account for 20-60% of the total heat loss in a dwelling, depending on the dwelling type and its properties. Consequently, it is essential to consider the effect of heat losses due to ventilation when renovating dwellings to minimise heating demands for using LTH.

2.3.1.4 Space heating systems

Regarding space heating systems, conventional hydronic radiators are generally designed to operate at higher temperatures of 90/70 °C. Nevertheless, in some cases from Denmark and Sweden (Harrestrup & Svendsen, 2015; Østergaard & Svendsen, 2016b) the radiator was designed for lower temperatures of 70/40 °C, as required by national regulations. As mentioned in section 2.3.1.2, the space heating system's heating output designed for higher supply temperatures will be reduced under lower supply temperatures (Østergaard & Svendsen, 2018; Ovchinnikov et al., 2017). Significantly, higher heat losses in existing dwellings and the reduced heating capacity of the radiators may result in thermal comfort issues for the occupants. However, many authors assert that existing radiators designed for HT supply are frequently over-dimensioned due to having been designed for extreme conditions as well as due to a lack of consideration for solar or internal heat gains, part-load operation in a year, reduction in energy demands due to renovations and reduced heating days resulting from climate change (Østergaard & Svendsen, 2016b, 2018; Ovchinnikov et al., 2017; Reguis et al., 2021). As a result, it is essential to evaluate the possibility of existing radiator systems for adequately heating a dwelling even when the temperature supply is reduced.

2.3.1.5 Heat generation systems

The heat generation systems investigated by different authors were further categorised as collective, individual, or combined systems. In this study, collective systems represent the centralised heat generation on a neighbourhood level, commonly known as district heating (DH) (Lund et al., 2014; Niessink, 2019). A DH system distributes heat through insulated pipes or heat networks using water as a medium to meet space heating and hot water demands (Lund et al., 2014; Niessink, 2019). It is considered an efficient and cost-effective way of delivering heat to dense urban areas where many houses can be connected to the heat network (Averfalk et al., 2017; Zach et al., 2019).

Table 2.3 shows that most studies using the DH system were conducted in Sweden or Denmark. The prime reason is the early uptake of DH technologies with supply temperatures lower than 100˚C in those countries, also referred to as the third generation of DH technology (Averfalk et al., 2017). In addition, the vast majority of the buildings there are already connected to DH networks. For instance, around 40% of single-family houses in Denmark are connected to the DH (Østergaard & Svendsen, 2016b), while 35% of the multi-family houses in Sweden are connected to the DH network (Q. Wang, Ploskic, et al., 2015). Therefore, the usability of lower-temperature DH would largely depend on the available infrastructure.

On the other hand, individual systems, such as boilers and heat pumps, correspond to locally installed heat generation systems in a dwelling. Several authors have investigated the transition from fossil fuel-based to individual electric solutions (Anastaselos et al., 2011; Nagy et al., 2014) either due to a lack of DH networks (Terés-Zubiaga et al., 2016) or higher connection costs to DH networks because of poor dwelling conditions (Millar et al., 2019). In contrast, some authors have also investigated the combination of collective and individual systems for meeting residential heating demands (Gustafsson et al., 2016; Jansen et al., 2021; Lidberg et al., 2019; Q. Wang et al., 2016).

Regarding the existing heating supply system, most apartment blocks found in the studies are served by district heating systems with local substations that include circulation pumps to maintain hydronic circulation throughout the building (Q. Wang et al., 2016; Q. Wang, Ploskic, et al., 2015). Simultaneously, most single-family homes rely on individual heating systems to meet their heating needs (Ovchinnikov et al., 2017). However, it cannot be concluded that the size or type of the building has any bearing on the heating supply system chosen, as this would depend on the availability of infrastructure capable of providing lower temperature heat.

TABLE 2.3 Data collection: Different authors investigated primary heating systems, heating sources, and existing high supply temperatures. The table also indicates the new lower supply temperature levels studied by different authors.

Author	Country	Existing High-Temperature Heating			Lower Temperature Heating		
		Supply system	Heating source	Temperature (supply/re-turn) in ˚C	Supply system	Heating source	Temperature (supply/re-turn) in ˚C
Collective Systems							
Brand & Svend-sen, 2013	Denmark	3GDH	-	70/40	4GDH	100% re-newable heat source	50/24[1]
Q. Wang, Laurenti, et al., 2015	Sweden	3GDH	Bio-mass-based CHP	75/50	4GDH	Bio-mass-based CHP	MT: 55/45[2] LT: 35/28[2]
		Electric heating	Electricity, Swedish mix	-			
Q. Wang, Plos-kic, et al., 2015		3GDH	Biomass, biogas, sew-age sludge and surplus heat from the industrial process as CHP sources	75/50	3GDH	Biomass, biogas, sew-age sludge and surplus heat from the industrial process as CHP sources	45/40[2]
Prando et al., 2015	Italy	3GDH	Biomass boiler	90	3GDH	Biomass boiler	65[2]
Harrestrup & Svendsen, 2015	Denmark	3GDH	-	70/40	4GDH	-	55/25[1]
Østergaard & Svendsen, 2016a	Denmark	Gas boilers	Natural gas	70/40	4GDH	-	50/27[1]
Østergaard & Svendsen, 2016b	Denmark	Fossil fuel-based burners or 3GDH	Fossil fuels: coal, coke, oil or natural gas	90/70 to 70/40	4GDH	-	55/35[1]
Zajacs & Borodiņecs, 2019	Latvia	3GDH	Natural gas-fired water boilers	75/55	4GDH	Natural gas co-gener-ation unit and wooden biomass water boiler and natural gas water boiler	55/35[2]
Østergaard & Svendsen, 2019	Denmark	3GDH	-	80/45	4GDH	-	55/30[2]
Individual Systems							

>>>

TABLE 2.3 Data collection: Different authors investigated primary heating systems, heating sources, and existing high supply temperatures. The table also indicates the new lower supply temperature levels studied by different authors.

Author	Country	Existing High-Temperature Heating			Lower Temperature Heating		
		Supply system	Heating source	Temperature (supply/re-turn) in ˚C	Supply system	Heating source	Temperature (supply/re-turn) in ˚C
Anastaselos et al., 2011	Germany	Low-efficien-cy natural gas boiler	Natural gas	Supply more than 100	Infrared heating	Electricity	Supply<100
Nagy et al., 2014	Switzerland	Conventional boilers	Oil	55	Heat Pumps	Electricity	40[1]
Terés-Zubiaga et al., 2016	Spain	Electric heaters	Electricity	-	Gas boilers	Natural gas	60[1]
Millar et al., 2019	Scotland	Gas boiler	Natural gas	82/71	Boiler with HP	Natural gas and elec-tricity	65[1]
Combined Systems							
Q. Wang et al., 2016	Sweden	3GDH	Swedish mix	75/50	Heat pump for space heating, DH for hot water	Electricity	LT:45[2] ULT:35[2]
Gustafsson et al., 2016	Sweden	3GDH	Swedish mix	78	DH with HP	Swedish mix for DH and electricity	55[2]
Lidberg et al., 2019	Sweden	3GDH	-	78	DH with HP	-	55/25[2]
Jansen et al., 2021	Netherlands	Collective and individ-ual	Natural gas grid and electricity grid	HT thermal grid Supply > 65 Return: 45	3GDH	-	MT[2] Supply>55 Return: 35
					4GDH	-	LT[2] Supply: 30-35 Return: 20-25
					4GDH	-	ULT[2] Supply: 12-20 Return: 5-12

1: maximum supply temperature reduction achieved from the highest level of renovations.
2: fixed lower temperature levels considered for evaluation.

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2.3.1.6 Lower supply temperature level

Analysing the temperature provided by the supply systems from Table 2.3, it was observed that most of the higher temperature levels correspond to the supply temperature of 90-70°C, with return temperatures between 70-40°C. The reduced supply temperature investigated by different authors was either fixed for evaluation (Gustafsson et al., 2016; Jansen et al., 2021; Lidberg et al., 2019; Østergaard & Svendsen, 2019; Prando et al., 2015; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015; Zajacs & Borodiņecs, 2019) or was achieved after the highest level of renovations (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Millar et al., 2019; Nagy et al., 2014; Østergaard & Svendsen, 2016a, 2016b; Terés-Zubiaga et al., 2016).

The studies also found that the limiting factor for supply temperature reduction after renovations often relates to the preparation of hot tap water. For instance, the space heating demand with extensive renovations and efficient heating systems can be met by the supply system temperatures as low as 30°C (Østergaard & Svendsen, 2017). However, to prevent the risk of legionella growth, water must be heated to at least 60°C for hot tap water (Østergaard & Svendsen, 2017). In cases where the supply temperatures are lower than 60°C, heat can be upgraded through additional systems such as instantaneous heat exchangers, booster pumps or UV lamps to treat water (Brand & Svendsen, 2013; Østergaard, 2018). However, these additional systems often run on electricity, resulting in additional primary energy consumption (Brand & Svendsen, 2013; Q. Wang, Laurenti, et al., 2015).

The review of different studies further indicates a defragmented definition of lower supply and return temperatures to be considered for using LTH. Lower supply temperatures depend on supply systems (individual or collective), which are governed by available heat sources and countrywide infrastructure and regulations. Furthermore, reducing the supply temperature for LTH must be carefully selected as it will impact the necessity of additional systems for upgrading the heat for space heating or hot water. These additional systems may further affect the investment cost, primary energy consumption and environmental performance. Therefore, the range of supply temperatures must be based on the direct use of heat for space heating and hot water (Figure 2.5).

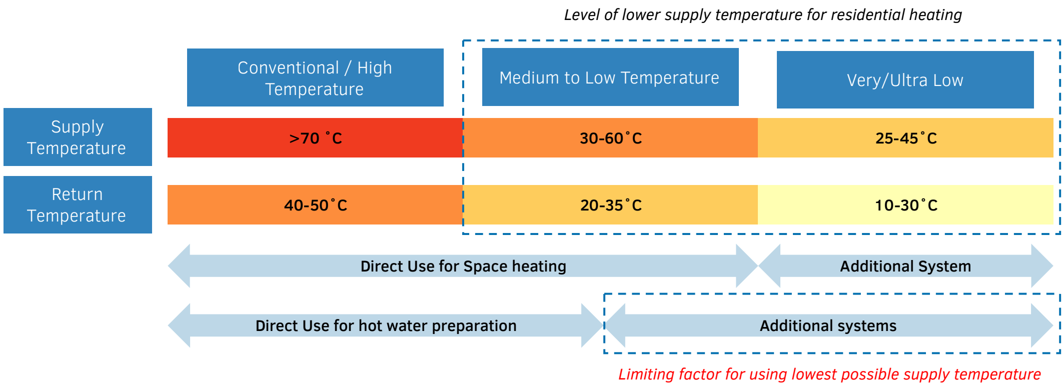

FIG. 2.5 Range of supply and return temperatures for lower temperature heating based on direct and indirect use of heat for space heating and hot tap water.

2.3.2 Overview of renovation options for using LTH

Developing viable strategies for retrofitting existing housing stock to accommodate lower temperature heating is a significant challenge (Q. Wang et al., 2016). One reason is that technical solutions are abundant on both the supply and demand sides. This issue can be resolved by systematically organising the renovation options needed for using LTH. Moreover, a well-organised solution space may facilitate the selection of retrofit options tailored to the specific needs of the dwelling in question. Thus, the renovation options investigated in the selected studies were organised systematically using the methodology for generating holistic renovation scenarios by Kamari et al. (2017; 2017). Figure 2.6 illustrates an adapted version of the methodology with its four essential components.

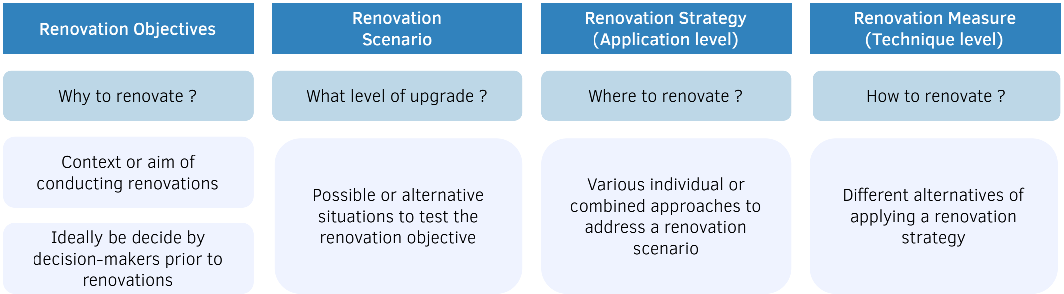

FIG. 2.6 Methodology for organising renovation options investigated by different authors. The methodology is adapted from Kamari, Jensen, et al. (2017).

The renovation objectives can be defined as the context or purpose of the renovations and should ideally be established by decision-makers before developing renovation scenarios (Kamari et al., 2018). After establishing the renovation objectives, various renovation scenarios can be developed as alternative situations to evaluate these objectives and determine the level of upgrade required to achieve the renovation goals (Kamari & Corrao, 2018). A renovation scenario can be segmented into distinct renovation strategies and measure combinations (Kamari et al., 2018), where a renovation strategy is either individual or a combination of different renovation approaches, while renovation measures correspond to various techniques within a renovation strategy (Kamari et al., 2018; Konstantinou, 2015). Additionally, the renovation measures can be extended to include available products with specific properties such as cost, thermal properties and environmental product declarations to aid the selection of renovation options in the decision-making process.

Table A.2.2 in the appendix illustrates the data extracted from the selected literature studies and organised using the methodology described above to comprehend the objectives of renovations, the scenarios for achieving the objectives, and the various renovation strategies and measures that comprise the scenarios.

2.3.2.1 Renovation objectives

Using the Soft System Methodology (SSM) and Value Focused Thinking (VFT), Kamari et al. (2017) identified three broad categories of sustainability-focused renovation objectives comprised of Functionality, Accountability, and Feasibility. These categories enable decision-makers to assess the quantitative and qualitative aspects of renovation options. The three categories are further subdivided into 18 sustainable-value-oriented criteria that indicate the performance indicators that must be used to evaluate a renovation scenario (Table 2.4).

TABLE 2.4 Sustainability objectives and value-focused criteria for developing holistic renovation scenarios. Adapted from Kamari, Jensen, et al. (2017).

Functionality	Accountability	Feasibility
Technical, environmental and used resources	Architectural, cultural, human and community	Financial, process management and education
Quantifiable (Hard Criteria)	Qualitative (Soft Criteria)	Mixed (Quantitative and Qualitative)
Indoor Comfort	Aesthetic	Investment Cost
Energy Efficiency	Integrity	Operation & Maintenance Cost
Material & Waste	Identity	Financial Structures
Water Efficiency	Security & Safety	Flexibility & Management
Pollution	Sociality	Innovation
Quality-of-services	Spatial	Stakeholders' Engagement & Education

Table 2.5 summarises the renovation objectives and associated value-oriented criteria identified from the selected literature studies. Under the quantitative functionality objective, the indoor comfort criterion assesses the impact of renovations on thermal comfort due to LTH. Furthermore, the energy efficiency criterion focuses on minimising operational or primary energy consumption, while materials & waste refer to the environmental impact of renovations due to direct or indirect embodied emissions. Finally, quality-of-services corresponds to maintaining lower supply and return temperatures in the heating supply systems.

Thirteen studies have looked at the functionality objective, the majority of which focused on energy efficiency and indoor comfort criteria. This corresponds to the studies examining the utilisation of LTH by lowering supply temperatures in conjunction with energy renovations while maintaining an acceptable level of indoor thermal comfort (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Nagy et al., 2014; Safizadeh et al., 2019; Q. Wang, Ploskic, et al., 2015). In some studies, the criteria for achieving energy efficiency and indoor comfort with lower temperatures also included assessing the renovation options' environmental impact (Millar et al., 2019; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015). However, few studies assessed indoor comfort associated with LTH without requiring renovations (Østergaard & Svendsen, 2016a; Zajacs & Borodiņecs, 2019).

TABLE 2.5 Renovation objectives and criteria investigated by different authors for using LTH.

Authors	Functionality				Feasibility
	Indoor Comfort	Energy Efficiency	Material & Waste	Quality-of-Services	Financial Structures and Investment Costs
Anastaselos et al. 2011	x	x	x		x
Brand & Svendsen, 2013	x	x		x	
Nagy et al., 2014	x	x			
Wang, Laurenti, et al., 2015		x	x		
Wang, Ploskic et al., 2015	x	x			
Wang et al., 2016	x	x	x		
Prando et al., 2015		x			x
Harrestrup & Svendsen, 2015	x	x		x	
Østergaard & Svendsen, 2016a	x	x		x	
Østergaard & Svendsen, 2016b		x			
Gustafsson et al., 2016		x	x		x
Terés-Zubaiga et al., 2016	x	x			x
Wu et al., 2017		x	x		x
Jin et al., 2017	x				
Safizadeh et al., 2019	x	x			
Millar et al., 2019		x	x	x	
Zajacs & Brodinecs, 2019	x				
Lidberg et al., 2019		x		x	

The feasibility renovation objective consists of criteria evaluating the economic viability of renovations for using LTH, where financial structures correspond to the affordability or payback period of the renovations. At the same time, investment costs include the cost incurred during the application of the renovations. A total of five studies evaluated the feasibility of the renovations in conjunction with the functional objectives. All five studies evaluated the feasibility of renovations for using LTH from a holistic or integrated perspective, taking into account the energy performance, thermal comfort, environmental and economic benefits over the life of the dwelling (Anastaselos et al., 2011; Gustafsson et al., 2016; Prando et al., 2015; Terés-Zubiaga et al., 2016; Wu et al., 2017).

The analysis of the identified renovation objectives shows that the current literature is limited to the quantifiable criteria of functionality and feasibility, and no direct relation was found between the qualitative criteria of accountability as renovation objective. Therefore, it is argued that the soft criteria should also be involved in selecting renovation options from the holistic decision-making perspective.

2.3.2.2 Renovation scenarios

The renovation scenarios investigated by various studies (Table A.2.2 in appendix) mostly begin with the base case scenario when evaluating renovations for LTH. The base case scenario is frequently referred to as the no-renovation stage or as-built condition of the dwelling (Anastaselos et al., 2011; Brand & Svendsen, 2013; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015; Wu et al., 2017) because it is used to ascertain the existing performance of the dwelling and ultimately develop the benchmarks for further evaluations. Next to the base case, the authors investigated scenarios with only one strategy (Nagy et al., 2014; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015) or with different strategies to evaluate the combined effect (Brand & Svendsen, 2013; Gustafsson et al., 2016; Harrestrup & Svendsen, 2015; Wu et al., 2017).

The scenarios that investigated combined strategies are often classified as “basic, minimum, or minor”, “light, intermediate, or partial,” or “deep, extensive or ambitious” (Brand & Svendsen, 2013; Gustafsson et al., 2016; Harrestrup & Svendsen, 2015; Millar et al., 2019; Safizadeh et al., 2019; Terés-Zubiaga et al., 2016). The minimum or minor renovations could relate to changing the radiator systems only to provide thermal comfort with LTH (Østergaard & Svendsen, 2016a; Zajacs & Borodiņecs, 2019). Even though the solutions are quick and cheap, with minor inconvenience to the occupants, they have a minimal impact on energy savings (Brand & Svendsen, 2013). On the other hand, the light renovations would correspond to selected improvements to the building envelope, mainly with window improvements, as they can provide significant energy benefits with a comparatively small investment (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015). This level could also include improving the ventilation systems, airtightness and thermal bridges (Safizadeh et al., 2019; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Q. Wang, Ploskic, et al., 2015). Finally, extensive renovations result in the most significant changes to the building with maximum energy savings while incurring high costs and inconvenience for the occupants (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Safizadeh et al., 2019; Terés-Zubiaga et al., 2016).

For developing renovation scenarios with relevant strategies, it is necessary to determine the depth of the renovations, which is defined as the extent of renovation interventions necessary to achieve a predetermined level of performance (Kamari et al., 2019). Some literature defines the depth of renovations to achieve operational or primary energy savings due to renovations in a given year (Hermelink et al., 2019; Kamari et al., 2019), commonly implemented measures in practice (Nagy et al., 2014; Østergaard & Svendsen, 2016b; Prando et al., 2015; Q. Wang, Ploskic, et al., 2015) or the percentage of envelope renovated (Bouwbesluit, 2021, Chapter 5).

Although, it can also be argued that the depth of renovations may stem from the constructional limitations of the dwelling depending on the construction year and compactness ratio. Therefore, determining the depth of renovations is an essential step in the decision-making process from the perspective of making renovation scenarios for evaluating different strategies required to integrate LTH.

2.3.2.3 Renovation strategies and measures

The renovation scenarios indicate renovation strategies and specific measures for achieving the renovation objectives, where renovation strategies are the different approaches to addressing a renovation scenario, and renovation measures are the alternative techniques for a particular renovation strategy. A wide-ranging list of numerous strategies for renovating an existing building was developed by Kamari and Corrao (2018), where 26 categories of renovation strategies were identified through a comprehensive review of the literature, various databases and European renovation projects.

Table 2.6 illustrates the different renovation strategies investigated by the studies, which were divided into building envelop, system and control levels. The strategies at the building envelope level focused on reducing the heat losses due to transmission, infiltration and ventilation. The system-level strategies correspond to approaches focused on improving the efficiency of active systems for space heating, hot water, ventilation, heating supply and electrical systems. Finally, the control level includes strategies for indoor setpoint temperature or maintaining the supply and return temperature from the heating systems. Table 2.7 and Table 2.8 summarise the renovation strategies and corresponding measures investigated by different authors applicable to building envelopes, systems and services.

TABLE 2.6 Renovation strategies for using LTH identified from the selected literature.

Authors	Building Envelope			Systems					Control
	Insulation Approaches	Window & Door Replacement	Airtightness and Thermal Bridges	HVAC (SH)	HVAC (DHW)	HVAC (Ventilation)	Heat Generation Systems	Electrical Systems	
Anastaselos et al. 2011	x	x					x		
Brand & Svendsen, 2013	x	x	x	x					x
Nagy et al., 2014	x	x	x						
Wang, Laurenti, et al., 2015	x	x	x	x				x	
Wang, Ploskic et al., 2015	x	x	x	x		x			
Wang et al., 2016				x		x	x		
Prando et al., 2015	x	x		x		x			
Harrestrup & Svendsen, 2015	x	x				x			x
Østergaard & Svendsen, 2016a				x					
Østergaard & Svendsen, 2016b	x	x							
Gustafsson et al., 2016	x	x		x	x	x	x		
Terés-Zubaiga et al., 2016	x	x		x			x		x
Wu et al., 2017	x	x					x		
Jin et al., 2017				x					
Safizadeh et al., 2019	x	x	x						x
Millar et al., 2019	x	x					x		
Zajacs & Brodinecs, 2019	x	x	x			x			x
Lidberg et al., 2019	x	x		x		x	x		

TABLE 2.7 Renovation strategies and measures investigated by authors at the building envelope level. Different standards used by authors are indicated.

Renovation Strategies	Renovation Measures	Component	EnEV09	EnEV 2016	Passive House	SIA 380 Target	SIA 380 Limit
Insulation Approaches	Higher insulation values for opaque elements. Insulation values to comply with country-specific standards.	Façade (W/m^2K)	0.28	0.25	0.14	0.25	0.15
		Roof (W/m^2K)	0.2	0.2	0.11	0.25	0.15
		Floor (W/m^2K)	0.2	0.32	0.23	0.3	0.2
Window and Doors Replacement	High-performance glazing is often (DGU or TGU) accompanied by changing frames with better insulation. Insulation values to comply with country-specific standards.	Windows (W/m^2K)	1.3	1.2	0.89	1.3	0.9
	Replacing windows that exceeded 30 years of service life.						
	PVC, aluminium Window frames						
Airtightness	Often followed by improved window frames. The airtightness values to comply with country-specific standards	Airtightness (1/h)	-	0.2-0.1	0.1-0.05	0.4	0.3
Envelope (Exterior and Interior Finishes)	Increasing insulation thickness						
	Plaster insulation						
	Aerogel thickness						
Solar Gain	Sun shading systems						
Thermal Bridges	Sealing all joints and intersections between the balcony and external wall.						

TABLE 2.8 Renovation strategies and measures investigated by authors for building services and systems.

Renovation Strategies	Renovation Measures
HVAC (Space Heating)	Existing Radiators
	Low-Temperature Radiators
	Low-Temperature Radiators with add-on fans
	Low-Temperature Ventilation Radiators
	Baseboard Radiators
	Infrared Panels
	Underfloor Heating Systems
HVAC (Hot Water Preparation)	Showering Heads
	Flow Reducing Taps
	Instantaneous Heat Exchanger
	Heat Pump Boosting at Substations
HVAC (Ventilation)	Mechanical Ventilation with Heat Recovery
	Ducts and Air Handling Units
Heat Generation Systems	High-Efficiency Gas Boiler
	Condensing Boiler
	Biomass Boiler
	Ground Source Heat Pump
	Water Source Heat Pump
	Exhaust Air Heat Pump
	Low-Temperature District Heating
	Photovoltaic Panels
	Solar Thermal Collectors
Electrical Systems	Efficient Lighting
	Efficient Circulation Pump for Hydronic System
Controls	Indoor Operative Temperature Control between 19-22˚C
	30K-20K Temperature Difference between Supply/Return.

From the analysis, it is observed that for using LTH, most of the studies investigated the strategies applicable to the building envelope, where upgrading the window can be considered a low-hanging fruit due to the fact that new windows with better insulation and airtightness can reduce space heating demands with relatively less investment (Brand & Svendsen, 2013; Konstantinou, 2015). At the system level, strategies to upgrade the space heating system are often combined with envelope strategies, followed by ventilation strategies. Few studies have also investigated the combination of space heating and ventilation strategy through measures such as ventilation radiators (Jin et al., 2017; Lidberg et al., 2019; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015). However, there is a probability that the ventilation radiator will interfere with the otherwise well-balanced mechanical ventilation system in the house (Ovchinnikov et al., 2017). Therefore, it is essential to identify the conflicts between different approaches while selecting renovation strategies. From identifying the different renovation measures, it was observed that most studies are limited at the strategy level. However, in practice, it is essential to understand the exact techniques required for deciding on renovations. Therefore, it is argued that the renovation measures must be elaborated with product-level information in the decision-making process for analysing renovation options to select them effectively for using LTH.

2.3.3 Overview of performance evaluation parameters

The methodology of organising renovation options discussed in section 2.3.2 inherited the decision-making aspect of evaluating renovation scenarios and selecting strategies and measures for using LTH. As mentioned before, the stakeholder must determine the renovation objectives and criteria before the renovation process. These objectives can also dictate the selection of key performance indicators (KPIs) that enable evaluating possible renovation scenarios and quantifying the progress towards achieving the renovation goals (Kamari et al., 2018; Kylili et al., 2016). Furthermore, the KPIs provide opportunities to identify the trade-offs due to the concurrent effects of various renovation strategies and measures. Therefore, this thematic category summarises the various KPIs, associated evaluation methods, and selection criteria used by the studies to assess the renovation options for using LTH.

Table 2.9 summarises the different KPIs found in the selected studies, where they are organised based on the renovation objective and value-oriented criteria identified in section 2.3.2.1. In addition to the KPIs, the table also shows the various evaluation methods used by the authors to quantify the KPIs and subsequent selection criteria to determine benchmarks or limiting values for choosing particular renovation options. For instance, some authors evaluated the impact of renovation options on thermal comfort using the PMV/PPD model as an evaluation method and selected the one with the performance within the acceptable range according to the ASHRAE or ISO standards (Anastaselos et al., 2011; Safizadeh et al., 2019; Q. Wang, Ploskic, et al., 2015).

TABLE 2.9 Key performance indicators and evaluation parameters used by different authors to investigate the performance of renovation scenarios. The tab

Renovation Objective		Key Performance Indicator	Evaluation Method	
Category	Criteria			
Functionality	**Indoor Comfort**	Thermal Comfort	Predicted Mean Vote (PMV)	
			Predicted Mean Vote (PMV) based Percentage of People Dissatisfied (PPD)	
			% Hours below set point temperature as discomfort hours due to underheating	
			Operative temperature fluctuations	
			Annual floor surface temperature	
			Thermal sensation survey according to ISO 2005	
		Indoor Air Quality	CO_2 concentration	
			Percentage Dissatisfied (PD) due to air quality	
			Relative Humidity (RH)	
	Energy Efficiency	Final Energy Consumption	Space heating energy/ demand and heat losses	
			Heat Losses	
			Space heating peak loads	
			Space Heating capacity of emission systems	
			Annual Net energy demand for space heating, hot water and electricity	
		Total Primary Energy Consumption	Total Primary energy consumption	
		Prebound Effect	The ratio between theoretical and actual energy savings after renovations	

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le also provides information on the selection criteria as benchmarks used by different authors.

Selection Criteria	Authors
Within acceptable range according to ASHRAE standard 55.	Anastaselos et al., 2011; Safizadeh et al., 2019
At least 15% PPD, according to ISO 7730.	Q. Wang, Ploskic, et al., 2015
Lowest % of discomfort hours compared to the base case.	Harrestrup & Svendsen, 2015; Safizadeh et al., 2019; Terés-Zubiaga et al., 2016; Zajacs & Borodiņecs, 2019
Comfortable temperature range 20-24˚C according to Swiss standard SIA 2024.	Nagy et al., 2014
Operative temperatures 0.5 ˚C below set point temperatures for identifying critical radiators.	Østergaard & Svendsen, 2016a
1˚C allowable variation limit according to ASHARE for drifts and ramps.	Q. Wang, Ploskic, et al., 2015
Annual floor surface temperature ranges from 21-28.5˚C for bare feet.	Q. Wang, Ploskic, et al., 2015
	Jin et al., 2017
CO_2 concentration within 700 ppm from annual outdoor CO_2 concentration.	Q. Wang, Ploskic, et al., 2016
Below 20% PD.	Q. Wang, Ploskic, et al., 2016
Acceptable RH range according to ASHRAE: 25-60%.	Q. Wang, Ploskic, et al., 2016
The highest energy savings compared to the base case.	Anastaselos et al., 2011; Brand & Svendsen, 2013; Millar et al., 2019; Nagy et al., 2014; Østergaard & Svendsen, 2016b, 2016a
The highest reduction in heat losses compared to the base case.	Safizadeh et al., 2019
The highest reduction in space heating peak loads compared to the base case.	Harrestrup & Svendsen, 2015
If heating capacity could compensate for space heating demands.	Østergaard & Svendsen, 2016b
Compared to the base case or following country regulations. Swedish BBR limitations for annual net energy demand. Non-electrically heated: 90kWh/m^2 Electrically heated: 55 kWh/m^2 Danish building regulations limitations: (52.5+1650/A) kWh/m^2, A is the heated area.	Harrestrup & Svendsen, 2015; Lidberg et al., 2019; Prando et al., 2015; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015; Wu et al., 2017
The highest primary energy savings compared to the base case.	Anastaselos et al., 2011; Gustafsson et al., 2016; Terés-Zubiaga et al., 2016; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015; Q. Wang, Ploskic, et al., 2015
Evaluating the effect of occupants on energy consumption after renovations.	Terés-Zubiaga et al., 2016

TABLE 2.9 Key performance indicators and evaluation parameters used by different authors to investigate the performance of renovation scenarios. The tab

Renovation Objective		Key Performance Indicator	Evaluation Method	
Category	Criteria			
Functionality	Material & Waste	Environmental Impact Categories	Emissions for impact categories Climate change: CO_2 eq. Acidification: SO_2 eq. Eutrophication: PO_4 eq. Photochemical oxidation: C_2H_4 eq.	
			16 environmental impact categories according to IPCC 2013 GWP 100a and ILCD 2011 midpoint+ methods	
		Embodied Energy and GHG Emissions	Estimation of Embodied energy and GHG emission for all the materials in retrofit options	
		Break-Even Years	Timespan required by the primary energy savings by a retrofit option to offset embodied energy of the retrofit	
		CO_2 Emissions		
	Quality-of-Services	Supply/Return Temperatures	Lowest Supply Temperature	
			Lower supply/return temperature regime	
			Difference between supply and return temperatures	
			Logarithmic mean temperature difference (LMTD) between supply and return temperatures. Calculated for each room and average of the entire house	
Feasibility	Financial Structures	Net Present Value (NPV)	Long term economic performance of renovation scenario using NPV	
			Calculated using the methodology of EU244/2012 and computed according to EN15459:2009	
			Discounted payback period using NPV	
	Investment Costs	Investment Costs	Life cycle cost analysis (LCCA)	
			LCC as a function of investment costs and operation costs in two scenarios: 1. Retrofit and energy system upgrades combined. 2. Retrofit prior to energy system upgrade	
			Retrofit costs evaluated using Swiss building energy and retrofit tool	

le also provides information on the selection criteria as benchmarks used by different authors.

	Selection Criteria	Authors
	The highest reduction in emissions compared to the base case and evaluated using LCC methodology for 30 years life span.	Anastaselos et al., 2011
	Analysing the positive and negative effects of renovation strategies on impact categories.	Q. Wang, Ploskic, et al., 2016
	Comparison of the impact of retrofit option on energy savings with embodied energy and GHG emissions.	Q. Wang, Laurenti, et al., 2015; Wu et al., 2017
	Lowest time span.	Q. Wang, Laurenti, et al., 2015
	The highest reduction in CO_2 emission due to renovations compared to the base case.	Gustafsson et al., 2016; Millar et al., 2019
	Lowest supply temperature to maintain the setpoint temperature.	Brand & Svendsen, 2013b; Millar et al., 2019
	Maintaining a lower supply/temperature regime of 55/25°C for most parts of the year.	Lidberg et al., 2019
	Maintaining a 30K temperature difference for most of the year due to the existing capacities of DH networks.	Harrestrup & Svendsen, 2015
	LMTD of a room above average LMTD of the dwelling indicates the presence of critical radiators.	Østergaard & Svendsen, 2016a
	Positive NPV for an evaluation period of 30 years.	Anastaselos et al., 2011
	Minimum NPV for an evaluation period of 30 years.	Prando et al., 2015
	The minimum period taken by the savings due to renovations to repay investment costs.	Gustafsson et al., 2016; Terés-Zubiaga et al., 2016
	Lowest LCCA for an evaluation period of 30 years.	Gustafsson et al., 2016
	Lowest LCC for a period of 30 years.	Terés-Zubiaga et al., 2016
	Minimum retrofit costs in a period of 50 years.	Wu et al., 2017

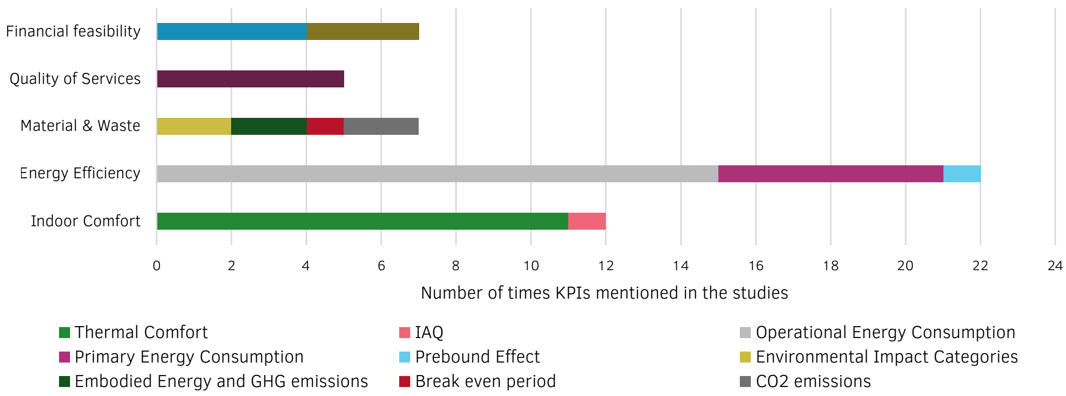

FIG. 2.7 KPIs used by different studies for evaluating the renovation options. The KPIs are arranged based on the renovation objectives described in section 2.3.2.1. The KPIs related to indoor comfort, energy efficiency, material & waste and quality of services correspond to the functionality objective, while KPIs for financial feasibility correspond to the feasibility objective.

As previously discussed, there is a direct relationship between the renovation objectives and criteria and the KPIs used to evaluate them. For example, Figure 2.7 shows that most studies used energy efficiency and indoor comfort KPIs, similar to the trend of renovation objectives and the criteria investigated by different studies, as shown in Table 2.5.

Regarding energy efficiency, the majority of studies assessed operational energy consumption, which corresponds to heating demands or net energy use due to space heating, hot water, and electrical consumption (Anastaselos et al., 2011; Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Prando et al., 2015; Q. Wang, Laurenti, et al., 2015). In addition, six studies assessed the effect of the shift toward sustainable heat generation systems and LTH on primary energy consumption (Anastaselos et al., 2011; Gustafsson et al., 2016; Terés-Zubiaga et al., 2016; Q. Wang, 2016; Q. Wang et al., 2016; Q. Wang, Laurenti, et al., 2015). However, only a single study by Terés-Zubiaga et al. (2016) examined the effect of occupants on the actual energy savings after renovations. The author demonstrated the impact of the rebound effect, i.e., increased energy consumption after energy-efficient renovations, by taking into account the general tendency of occupants to set higher indoor setpoint temperatures when utilising LTH. The author concludes that a 2°C increase in the indoor heating setpoint from 19°C can reduce the expected energy savings and economic viability of the renovations. This suggests that it is essential to evaluate occupants' impact along with energy efficiency indicators to minimise the gap between the theoretical and actual energy savings while considering LTH.

In addition to energy efficiency, studies have investigated the performance of renovations on thermal comfort when using LTH for evaluating indoor comfort. For example, several studies considered the impact of renovations in maintaining operative temperatures above desired setpoint temperatures (Harrestrup & Svendsen, 2015; Nagy et al., 2014; Østergaard & Svendsen, 2016a; Terés-Zubiaga et al., 2016; Zajacs & Borodiņecs, 2019), while others evaluated using the PMV/PPD thermal comfort models (Anastaselos et al., 2011; Safizadeh et al., 2019; Q. Wang, Ploskic, et al., 2015). Nevertheless, Safizadeh et al. (2019) argue that the PMV method is unsuitable for evaluating radiant heating effects using LTH-based solutions. Furthermore, Wang et al. (2015) analysed local comfort due to LTH by assessing annual surface and floor temperatures. There was only one study, however, that assessed other aspects of indoor comfort, i.e. indoor air quality (Q. Wang et al., 2016). In addition, no study thus far has considered the acoustical or visual aspects of indoor comfort nor the effect of summer overheating after renovations because of rising outdoor temperatures and the increasing need for cooling in the dwellings.

Seven studies evaluated the environmental and economic impact of renovations for using LTH. The KPIs related to material and waste criteria included environmental impact categories of different renovation options (Anastaselos et al., 2011; Q. Wang et al., 2016), reduction in GHG or carbon emissions (Gustafsson et al., 2016; Millar et al., 2019; Q. Wang, Laurenti, et al., 2015; Wu et al., 2017) and the period required by the primary energy savings to offset embodied energy of the retrofitted options (Q. Wang et al., 2016). The KPIs related to financial feasibility included the economic viability of carrying out renovations, where the indicators were used to determine the trade-offs between investment costs, payback periods and long-term economic performance of the renovation options (Anastaselos et al., 2011; Gustafsson et al., 2016; Prando et al., 2015; Terés-Zubiaga et al., 2016; Wu et al., 2017). Finally, the KPIs for quality-of-service criteria constituted maintaining the heating system's lower supply and return temperatures. This KPI is essential in identifying the critical radiators(Østergaard & Svendsen, 2016a), the lowest supply temperature required for maintaining thermal comfort (Brand & Svendsen, 2013; Lidberg et al., 2019; Millar et al., 2019), and the temperature difference between supply and return to increase heat generation systems' efficiency (Harrestrup & Svendsen, 2015; Nagy et al., 2014).

The analysis of the identified KPIs from the literature reveals a variety of indicators and evaluation methods representing a lack of a standard set of criteria to assess the effect of renovation on LTH utilisation. From the perspective of decision-making, this can result in challenges when selecting relevant KPIs and methods for aiding any decision on renovations. The complexity is exacerbated by the fact that indicators can be definitive, comparative or both. For instance, KPIs related to indoor comfort are definitive, i.e., benchmarks or limits can be quantified based on national or international standards, while KPIs related to environmental or economic impact are comparative, i.e., a benchmark needs to be defined from a base case, and the performance of renovation options are compared to this base case. Therefore, the indicators, evaluation methods and selection criteria must be chosen depending on the decision-making boundaries stemming from the renovation objectives decided early on by the stakeholders. For example, the KPIs related to energy efficiency and indoor comfort ascertain the "possible" renovation options that could provide thermal comfort by using LTH and achieving a certain level of energy efficiency. However, the "possible" renovation options may not be "desirable" in terms of service quality or environmental performance indicators, nor "feasible" in terms of financial investments. Similarly, "desirable" strategies may not be "possible" nor "feasible." As a result, it is essential to determine the KPIs and the renovation objectives by determining the possible, desirable, and feasible boundaries.

2.4 Conclusions

The purpose of this study was to review the scientific literature on integrating LTH into existing dwellings. The study aimed to identify the parameters that can help inform the decision-making process when selecting appropriate renovation solutions for using LTH. The study employed the SALSA (search, appraisal, synthesis and analysis) framework for a systematic review to address the decision-making challenges that arise due to the heterogenous dwelling stock with varying building characteristics, a wide range of renovation solutions, and various key performance indicators for evaluating the trade-offs and selection of renovation options for using LTH.

The findings from the review suggest that dwelling characteristics such as compactness ratio, thermal insulation, thermal bridges, airtightness of the building envelope, ventilation systems, the capacity of the existing space heating system and supply temperatures are essential parameters when investigating the potential of the existing dwelling to be heated with LTH and the necessity of renovations.

The parameters indicated above can be collected for a specific dwelling case, although different archetypes representing the most typical properties could be developed for investigating the diverse residential stock. Most studies identified archetypes based on dwellings representative of different construction years. It can indicate the dwelling's standard thermal properties and prevalent construction style in the selected year. However, it is argued that a performance gap may occur when selecting representative dwellings based on construction year, as in reality, the dwellings may already be renovated to improve energy efficiency. Furthermore, no significant relationship was found between dwelling size and the usability of LTH. In contrast, the compactness ratio, which includes the dwelling size and position, might help develop archetypes when combined with typical construction years.

Another decision-making challenge is related to numerous renovation alternatives available at the building level, some of which may nullify one another's impacts, thus making selection difficult. Therefore, the study adopted a systematic approach to developing a renovation solution space by identifying renovation objectives, depth of renovations as renovation scenarios, application-level strategies and product-level measures. Although this allowed us to narrow down the options depending on the context of the dwelling, the study found that research is limited to evaluating quantitative renovation objectives, including functionality and feasibility criteria. Therefore, the soft criteria involving qualitative aspects of renovations must be considered while developing renovation objectives. Additionally, it is argued that the existing studies are also limited to evaluating strategy-level renovation options, while product-level information is essential for making effective decisions regarding selecting renovations option for using LTH.

Finally, the study summarised the various KPIs, evaluation and selection criteria used by different studies and found a lack of standard set of criteria for indicating the readiness of a dwelling for using LTH. However, the findings suggest that KPIs related to energy efficiency, indoor comfort, and quality-of-services are essential for investigating possible renovation solutions. On the other hand, environmental and economic performance KPIs are considered constraints to evaluate the feasibility of possible renovation options. Furthermore, since the renovation objectives determine the performance indicators, this study argues that the performance indicators must be selected in collaboration with the stakeholders while developing renovation objectives.

From a decision-making perspective, it is essential to identify dwelling cases and collect data on the sensitive parameters to determine and evaluate the need for renovations for using LTH. This preliminary investigation provides the decision-makers with pertinent data for determining the renovation's objectives, intervention depth, performance assessment, and selection criteria. In addition, such boundary conditions are essential for dictating the development of renovation solution space, their evaluation, and ultimately selecting the optimal solutions by balancing all trade-offs. Therefore, stakeholder participation is a crucial part of the decision-making process. However, due to the nature of the search terms used, no studies were found that included stakeholders in decision-making when selecting LTH renovations. Thus, future review studies should explore the participation of stakeholders and their requirements for selecting renovations for using LTH from a decision-making standpoint.

Appendices

A. 2.1 Search strings

TABLE A. 2.1 Search strings used on scientific databases and the number of articles found.

SCOPUS	Articles Found
TITLE-ABS-KEY (“low* temperature” PRE/2 (heat* OR supply)) **AND** TITLE-ABS-KEY (residen* OR “Residential existing building” OR (existing W/1 building) OR dwelling OR hous* OR “Single Family House” OR “Multi Family House” OR apartment) **AND** TITLE-ABS-KEY (renovation OR refurbishment OR retrofit OR renewal OR improvement OR repair OR upgrade)	**54**
Web of Science	
Web of Science TS= (“low temperature” NEAR/2 (Heat* or supply))) **AND** TS= (Residen* OR “Residential existing building” OR Existing SAME/1 Building OR dwelling OR hous* OR “Single Family House” OR “Multi Family House” OR Apartment)) **AND** TS= (Renovation OR refurbishment OR retrofit OR renewal OR improvement OR repair OR upgrade)	**51**
Science Direct	
Article with these terms (“Low Temperature Heating” OR “Low Temperature Supply”) **AND** (Residential OR House OR Dwelling OR “Single Family House” OR “Multi Family House” OR Apartment) **AND** Title, abstract or author-specified keywords (Renovation OR Retrofit OR Refurbishment OR renewal OR improvement OR repair OR upgrade)	**136**
Total Article Found	**241**

A 2.2 Data collection

TABLE A. 2.2 Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovatio

Author	Country	Dwelling Typology			Renovation Objective	
		Size	Subtype	Age	Category	Criteria
Anastaselos et al., 2011	Germany	-	Semi-Detached (2)	1970 & 1992	Functionality	Indoor Comfort
						Energy Efficiency
						Material & Waste
					Feasibility	Financial Structures
Brand & Svendsen, 2013	Denmark	SFH	Detached	1973	Functionality	Indoor Comfort
						Energy Efficiency
						Quality of Service
Nagy et al., 2014	Switzerland	AB	-	-	Functionality	Indoor Comfort
						Energy Efficiency

n scenarios as the combination of renovation strategies and measures investigated by each study.

Renovation Scenario		Renovation Strategy	Renovation Measure
Total of 6 reno-vation scenarios	Base	As built condition in 1970 and 1992	No Renovations
	A - E	Insulation Approaches	Insulation according to EnEV09
		Window Replacement	
		HVAC	5 different primary heating systems with corresponding heat emitters, including gas boilers, heat pumps and radiative panels
Total of 4 reno-vation scenarios	No Renovation (basic and advanced)	As built condition in 1973	No renovation to the building envelope
		HVAC	Original radiator and LT radiators
		Controls	Fixed supply temperature of 70˚C
			Maximum flow rate of 264 L/H
			Operative temperature of 20 ˚C and 22˚C
	Light Renovation	Window Replacement	Changing windows with 30 years of service life
		Airtightness	Improved airtightness because of better windows
		HVAC	Original radiator and LT radiators
		Controls	Operative temperature of 20 ˚C and 22˚C
	Extensive Reno-vation	Insulation Approaches	Insulating envelope and reducing linear thermal loss
		Window Replacement	Windows facing west and north with a triple-glazing unit
		Airtightness	Improved airtightness because of better windows
		HVAC	Original radiator and LT radiators
		Controls	Operative temperature of 20 ˚C and 22˚C
Total of 7 reno-vation scenarios	Individual	Window Replacement	-
		Insulation Approaches	Plaster insulation with 4cm on the north and east, 6 cm on south
			Aerogel insulation on all facades
		Airtightness	Medium
			High
	Combination 1	Window, insulation and airtightness	Plaster insulation and high airtightness
	Combination 2	Window, insulation and airtightness	Aerogel insulation and high airtightness

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TOC

TABLE A. 2.2 Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovatio

Author	Country	Dwelling Typology			Renovation Objective	
		Size	Subtype	Age	Category	Criteria
Q. Wang, Laurenti, et al., 2015	Sweden	AB, MFH	Low rise	1946-1960	Functionality	Energy Efficiency
		AB, MFH	High rise	1961-1975		
						Material & Waste
		SFH	-	Before 1945		
Q. Wang, Ploskic, et al., 2015	Sweden	AB, MFH (2)	Low rise	1965-1975	Functionality	Indoor Comfort
						Energy Efficiency
Q. Wang et al., 2016	Sweden	AB, MFH (2)	Low rise	1965-1975	Functionality	Indoor Comfort
						Energy Efficiency
						Material and Waste
Prando et al., 2015	Italy	14 typical units representative of building stock		Before 1960	Functionality	Energy Efficiency
				1960-1991		
					Feasibility	Financial Structures
				After 1991		

n scenarios as the combination of renovation strategies and measures investigated by each study.

Renovation Scenario		Renovation Strategy	Renovation Measure
13 individual scenarios	RO1-RO13	Insulation Approaches	Insulating wall, ground floor and roof/attic
		Window Replacement	High-performance glazing and frames on the south and north facade
		Airtightness	Seal all cracks and air leaks
		HVAC (SH)	Ventilation control with heat recovery
			LTH radiator with add-on fans designed for 55/45
			LTH ventilation radiator designed for 35/28
		Thermal Bridges	Balcony thermal bridges
		Electrical Systems	Efficient lighting controls
			Efficient circulation pumps for space heating
1 base case, 5 individual scenarios, 1 combined scenario	Base case	As built condition	No Renovations
	R1-R5 with LTH radiators	Insulation Approaches	New insulation layer on external walls
			New insulation on the roof and attic
		Window Replacement	High-performance glazing and window frames
		Airtightness	Upgrading the airtightness by 60% by sealing all cracks, air leaks and joints in the balcony
		HVAC (V)	Ventilation system with heat recovery
		HVAC (SH)	Ventilation radiators designed for 45/40
	Combined	All combined with LTH radiators	
1 base case, two scenarios	Base case	As built condition	No renovations
	Two combi-nations of ventilation heat recovery joined with the LTH system	HVAC(V)	Ventilation with heat recovery
		HVAC (system)	ASHP for SH
		HVAC(SH)	Ventilation radiators
			Baseboard radiators
Multiple renovation scenarios cre-ated using genetic algorithms		Insulation Approaches	Insulation of roof, walls and floors with increasing thickness from 1-20cm.
		Window Replacement	4 different alternatives for high-performance glazing
			Aluminium frames instead of wooden frames
		HVAC(V)	Mechanical ventilation with heat recovery
		HVAC(SH)	Underfloor heating system

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TABLE A. 2.2 Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovatio

Author	Country	Dwelling Typology			Renovation Objective	
		Size	Subtype	Age	Category	Criteria
Harrestrup & Svendsen, 2015	Denmark	AB	-	1910	Functionality	Indoor Comfort
						Energy Effi-ciency
		AB	-	1906		
						Quality-of-Ser-vice
Østergaard & Svendsen, 2016a	Denmark	SFH (4)	-	1930	Functionality	Indoor Comfort Energy Effi-ciency
						Quality-of-Ser-vice
Østergaard & Svendsen, 2016b	Denmark	SFH (3)	-	1900-1960	Functionality	Energy Effi-ciency
		SFH	-	1961-1972		
		SFH	-	1973-1978		
		SFH	-	1979-1998		
Gustafsson et al., 2016	Sweden	MFH	-	1961-1980	Functionality	Energy Effi-ciency
						Material and Waste
					Feasibility	Investment Cost
						Financial Struc-tures

n scenarios as the combination of renovation strategies and measures investigated by each study.

Renovation Scenario		Renovation Strategy	Renovation Measure
1 base case, 3 scenarios	Base case	As built condition	No renovations
	Window Renovations	Window Replacement	High-performance windows with solar shading
		HVAC(V)	MVHR with 85% HR
	Intermediate Renovations	Window Replacement	High-performance windows with solar shading
		HVAC(V)	MVHR with 85% HR
		Insulation Approaches	Insulating ground floor and roof only
		Control	Operative temperature of 20 ˚C and 22˚C
	Extensive Renovations	Window Replacement	High-performance windows with solar shading
		HVAC(V)	MVHR with 85% HR
		Insulation Approaches	Insulating façade, roof, floor
		Control	Operative temperature of 20 ˚C and 22˚C
Only 1 scenario		HVAC(SH)	Replacing critical radiators without renovations
2 scenarios	Light Renovations (general maintenance)	Insulation Approaches	Roof insulation
		Window Replacement	Improving windows
	Energy Renovations	Insulation Approaches	Upgrading building envelope
		Window Replacement	High-performance glazing
15 different scenarios from three renovation levels and five different configurations of the HVAC system	L0: Reference	Envelope Repair	Basic repair and maintenance, including façade repair, changing windows, tunning of radiator system and changing water taps
		Window Replacement	
		HVAC(SH)	
		Plumbing (DHW)	
	L1	Window Replacement	High-performance triple-glazing unit
		Plumbing (DHW)	Installing shower heads and flow-reducing water taps
	L2	Insulation Approaches	Wall and roof insulation
		Window Replacement	High-performance triple-glazing unit
		Plumbing (DHW)	Installing shower heads and flow-reducing water taps
	0: Existing	As built HVAC system	As built for reference
	A	HVAC System	Mechanical ventilation with heat recovery
	B		Exhaust air heat pump for SH
	C1		Exhaust air heat pump for SH and DHW
	C2		Exhaust air heat pump for SH and DHW
			Ventilation Radiators

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TOC

TABLE A. 2.2 Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovatio

Author	Country	Dwelling Typology			Renovation Objective		
		Size	Subtype	Age	Category	Criteria	
Terés-Zubiaga et al., 201	Spain	MFH	-	1959-1961	Functionality	Indoor Comfort	
						Energy Efficiency	
					Feasibility	Investment Cost	
						Financial Structures	
Wu et al., 2017b	Switzerland	Detached Semi-detached Large		Before 1900	Functionality	Energy Efficiency	
		Detached and Large		1900-59			
						Material & Waste	
		Semi-detached, detached and large		1960-79			
		Semi-detached, detached and large		1980-99	Feasibility	Investment Costs	
Jin et al., 2017	Nordic countries	-		1975-2000	Functionality	Indoor Comfort	
Safizadeh et al., 2019	Germany	MFH		1958-1968	Functionality	Indoor Comfort	
						Energy Efficiency	

n scenarios as the combination of renovation strategies and measures investigated by each study.

Renovation Scenario		Renovation Strategy	Renovation Measure
A total of 54 scenarios were generated by combining three renovation levels and different heating system strategies.	NR: No Retrofit	As built condition	No renovations
	BAU: Business as Usual	Insulation Approach	Façade and roof insulation. Intermediate and usual level of energy renovations
	BO: Best Option	Insulation Approach	Higher insulation level of roof and façade
		Window Replacement	Triple glazing unit with PVC frame
	Heating Systems	HVAC (heating system)	Two individual gas boiler systems: Low temperature natural gas boiler and condensing boilers
		Control (heat production set point)	Three set points for heat production: 60, 55, 50 °C
		HVAC (SH system)	High-efficiency radiators designed for heat production set point temperatures with adjusted lengths
		Control (comfort temperature set point)	Three Comfort set point temperatures: 19, 20, 21 °C
Multiple scenario generation using GA	Original	As built condition	No renovations
	Base case	HVAC (heating system)	5 different primary heating systems with no renovations
	Windows and Airtightness	Window Replacement	According to SIA 380 limits
			According to SIA 380 targets
	Roof and Airtightness	Insulation Approaches	Roof according to SIA 380 limit
			Roof according to SIA 380 targets
	Façade and Airtightness	Insulation Approaches	Facade according to SIA 380 limit
			Facade according to SIA 380 targets
	Whole Building	Combined	According to SIA 380 limit
		Combined	According to SIA 380 target
Two scenarios		HVAC(SH)	Ventilation radiators
			Floor heating
30 scenarios	Base case	As built condition	No renovations
	Partial Renovations	Insulation Approaches	Improved external wall according to ENEV 2016
			Improved external wall according to passive house
		Window Replacement	According to EnEV 2016
			According to passive house
		Airtightness	According to EnEV 2016
			According to passive house
	Ambitious Renovations	Insulation Approaches, Window Replacement and Airtightness	Building envelope insulation according to EnEV2016
			Building envelope insulation according to passive house
	Supply Temperatures	Control	Six supply temperatures for radiant warm ceiling

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TOC

TABLE A. 2.2 Data collection: Organisation of renovation objectives and value-oriented criteria depending on the aim of the study, followed by renovatio

Author	Country	Dwelling Typology			Renovation Objective		
		Size	Subtype	Age	Category	Criteria	
Millar et al., 2019	Scotland	-	Tenement flat	Typical 20th century	Functionality	Energy Efficiency	
						Material & Waste	
						Quality-of-Service	
Zajacs & Borodiņecs, 2019	Latvia	-	Town house		Functionality	Indoor Comfort	
Lidberg et al., 2019	Sweden	MFH		1965-1974	Functionality	Energy Efficiency	
						Quality-of-Service	

n scenarios as the combination of renovation strategies and measures investigated by each study.

Renovation Scenario		Renovation Strategy	Renovation Measure
8 scenarios with four renovation cases and two heating systems	Case 1	As built condition	No renovations
	Case 2	Window Replacement	Improving existing windows to DGU
	Case 3	Insulation Approaches	Insulating the wall only
	Case 4	Window Replacement and Insulation Approaches	Insulating walls and windows both
	Heating Systems	HVAC (heating systems)	Two heating systems if the house could not be connected to DH
3 scenarios	No Renovation	As built condition	No renovations
	No Renovation with the reduced supply tempera-ture	Control (supply tempera-ture)	Reducing the supply temperature to 55/35
	Renovations with reduced supply tempera-tures	Insulation approaches, window replacements, airtightness, HVAC (V)	Improving overall building envelope
		Control (supply tempera-ture)	Reducing the supply temperature to 55/35 °C
Five scenarios	As built	As built condition	No renovations
	A	Insulation approaches	Wall and roof insulation
		Window replacement	High-performance glazing
		HVAC system	MVHR
	B: A + radiator	HVAC (SH)	Ventilation radiators
	C: B+ primary heating system	HVAC (primary heating system)	District heating + Exhaust air heat pump for space heating only
	D: C+ Primary heating system for DHW	HVAC (primary heating system)	District heating + Exhaust air heat pump for Space heating and hot water.

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3 Lower-temperature-ready renovation

An approach to identify the extent of renovation interventions for lower-temperature district heating in existing Dutch homes

First published as: Wahi, P., Konstantinou, T., Tenpierik, M. J., & Visscher, H. (2023). Lower-Temperature-Ready Renovation: An Approach to Identify the Extent of Renovation Interventions for Lower-Temperature District Heating in Existing Dutch Homes. Buildings, 13(10). https://doi.org/10.3390/buildings13102524

Aside from layout changes and minor textual changes to improve readability, this paper has not been amended for uptake in this dissertation.

ABSTRACT This study presents an approach to determine the extent of renovation interventions required for existing Dutch dwellings aiming to transition to lower-temperature district heating (DH) systems. The proposed method is applied to a typical intermediate terraced house built before 1945 in the Netherlands and consists of two steps: first, assessing the potential of a dwelling to be heated with a lower temperature supply from DH systems and subsequently developing and evaluating alternative renovation solutions if necessary. The study defines a set of criteria for evaluating the readiness of a dwelling for lower-temperature heating (LTH), considering energy efficiency and thermal comfort as non-compensatory criteria. Application of the approach reveals that the case study dwelling is presently unsuitable for medium-temperature (70/50°C) and low-temperature (55/35°C) supply compared to a high-temperature supply (90/70°C), thus requiring energy renovations. Furthermore, the study indicates that moderate intervention levels are required for the dwelling to be lower-temperature ready in both supply temperature goals. These interventions include strategies and measures that upgrade the

building envelope to the minimum insulation levels stipulated by the Dutch building decree, improve airtightness, and replace existing radiators with low-temperature radiators. By systematically narrowing down renovation options, this approach aids in simplifying the decision-making process for selecting renovations for heating dwellings with LTH through DH systems, which could reduce stakeholders' decision paralysis.

KEYWORDS District heating systems, Lower temperature heating, Energy renovations, Existing dwellings, Decision-making process

3.1 Introduction

The Netherlands is at the cusp of an energy transition from natural gas to sustainable sources in order to meet residential heating demands. The built environment accounted for 15% of the Netherlands' total greenhouse gas emissions in 2021, of which 73.5 % was attributed to the demands of residential heating (Centraal Bureau voor de Stastiek, 2022b). These demands correspond to space heating, hot water preparation and cooking, for which approximately 90% of Dutch homes continue to rely on natural gas (Centraal Bureau voor de Stastiek, 2021). The impact of carbon emissions from fossil fuels on climate change, in conjunction with earthquakes resulting from the natural gas extraction from underground reservoirs and recent geopolitical events, has prompted the Dutch government to reconsider its reliance on natural gas or fossil fuels in general to tackle climate change and secure an affordable heat supply to combat energy poverty (Rijksoverheid, n.d., 2023). As a result, the Dutch climate agreement focuses on gradually removing natural gas for 1.5 million homes in an effort to reduce 3.4 Mton of $CO_{2;eq}$ emissions by 2030 (Dutch Ministry of Economic Affairs and Climate, 2019).

To achieve this transition, the investigation of a variety of available heating supply systems, including collective (district heating), electric (heat pumps), hybrid (collective in combination with electric) or sustainable gases (Beckman & van den Beukel, 2019; van Vliet et al., 2016), is central in replacing natural gas with a viable alternative for residential heating. The district heating (DH) systems in the Netherlands currently supply high-temperature (HT) heat, between 70 and 90°C, with high-value fossil fuels such as coal or natural gas as primary energy sources (Niessink, 2019; van Egmond, 2020). Nevertheless, there is a shift towards reducing the supply temperatures in the heat networks from HT(>75 °C) to lower temperatures (<75 °C) for meeting residential heating demands. Table 3.1 illustrates the DH temperature levels distinguished in the Netherlands based on the direct use of heat for space heating and hot tap water, along with their corresponding heat sources. In this study, the temperature levels "Medium", "Low", and "Very/Ultra Low" are collectively considered as lower supply temperature levels.

TABLE 3.1 Table 3.1 District heating supply temperatures based on heat use and its subsequent sources available in the Netherlands. The Ta corresponds to the supply temperatures. (DNE Research, 2020; Niessink, 2019; van Egmond, 2020)

Temperature Level	Supply Temperature	Use of Heat		Heat Source
		Space Heating	Hot Tap Water	
HT: High Temperature	$T_a > 75$ °C	– Direct use	– Direct use	– Combined heat and power (CHP) fired with coal, natural gas, solid waste or biomass. – Heat plants fired with biomass and natural gas. – Ultra deep geothermal energy. – Residual heat from industry, power plants and waste incineration
MT: Medium/ Middle Temperature	55 °C $\leq T_a \leq$ 75 °C	– Direct use.	– Direct use. – Heating of tap water ≥ 65 °C to prevent the risk of legionella	– Geothermal energy – Biomass boilers – Residual heat from industry, power plants and waste incinera3tion – Solar thermal and heat pumps.
LT: Low Temperature	30 °C $\leq T_a \leq$ 55 °C	– Direct use of heat only with LT delivery systems	– Upgrading heat for hot tap water	– Shallow geothermal energy – Low-temperature residual heat from the cooling process of data centres, ice rinks, and cold storage. – Solar thermal plants and heat pumps with ULT sources.
ULT: Very/Ultra Low Temperature	$T_a \leq 30$ °C	– No direct use of heat – Upgrading heat for both space heating and hot tap water		– Aquathermal from sewage and surface water. – ULT residual heat from the cooling process of data centres and supermarkets. – Solar thermal systems.

The use of the DH system has the potential to provide cost-effective heat to densely populated areas (Averfalk et al., 2017; Harrestrup & Svendsen, 2015; Zach et al., 2019). Currently, only 6.4% of households in the Netherlands are connected to a DH system (Centraal Bureau voor de Stastiek, 2022a), although it is projected that by 2050, the share of DH systems will increase to 50% (Beckman & van den Beukel, 2019). Given the vital role DH systems will play in achieving the Netherlands' energy transition goals when combined with lower supply temperatures, it is necessary to examine the integration of lower-temperature DH into the existing built environment.

On the heating supply side, reducing the supply temperature in the DH network enables the integration of sustainable heat sources (Averfalk et al., 2017; Brand & Svendsen, 2013; Dahl et al., 2017), reduces heat losses in the network and improves distribution efficiencies (Averfalk et al., 2017; Dahl et al., 2017; Schmidt et al., 2017). Meanwhile, on the demand side (i.e., *dwellings*), the use of lower-temperature heat (LTH) improves thermal comfort and indoor air quality (Eijdems et al., 1999; Ovchinnikov, Borodinecs, et al., 2017; Wang et al., 2016). The potential reduction in the DH supply temperatures depends on the dwelling's space heating and hot water demands (Østergaard & Svendsen, 2017). The space heating demand is determined according to the transmission, infiltration and ventilation heat losses combined with solar and internal heat gains, while the hot water demand is related to cooking and bathroom use (Itard, 2012). Regarding space heating, newly constructed dwellings with improved energy efficiency can address the lower demands for space heating through supply temperatures closer to ambient temperatures (Hesaraki et al., 2015). Nevertheless, challenges arise in the case of existing dwellings with high space heating demands. As the supply temperature is reduced, the heating output of the existing heat emission systems, such as radiators, also diminishes (Ovchinnikov, Borodiņecs, et al., 2017; Tunzi et al., 2016). Consequently, the reduced heating output may not compensate for the high heat losses, resulting in thermal discomfort for the occupants. Therefore, to ensure adequate thermal comfort, existing dwellings would require an HT supply from DH, which would limit reduction in the supply temperature in the DH system. Furthermore, the higher heating loads associated with existing dwellings could create bottlenecks in designing future lower-temperature DH systems based on sustainable heating sources (Harrestrup & Svendsen, 2015). As a result, existing dwellings with high heating demands may require energy renovations prior to connecting to a DH system with a lower temperature supply (Acheilas et al., 2020). In this study, energy renovations correspond to modifications at the building level to reduce the heating demands of a dwelling, thus preparing them for LTH through supply systems using sustainable heat sources (Asdrubali & Desideri, 2018; BTIC, 2020; TKI Urban energy, 2019).

Recent studies in the Netherlands indicate a growing interest towards integrating LTH from DH systems in the existing residential dwelling stock. The existing research focuses on LTH network design (Kneppera et al., 2021), sustainable energy concepts at the neighbourhood level (Jansen et al., 2021) or maximum reduction of supply temperatures in existing heating systems under design conditions (Pothof et al., 2022). However, little attention is paid towards assessing the readiness of existing dwellings to be heated with lower temperature supply from DH systems. Furthermore, identifying the level of renovation intervention required for preparing the existing dwellings for LTH integration remains unexplored. This research gap is critical for private individuals and professional parties, such as developers or housing associations, who encounter decision-making challenges when selecting suitable renovation measures specific to their context (TKI Urban energy, 2019). The decision-making landscape surrounding the selection of renovation interventions for buildings is often complex (Jafari & Valentin, 2018; Serrano-Jiménez et al., 2021) as it involves multiple, often conflicting objectives and criteria (Cajot et al., 2017; Ma et al., 2012; Pohekar & Ramachandran, 2004) alongside diverse stakeholder preferences (Jafari & Valentin, 2018; Jensen & Maslesa, 2015). To facilitate the evaluation of trade-offs among these conflicting factors, the structured approach of multi-criteria decision-making (MCDM) has been well-documented in the literature on building renovations (Amorocho & Hartmann, 2022; Granacher et al., 2022; Kamari et al., 2018; Nielsen et al., 2016; Romani et al., 2022; Serrano-Jiménez et al., 2021). This approach aids in streamlining the decision-making process by accounting for conflicting criteria and stakeholder preferences (Marttunen et al., 2015). However, the application of MCDM methods is often complex and requires the integration of multiple techniques to ensure reliable decision-making.

Furthermore, several studies emphasise the challenges arising from the availability of various renovation options and the assessment of possible combinations resulting in many alternatives, leading to decision paralysis (P. Amorocho et al., 2020; Gustafsson, 2000; Jafari & Valentin, 2017; Taillandier et al., 2016; Wu et al., 2017). Numerous studies have focused on generating alternative renovation solutions based on intervention levels derived from investment cost or construction limitations (Rosenfeld & Shohet, 1999; Serrano-Jiménez et al., 2021; Zavadskas et al., 2008), literature and empirical studies (Hashempour et al., 2020; Romani et al., 2022), and digital databases (Jaggs & Palmer, 2000) combined with algorithms (Kamari et al., 2018). However, it is still unclear how these approaches for generating alternatives can be applied to mitigate the decision paralysis caused by numerous renovation options for making existing dwellings suitable for lower temperature supply from DH systems. In addition to that, insufficient knowledge regarding available renovation options, high costs and limited customisability (D'Oca et al., 2018), lack of time and expertise to appraise the available renovation options properly (Mjörnell et al., 2014), and limited decision support based on individual preferences (Huang & Zhang, 2011; TKI Urban energy, 2019) further contribute to the decision-making struggle towards selecting appropriate renovation solutions. Consequently, to alleviate this decision-making struggle, it is essential to eliminate the solutions that are not technically desirable to comfortably heat dwellings with LTH from DH systems, given the dwelling's context. As a result, this paper aims to address these research gaps by evaluating the suitability of an existing dwelling in the Netherlands and identifying appropriate renovation options for using LTH from DH systems.

The primary objective of this study is to test an approach for determining the extent of renovation intervention necessary for preparing existing dwellings in the Netherlands to be connected with DH systems with lower temperature supply. To accomplish this, the study proposes a two-step approach. The initial step involves evaluating the suitability of utilising LTH by establishing criteria to determine the readiness of the existing dwellings. Subsequently, if the dwellings are found unsuitable for using LTH, then the lower-temperature-ready criteria can be employed to filter out potential solutions from various available options depending on the context of the dwelling. The proposed approach was applied to a typical terraced house built before 1945 to assess the readiness of the dwelling to be heated with lower temperature supplies of MT(70/50 °C) and LT(55/35 °C) from DH systems, compared to the original HT(90/70 °C) from a natural gas boiler. Additionally, if applicable, the study aims to identify and compare the renovation interventions required for preparing the case study dwelling for the two supply temperature transition goals. This study argues that the proposed approach facilitates the narrowing down of the possible renovation solutions from a diverse range of solutions, thus limiting the solution space and reducing the decision-making struggles in selecting appropriate renovation solutions for gas-free heating with LTH from DH systems.

Following the introduction, Section 3.2 provides an overview of the two-step approach, its application to the case study dwelling, exploration of various applicable renovation options, and utilisation of the dynamic simulations for analysing them. Subsequently, Section 3.3 and 3.4 illustrate both the intervention level required for the case study to be comfortably heated with LTH using the two-step approach and the broader implication of the study's findings. Finally, Section 3.5 summarises the main findings, acknowledges its limitations, and suggests future research directions.

3.2 Materials and Methods

This study proposes a two-step approach to determine the extent of renovations required by existing dwellings in the Netherlands when transitioning from HT heating supply to LTH supply from DH systems. First, the lower-temperature-ready criteria are introduced, which serve as the guiding principle for evaluating the readiness of the dwelling for LTH, followed by the proposed two-step approach. Additionally, the case study and the dynamic simulation methods utilised by the study to implement the proposed approach are described in detail.

3.2.1 Lower-temperature-ready criteria

As discussed in the Section 3.1, reducing the supply temperature also reduces the capacity of the heat emission systems initially designed for HT supply. Consequently, the inability of the heating systems to compensate for the high heat losses of the existing dwellings may result in thermal discomfort for the occupants. One strategy to address this could be by increasing the heating system's output, for instance, by adding radiator fans, although this has minimal potential for energy saving, which is counterintuitive for energy renovations (Brand & Svendsen, 2013; Wang, 2016). Additionally, our recent review on integrating LTH in existing dwellings revealed that despite lacking a standard set of criteria, a dwelling's performance or renovation options for using LTH were widely assessed based on energy efficiency and thermal comfort criteria (Wahi et al., 2023). As a result, this study proposes a definition of readiness for a dwelling to be heated with LTH from DH, which corresponds to an improvement in both the thermal comfort and energy efficiency of the dwelling compared to its existing conditions with HT supply. This definition is based on the non-compensatory decision-making model in the MCDM approach, where trade-offs between the criteria are not allowed (Hwang & Yoon, 1981; Xu & Yang, 2001). As a result, in the context of the proposed approach, different options must simultaneously satisfy the energy efficiency and thermal comfort improvement criteria to be considered technically desirable solutions for preparing a dwelling to be supplied with LTH from DH systems. This study used annual space heating demand and occupied cold hours as key performance indicators (KPIs) for evaluating the energy efficiency and thermal comfort criteria, as elaborated on in section 3.2.4.2.

3.2.2 Proposed two-step approach

The two-step approach presented in this study focuses on assessing the readiness or potential of the existing dwelling to be heated with LTH and suggests renovation options that could prepare the dwelling for the same by filtering out options that are not technically desirable. As previously discussed, the technically undesirable options correspond to renovation solutions that do not meet the criteria set by the lower-temperature-ready definition (Section 3.2.1). Figure 3.1 illustrates the overall framework of the proposed approach.

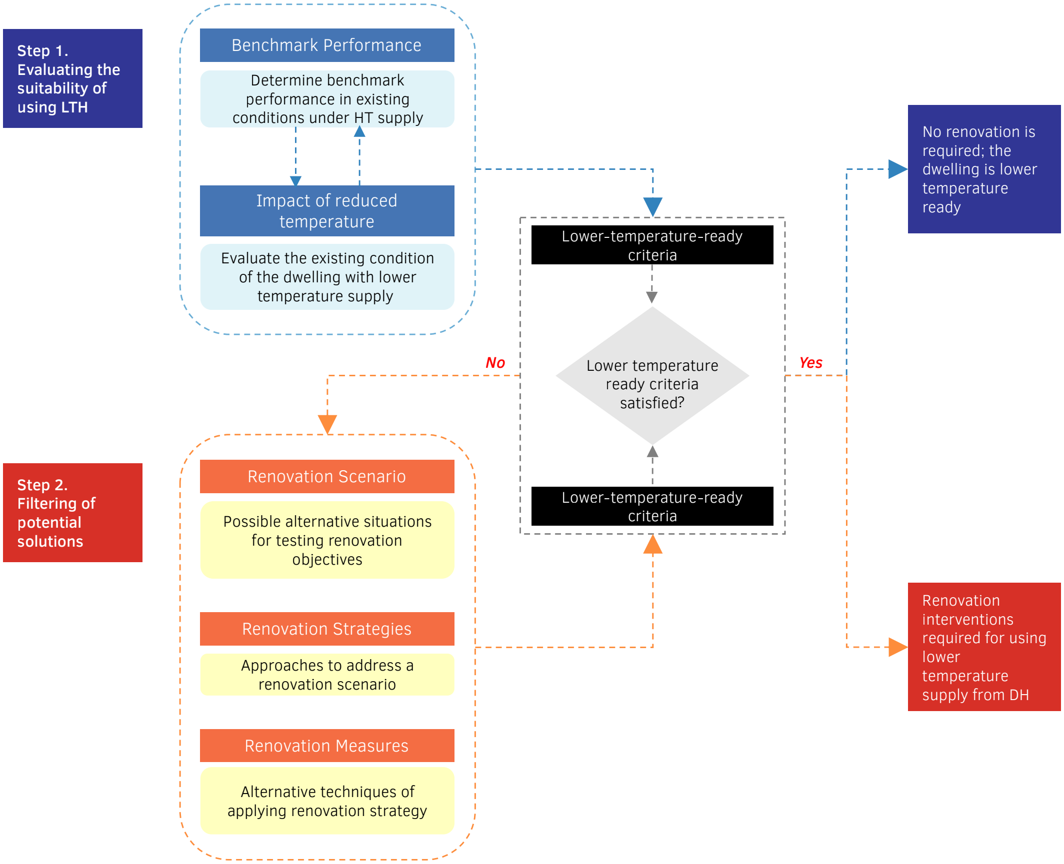


FIG. 3.1 Proposed two-step approach.

3.2.2.1 Step 1: Evaluating the suitability of using LTH

For evaluating the readiness of a dwelling to be heated with lower supply temperature from DH systems, it is imperative first to establish the benchmark performance of the dwelling's current performance with the original HT supply in terms of annual space heating demand and occupied cold hours. For the same, building diagnostics can be performed by utilising simulation models, which can be steady-state or dynamic calculation models (Jafari & Valentin, 2017; Kamari et al., 2018; Ma et al., 2012; Murray et al., 2012).

Next, the two KPIs are recalculated for the existing dwelling condition with lower supply temperatures of MT and LT and are compared with the benchmark performance of the dwelling with an HT supply. According to the lower-temperature-ready criteria described in section 2.1, if the dwelling's performance in lower temperatures does not satisfy the benchmark performance, it can be considered that the dwelling is not ready for LTH. In such a case, the next step would involve developing the renovation solution space based on the dwelling context.

3.2.2.2 Step 2: The filtering of potential solution

The renovation solution space, including all potential renovation options given the dwelling's context, is developed in this step. This study employs a scenario-based approach, in which scenarios represent alternative situations for addressing single or multiple renovation objectives (Kamari et al., 2018; Pinzon Amorocho & Hartmann, 2022). A renovation scenario can be decomposed into different renovation strategies followed by subsequent measures (Kamari et al., 2018), where a renovation strategy comprises either an individual or a combination of distinct renovation approaches. Alternatively, renovation measures correspond to various techniques within a strategy (Kamari et al., 2018; Konstantinou, 2015). Furthermore, the renovation measures can be broadened to encompass available products with specific attributes such as cost, thermal properties and environmental product declarations, thereby streamlining the process of selecting renovation options.

In this study, the objective of renovations is to prepare the existing dwellings for transitioning from existing HT supply to lower (MT and LT) supply temperatures from DH systems. As a result, the renovation scenarios are developed depending on the depth or extent of renovation interventions required to achieve the renovation objective (Kamari et al., 2019). Since every dwelling in a neighbourhood has different renovation potentials and limitations, due to varied building characteristics, envelope properties, and construction styles, three intervention levels were defined, covering different possibilities to prepare dwellings for lower supply temperatures from DH systems.

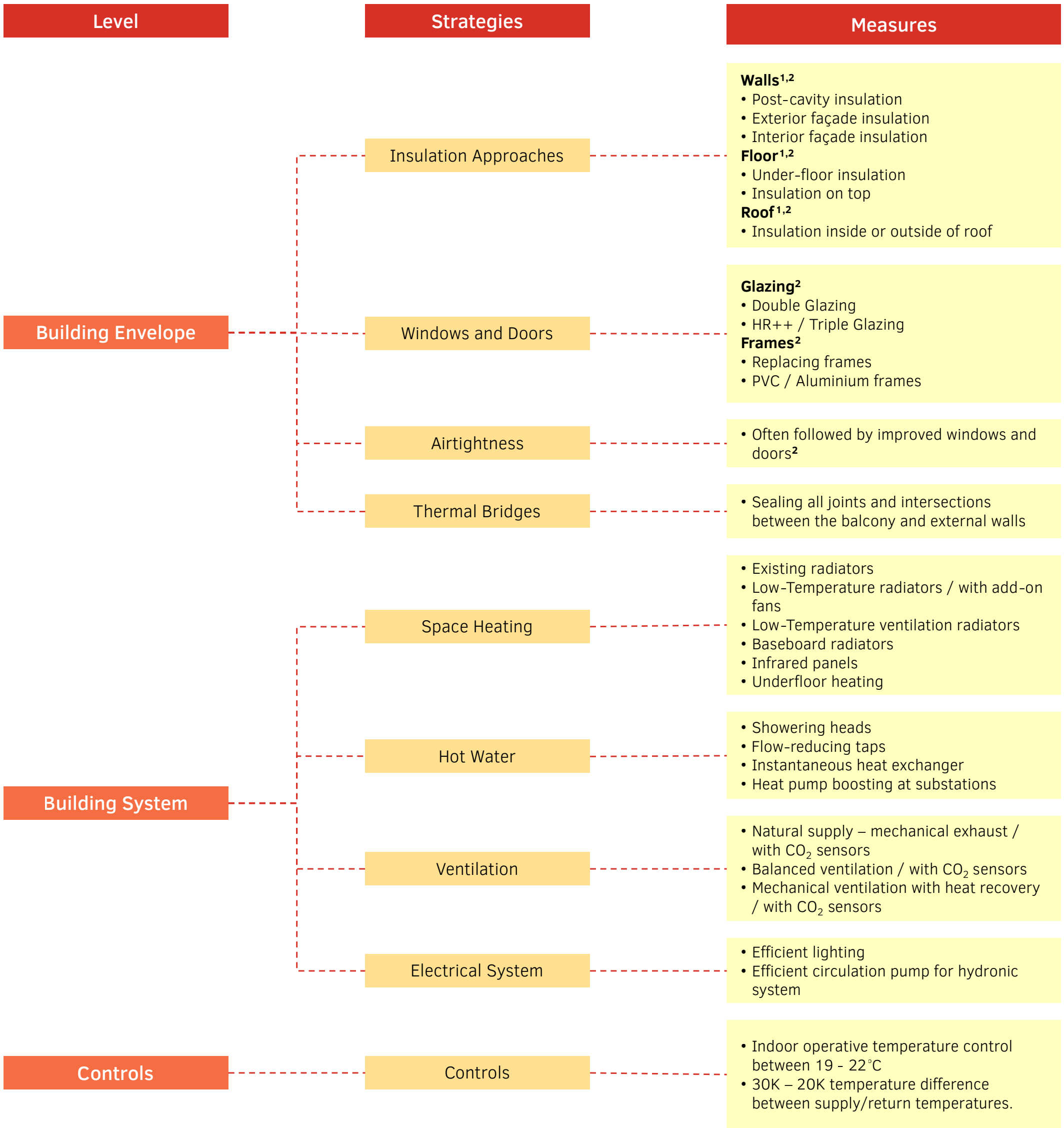
- **Basic renovation.** At this level of intervention, the primary focus of the renovation is to increase the space heating system's heat output with no modification to the building envelope.

TOC

- **Moderate renovation.** As the Dutch Building Decree (Bouwbesluit, 2021) defines, partial or moderate intervention constitutes renovations lower than 25% of the building envelope’s surface area. Some research studies (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Nagy et al., 2014) also describe this intervention level as “light renovations”, which involve specific upgrades at the building envelope level. These improvements include window replacements, post cavity insulation of walls, insulating floors or roofs. These improvements can be applied either individually or in combination.

- **Deep renovation**. In contrast to moderate renovations, the Dutch Building Decree (Bouwbesluit, 2021) defines deep renovation as interventions that address more than 25% of the building envelope’s surface area. This involves the comprehensive renovation of the dwelling involving essential changes such as the complete replacement of the existing roof. Additionally, studies (Brand & Svendsen, 2013; Harrestrup & Svendsen, 2015; Nagy et al., 2014; Wang et al., 2015) indicate that deep renovations typically entail higher insulation of the envelope, mitigation of thermal bridges, improved airtightness and upgraded ventilation systems.

Depending on the definition of intervention levels, single or multiple renovation strategies can be identified, followed by specific techniques or measures to implement these strategies, depending on the context of the dwelling in question. Figure 3.2 illustrates the different renovation strategies and measures that can be applied at the building envelope, system and control level for preparing dwellings for LTH (Konstantinou, 2015; Wahi et al., 2023). While Figure 3.3 illustrates the process of developing the renovation solutions space in relation to the scenarios, strategies and measures.



[1]Higher insulation measures considering dwelling's constructional limitations
[2]Complying with Dutch building decree.

FIG. 3.2 Selection of renovation strategies and measures applicable at the building envelope, system and control level (Konstantinou, 2015; Wahi et al., 2023).

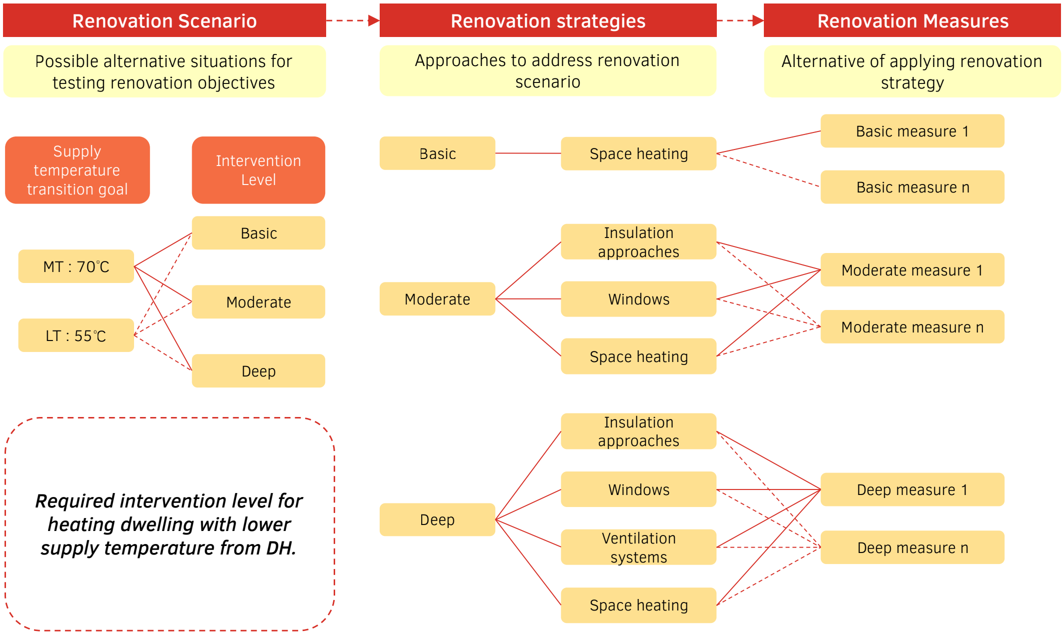


FIG. 3.3 Process of developing the renovation solutions space in relation to the scenarios, strategies and measures.

Once the renovation solution space is developed, the performance of different measures, stemming from the renovation scenarios and strategies, are quantified using the two KPIs and compared with the benchmark performances calculated in Step 1. Only those solutions or measures that demonstrate a reduction in space heating demand and occupied cold hours compared to the benchmark performance were considered technically desirable solutions for preparing the dwelling for the lower MT or LT temperature level when supplied from DH systems.

3.2.3 Case study dwelling

The dwellings with high heating demands connected to the DH system can affect the maximum reduction of the supply temperatures of the DH system. Such dwellings can negatively impact the energy and economic performance of the DH system and may also lead to higher investment costs in designing future lower-temperature DH systems using renewable energy sources (Harrestrup & Svendsen, 2015; Prando et al., 2015). Consequently, this study selected a case study dwelling of a typical Dutch intermediate terraced house constructed in 1938. Terraced houses, or “rijwoningen” in Dutch, account for 42% of the total residential dwelling stock in the Netherlands (Centraal Bureau voor de Stastiek, 2022c; Rijksdienst voor Ondernemend, 2023). As illustrated in Figure 3.4, 30% of these terraced dwellings were built before 1945 (Centraal Bureau voor de Stastiek, 2022c) with an average energy label of “G” (Van Beijnum & Van den Wijngaart, 2023), exhibiting high heating demands. As a result, it is argued that these dwellings would require energy renovations in order to utilise a lower temperature supply from DH systems. Additionally, analysing them under different lower supply temperature transition goals, will provide insights into the minimum renovation requirements necessary for the worst-performing dwellings in the neighbourhood, to prepare them for heating with LTH supplied from the DH systems.

FIG. 3.4 A typical terraced house constructed prior to 1945. The red box illustrates the dwelling’s intermediate (in-between) position within the adjoining row houses (Rijksdienst voor Ondernemend, 2023).

3.2.4 Dynamic simulation models

Dynamic simulations were performed to analyse the impact of lower supply temperatures on the dwelling case, using DesignBuilder® V7.0 bundled with EnergyPlus® V9.4 as simulation tools. The building profile data of the case study dwelling was acquired from the ‘LT Ready’ research project by TU Delft, where the case study dwelling was renovated in 2020 as part of the project (van den Brom & van den Ham, n.d.). Therefore, calibrated models[3] were prepared with the renovated conditions of the dwelling, and later reverted to illustrate the characteristics before

3 Calibrated using the statistical index recommended by ASHRAE guidelines (Ruiz & Bandera, 2017).

renovations. The dwelling characteristics before and after the renovation (Table A.3.1), the input parameters used to create the simulation model (Table A.3.2), and calibration results (Section A.3.3) can be found in the appendix. Figure 3.5 depicts the spatial characteristics, heating conditions, size and type of radiators for each thermal zone.

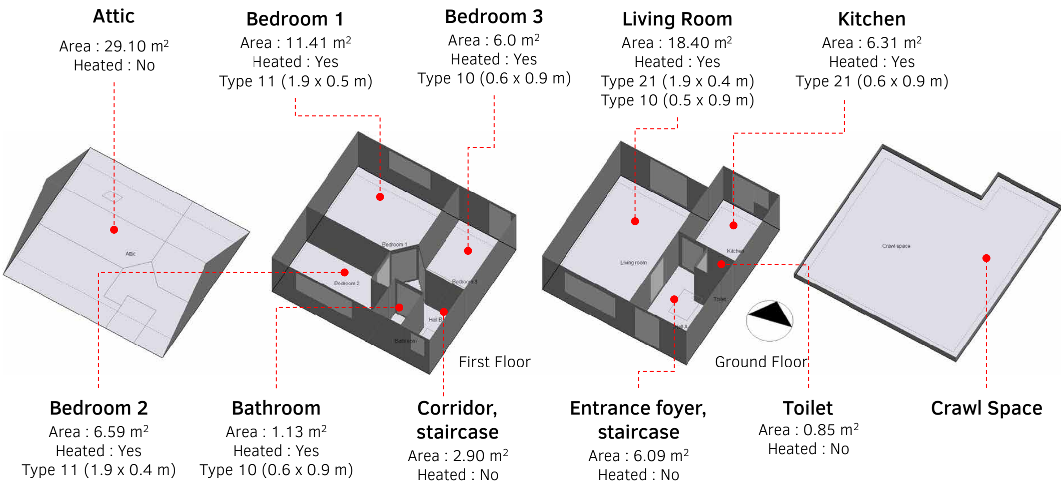


FIG. 3.5 The figure illustrates the case study dwelling's surface area, heating condition, radiator type and size in meters (length x height).

The existing radiators were positioned beneath the windows to counteract the cold draught due to window glazing. During the LT-ready project, interviews were conducted with the occupants, although it is to be noted that the interview results are not made public at this time. According to the interviews, the heating system was scheduled to operate between 8:00-23:00, with an indoor set-point of 20˚C, and a night set-back of 18˚C between 23:00 and 8:00. According to the study conducted by Guerra-Santin & Silvester (2017), on the development of occupancy and heating profiles of Dutch households for building simulations, the heating schedule can be kept constant for the entire week to simplify the simulation process. The interviews also revealed that occupants heated all the rooms except 'Bedroom 3' on the first floor. Since the thermostat controlling the heating system is located in the living room, the study considered the same heating set-point and set-back for all the heated spaces with individual heating capacities of the installed radiator identified in the LT-ready project. The original heating capacities of the radiator HT(90/70 °C) for each heated space can be found in Table A.3.2 of appendix.

TOC

3.2.4.1 Modelling lower supply temperature from the DH system

The simulation model developed in this study is an aggregate or lump model, thus limiting the dynamic modelling of return temperatures or advanced ventilation air loops. For modelling lower supply temperatures, this study utilised the reduced heating capacities of the existing radiator in both MT and LT supply scenarios, which were calculated using equations 3.1 and 3.2 (Østergaard & Svendsen, 2016).

$$\varnothing = \varnothing_0 \times \left(\frac{\Delta T}{\Delta T_0} \right)^n \tag{3.1}$$

Where $\varnothing$ and $\varnothing_0$ represent the radiator heating power in watts at the new and original temperature set, respectively, ΔT and ΔT_0 are the logarithmic mean temperature difference at the new and original temperature set, and n is the radiator exponent with a fixed value of 1.33.

$$\Delta T = \left(T_s - T_r\right)\left[\ln\left(\frac{T_s - T_i}{T_r - T_i} \right) \right]^{-1} \tag{3.2}$$

Where ΔT is the logarithmic mean temperature difference, T_s and T_r are the supply and return temperature in °C, respectively. T_i is the indoor design temperature of 20 °C (Stichting Koninklijk Nederlands Normalisatie Instituut, 2014).

The heating capacities of the radiators were calculated with a temperature differential of 20K between supply and return temperatures to maintain the mass flow rate of the existing distribution pipes of the DH system. In other words, if the supply temperature were lowered, the mass flow rate could not be increased to achieve the same heating power (Harrestrup & Svendsen, 2015) as the original HT supply. As a result, the lower-temperature DH system would be unable to satisfy the peak heating demand of the dwelling, resulting in thermally uncomfortable hours or increased cold hours.

3.2.4.2 Key performance indicators (KPIs)

The KPIs associated with the energy efficiency and thermal comfort criteria were annual space heating demand and occupied cold hours (underheated hours), respectively. The annual space heating demand, simulated using DesignBuilder, was normalised based on the usable area of the dwelling, as calculated following the NEN 2580:2007 standard (Stichting Koninklijk Nederlands Normalisatie Instituut, 2021) and reported in kWh/m^2/year. This area-weighted space heating demand reflects the energy utilised by the space heating system to counteract heat losses caused by transmission, infiltration and ventilation while also considering heat gains from solar radiation and internal heat sources (Itard, 2012; Wang, 2016).

Additionally, this study employed the adaptive thermal limit (ATL) method to analyse thermal comfort to determine occupied cold hours. The ATL method, as outlined by Peeters et al. (2009), takes into consideration the adaptive behaviour of occupants by establishing comfort temperature and defining the comfort ranges with upper and lower limits to achieve 90% (10% PPD) and 80% (20% PPD) acceptability of indoor operative temperatures. Peeters et al. proposed the division of a dwelling into three zones with different thermal comfort requirements, such as living room, bathrooms and bedrooms[4] and provided algorithms for computing the comfort temperatures and comfort ranges for these spaces. In this study, the thermal comfort analysis excludes short presence spaces like corridors and bathrooms (Guerra-Santin & Silvester, 2017). Consequently, the analysis focuses on living rooms, considered occupied during the day, and bedrooms, which are occupied during the night (Guerra-Santin & Silvester, 2017). For calculating the occupied cold hours using the ATL method, the operative temperatures during the occupied hours were compared to the running mean outdoor temperature over the preceding three days. Subsequently, the occupied hours during which the operative temperature fell below the lower limit of 20% PPD were identified as underheated or occupied cold hours.

4 The equation proposed by Peeters et al. (2009) for calculating the lower thresholds of the comfort range for bedroom spaces, yielded temperatures above neutral or comfort temperature. This is counterproductive as it implies that occupied hours at comfort temperature would be perceived cold hours. Therefore, in this study, the equation from Peeters et al. for calculating the lower bounds of thermal comfort was adapted as $T_{lower} = \max\left(16^{\circ}C, T_n + (1-\omega)\times\alpha\right)$

3.3 Results

This study aimed to evaluate the effectiveness of the two-step approach outlined in section 3.2.2 on a case study dwelling to determine the level of renovation intervention required to heat the house using LTH from the DH system. The proposed approach was designed to alleviate the decision-making struggle of selecting suitable renovation solutions by narrowing down the technically desirable solutions for using LTH. Accordingly, this section follows the structure of the proposed two-step approach. First, the case study dwelling is assessed in its existing condition for its readiness to be heated with LTH. Subsequently, the renovation solution space is developed, guided by the current guidelines in the Netherlands, and finally evaluated to narrow down possible options to make the dwelling lower-temperature ready.

3.3.1 Evaluating the suitability of using LTH

To assess the existing condition of the case study dwelling for heating with a lower temperature supply from the DH system, it is necessary to establish the benchmark performance of the dwelling under the original HT (90/70°C) supply. Therefore, the calibrated simulation model was simulated annually using the test reference year specified by NEN 5060 (Stichting Koninklijk Nederlands Normalisatie Instituut, 2021). Table 3.2 provides the area-weighted annual space heating demand and the occupied cold hours for the existing condition, with HT (90/70°C) supply as the benchmark performance. The case study dwelling was estimated to require an annual space heating demand of 172 kWh/m^2/year. Throughout the year, the living room is occupied for 5840 hours between 8:00-23:00, of which nearly 13% (743 hours) were below the 20% PPD lower limit, while the bedroom spaces were occupied for 3650 hours between 23:00-8:00, with very few occupied cold hours. For analysing the readiness of the case study for lower temperature supply, the heating capacities of radiators were calculated for MT (70/50°C) and LT(55/35°C) supply using equations 3.1 and 3.2. As illustrated in Figure 3.6, the heating capacities of existing HT radiators in the living room and bedrooms were significantly reduced by 42% under MT supply and 70% under LT supply.

TABLE 3.2 Annual simulation results of the dwelling in existing conditions under MT and LT supply, compared to the benchmark performance under HT supply.

Supply Temperature	Annual Space heating demand [kWh/m²/year]	Occupied cold hours below 20% PPD [h]			
		Living Room	Bedroom 1	Bedroom 2	Bedroom 3
Benchmark Performance: HT supply (90/70°C)	172	743	1	1	4
MT Supply (70/50°C)	165	879	1	2	9
LT Supply (55/35°C)	143	2376	137	94	653

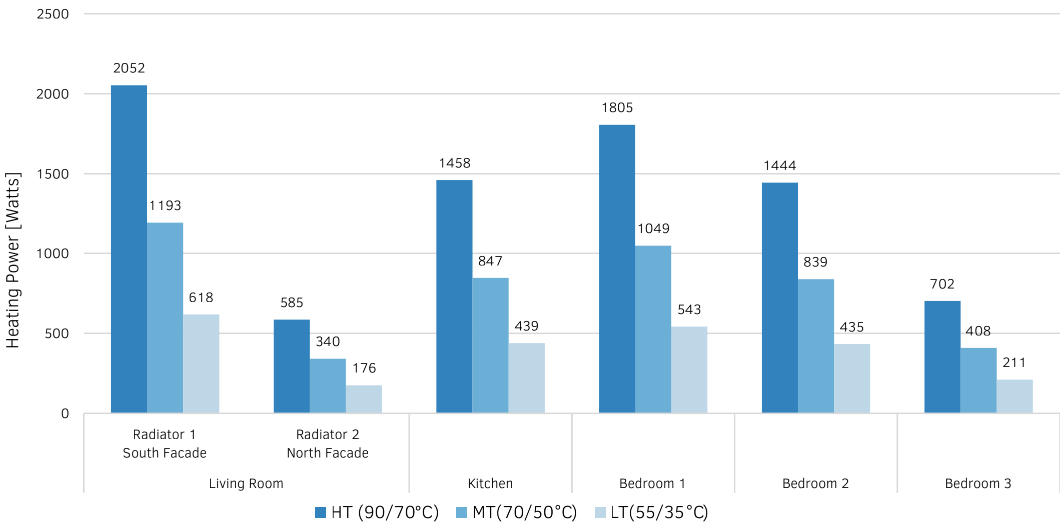


FIG. 3.6 Heating capacities of existing radiators under MT (70/50 °C) and LT (55/35 °C) supply compared to existing.

As depicted in Table 3.2, the reduced heating capacities have a noticeable effect on the performance of the dwelling. The heating delivered by the existing radiators proves insufficient in offsetting heat losses, resulting in increased occupied cold hours and consequent thermal discomfort for the occupants when compared to the HT supply. This is particularly pronounced in the living room, where, in contrast to the HT supply, the occupied cold hours increased to 15% (879 hours) and 40% (2376 hours) under MT and LT supply conditions, respectively. However, the bedrooms only experienced significant discomfort, under LT supply. Thus, it can be argued that compared to the bedrooms, the living room exhibits a higher risk of discomfort. Consequently, if the living room is prioritised to improve thermal comfort, the other spaces might inherently become comfortable. Therefore, the living room can serve as a proxy for evaluating the impact of renovation strategies in improving the thermal comfort of the dwelling under different lower supply temperatures in subsequent steps.

Additionally, these findings indicate that compared to the benchmark performance of the case study dwelling under HT supply, the dwelling could not comfortably be heated with lower supply temperatures in its current condition. As a result, the dwelling requires renovations before using MT or LT supply levels from the DH system.

3.3.2 Evaluating the performance of alternative renovation options

3.3.2.1 Developing alternative renovation options

As described in section 3.2.2.2, three renovation intervention levels (basic, moderate and deep) were tested on two supply transition goals (MT and LT), thus giving rise to six renovation scenarios. Moreover, depending on the definition of the intervention level, each renovation scenario can be approached by a combination of renovation strategies and related renovation measures (Figure 3.3).

The basic renovation level strategy corresponds to increasing the heat output of the existing heat emission systems. In this study, the chosen measure involved replacing the existing radiators with LT radiators, which included additional plates and convectors. For example, in the living room (Figure 3.5), type 21 and 10 radiators were replaced by type 33 and type 20, respectively. Consequently, the LT radiators maintained the length and height of the original radiators while only increasing the depth to accommodate the added plates and convectors. Moreover, in this way, the original radiators can be replaced easily without any changes to the piping system (Brand & Svendsen, 2013).

Next, for moderate renovations, selected improvements to the building envelope with three different measures were chosen: 1) improving window insulation due to its potential towards a significant reduction in heating demand (Majcen et al., 2016; Wahi et al., 2023), 2) minimum insulation levels for the building envelope, as recommended by the Dutch building decree (Bouwbesluit, 2021), and 3) energy-saving measures (besparingspakket), as recommended by studies on reference homes by the Dutch government (AgentschapNL, 2011). Finally, higher insulation values, similar to new construction, as suggested by the Dutch building decree and the latest study on reference homes in the Netherlands (Rijksdienst voor Ondernemend, 2023) were considered for deep renovations along with improvements to infiltration and ventilation systems. Furthermore, the existing radiators might become over-dimensioned post renovations due to reduced heating demands. As a result, the measures from moderate and deep intervention levels were also simulated, with or without changing the existing radiators. As the next step, the strategies and measures described in Table 3.3 were tested for MT and LT supply transition goals against the benchmark performance of the dwelling using HT supply, as indicated in Table 3.2.

TABLE 3.3 Renovation measures are categorised into three distinct intervention levels, with no renovation level representing the existing condition of the case study dwelling. MD1, MD2 and MD3 denote moderate renovation measures, while DP1 and DP2 signify deep renovation measures. The U-value of window insulation in MD1 and the envelope insulation, as well as infiltration values in MD2 and DP2, adhere to the Dutch Building decree (Bouwbesluit, 2021). In contrast, MD3 and DP1 derive their values from (AgentschapNL, 2011) and (Rijksdienst voor Ondernemend, 2023), respectively.

Component	No renovation	Basic	Moderate			Deep	
			MD1	MD2	MD3	DP1	DP2
Space Heating System	Existing Radiators	LT Radiators	Existing or LT Radiators			Existing or LT Radiators	
External Wall (U-Value in W/m²K)	1.45	1.45	1.45	0.71	0.40	0.58	0.21
Floor (U-Value in W/m²K)	1.45	1.45	1.45	0.38	0.40	0.28	0.27
Roof (U-Value in W/m²K)	0.58	0.58	0.58	0.47	0.40	0.28	0.16
Glazing (U-Value in W/m²K)	2.40	2.40	1.9	1.9	1.8	1.4	1.1
Internal Partition (U-Value in W/m²K)	2.40	2.40	2.40	2.40	2.40	0.40	0.21
Infiltration (Air change rate in h^{-1})	0.4	0.4	0.4	0.3	0.3	0.2	0.2
Ventilation System	Natural Ventilation					Exhaust ventilation with CO_2 sensors	Balanced mechanical ventilation with heat recovery

3.3.2.2 Renovation scenarios for using Medium-Temperature (MT:70/50°C) supply

The renovation measure only involved substituting the existing radiators with LT radiators for the basic intervention level. As mentioned in Section 3.3.2.1, the LT radiators maintained the dimensions of the original radiator (length and height) due to space limitations preventing the installation of bigger radiators in the dwelling.

Figure 3.7 illustrates that the basic intervention level involving LT radiators has only a limited effect on lowering space heating demand and occupied cold hours when compared to the benchmark performance with HT supply. The replacement of existing radiators with higher capacity LT radiators can provide a quick and cost-effective approach for utilising LTH. However, it is essential to note that these solutions offer minimal potential for energy savings. Therefore, the emphasis should be placed on prioritising improvements to the building envelope to reduce heat losses, as this is considerably more crucial than increasing the heating capacity of the space heating systems.

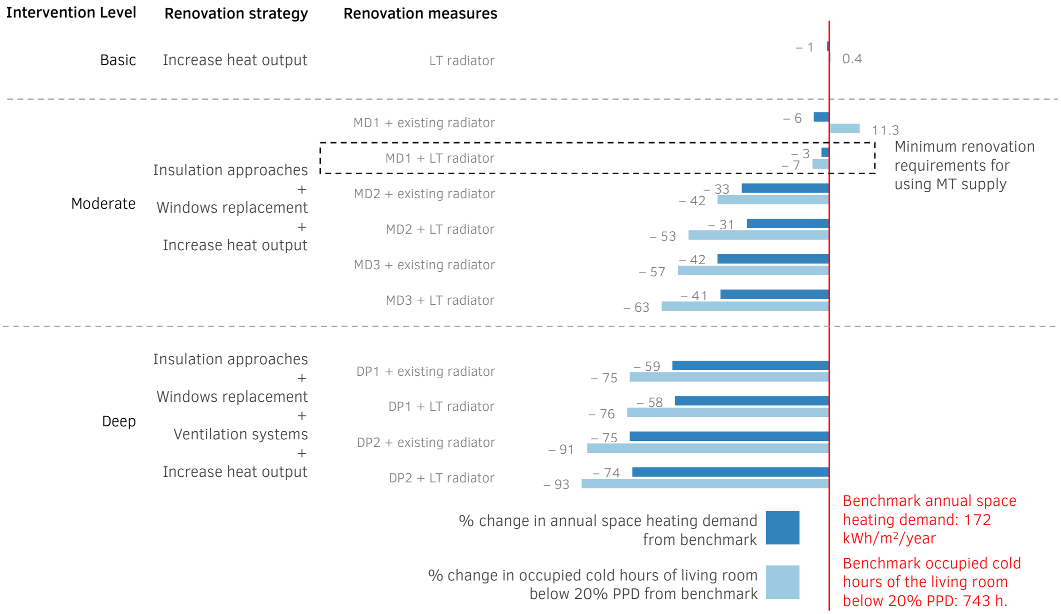


FIG. 3.7 Annual space heating demand of the dwelling and occupied cold hours of the living room with different renovation measures under MT supply.

In the context of moderate renovations, implementing measure MD1 alongside existing radiators resulted in a 6% reduction in the space heating demand. However, applying this measure does not lead to an improvement in the occupied discomfort hours compared to the benchmark performance. It was only when this measure was combined with LT radiators that a 6.5% reduction was achieved in occupied cold hours compared to the benchmark performance, with a slight increase in energy demand (decrease in % change) due to higher heating power (larger heating surface area). For measures MD2 and MD3 with existing radiators, measure MD2, in accordance with the recommended minimum insulation levels according to the Dutch building decree, contributed to a 33% reduction in the space heating demand and a 42 % decrease in the occupied cold hours. Similarly, measure MD3, in conjunction with existing radiators, demonstrates a substantial 42% and 57% reduction in the space heating demand and occupied cold hours, respectively. Additionally, combining MD2 and MD3 with LT radiators could extend their impact by reducing the occupied cold hours by 53% and 63%, respectively.

Moreover, deep renovation strategies involving holistic improvements to the building envelope, heating and ventilation systems resulted in substantial reductions in both space heating demand and occupied cold hours. For example, measure DP1 alongside existing radiators achieved a significant 59% reduction in the space heating demand and 75% in the occupied cold hours. On the other hand, compared to the benchmark, measure DP2 with existing radiators resulted in a 75% and 91% reduction in the space heating demand and occupied cold hours, respectively. While the existing radiators provide adequate heating power to offset heat losses in deep renovation, in practice, they could also be replaced with LT radiators during deep renovations. This could further reduce the occupied cold hours, although with a minor increase in energy consumption. Nevertheless, it is essential to note that deep renovations might result in the risk of overheating during the summer period. Therefore, additional strategies might be required for preventing and controlling heat gain to avoid overheating in summer. Therefore, a comprehensive evaluation of renovation measures for utilising LTH at the deep intervention level should include a thorough analysis of potential summer overheating.

The results indicate that improving the existing windows and radiators could be regarded as the minimum intervention required for comfortably heating the case study dwelling with an MT (70/50°C) supply. Nevertheless, it is essential to evaluate whether the specific MD1 measure with LT radiators would be adequate to ensure comfortable heating of the dwelling, even with LT (55/35°C) supply.

3.3.2.3 Renovation scenarios for using Low-Temperature (LT:55/35°C) supply

The highest level of discomfort is observed when the supply temperature is further reduced to the LT supply (Figure 3.8). In the case of basic renovations, the occupied cold hours remain above the benchmark performance. While the three moderate renovation measures (MD1, MD2, MD3) could reduce the space heating demand, they fail to improve the thermal comfort of the living room compared to the benchmark conditions. However, when MD2 and MD3 are implemented in conjunction with LT radiators, there is a notable reduction of 37% and 52%, respectively, in the occupied cold hours. This suggests that MD2, combined with LT radiators, can be considered as the minimum renovation required for transitioning to LT supply. Deep renovation measures can further reduce the space heating demand by 60-75% and occupied cold hours by 65-90%.

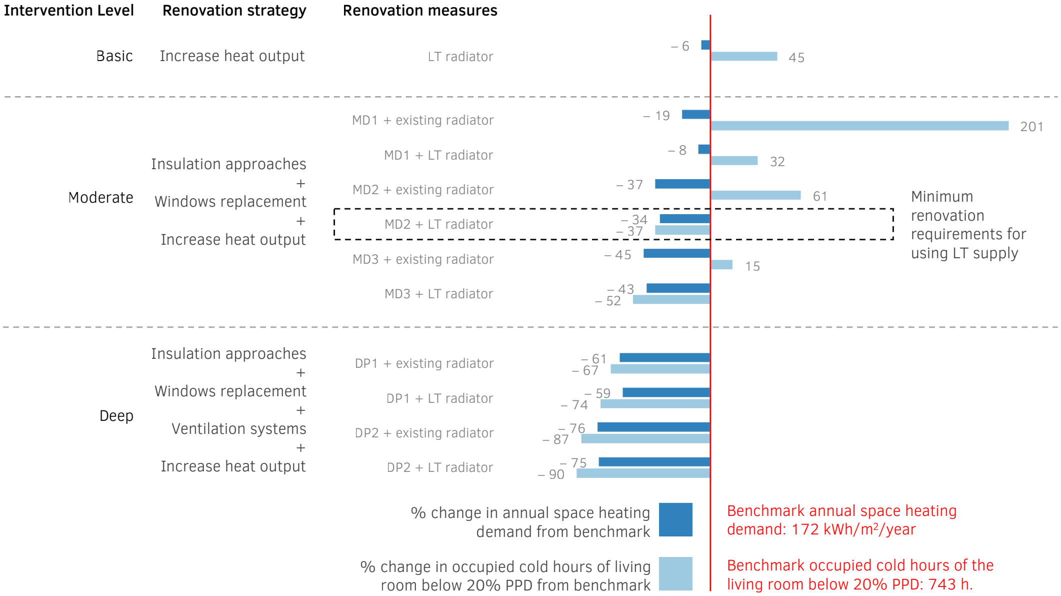


FIG. 3.8 Annual space heating demand of the dwelling and occupied cold hours of the living room with different renovation measures under LT supply.

3.4 Discussion

3.4.1 Case study: Renovation interventions for using LTH

Applying the two-step approach to the case study revealed that the intermediate terraced house built before 1945 cannot be heated comfortably with the reduced supply levels of MT and LT. As a result, the dwelling would require energy renovations before being connected to a DH system with a lower temperature supply. Upon evaluating specific renovation options derived from Dutch reference homes studies (AgentschapNL, 2011; Rijksdienst voor Ondernemend, 2023) and the building decree (Bouwbesluit, 2021), it became evident that utilising LTH from DH systems requires at least moderate renovation interventions. Implementing measure MD1 with LT radiators could prepare the dwelling for heating with the MT supply. However, insulating the closed part of the envelope in addition to MD1—resulting in measure MD2 with LT radiators could prepare the dwelling for an LT supply.

These findings align with recent standards and target values for home insulation in the context of gas-free heating in the Netherlands (Cornelisse et al., 2021). According to the study, if a dwelling meets the standard value of net heat demand, derived based on its compactness ratio (the ratio of envelope heat loss area to usable area), type (single or multi-family) and construction year (>1945 or <1945), then the dwelling can be considered prepared for future gas-free heat networks or individual solutions with lower temperature supply. For the case study dwelling, an intermediate terraced house built before 1945, with a compactness ratio of approximately 2.0, the standard for net heating demand was calculated at 164 kWh/m^2/year. Compared to the benchmark performance of the dwelling at 172 kWh/m^2/year, only a 5% reduction in the heating demand would suffice for the dwelling to use an MT supply. This implies that measure MD1 with a 6% (161 kWh/m^2/year) reduction in net heating demand (Figure 3.7) without changing the radiator is an MT-ready solution. However, according to the lower-temperature-ready criteria, this solution is insufficient to improve thermal comfort compared to benchmark performance. Consequently, LT radiators with measure MD1 reduced the occupied discomfort hours. Nevertheless, this increased heating energy consumption to 167 kWh/m^2/year, exceeding the standard net heating demand of 164 kWh/m^2/year. As a result, the subsequent moderate renovation measure MD2 should be considered as the minimum renovations required for MT supply, as it satisfies both the net heating demand standard and lower-temperature-ready criteria.

TOC

Additionally, deep renovation measures yielded the most substantial reduction in space heating demand and occupied cold hours. However, it is worth noting that deep renovations may introduce the potential risk of overheating during the summer months. Furthermore, when deep renovations are combined with other systems to prevent legionella growth in domestic hot water systems, they can lead to expensive solutions for property owners. Consequently, it is imperative to assess the financial and environmental implications of these measures during the decision-making stage.

Furthermore, for evaluating the thermal comfort criteria, only the living room was analysed under the assumption that improving the living room's occupied cold hours could also solve the thermal comfort problems in the bedroom spaces. This assumption is crucial for transitioning to LT supply, as seen in Table 3.2, where the bedroom spaces had higher occupied cold hours with LT supply than the MT supply. Therefore, measure MD2 with LT radiators was also evaluated for bedroom comfort. As shown in Table 3.4, the findings reveal a complete reduction of the occupied cold hours below 20% PPD compared to the benchmark performance and with LT supply without renovations. Consequently, it can be concluded that the living room can be utilised as a proxy to evaluate the thermal comfort criteria of the dwelling.

TABLE 3.4 Improvement in space heating demand and thermal comfort hours in the living room and bedroom spaces under LT supply due to moderate renovation measure MD1 with LT radiators.

	Annual Space heating demand [kWh/m^2/year]	Occupied cold hours below 20% PPD [h]			
		Living Room	Bedroom 1	Bedroom 2	Bedroom 3
Benchmark Performance: HT supply (90/70°C)	172	743	1	1	4
Existing condition: LT Supply (55/35°C)	143	2376	137	94	653
MD2 + LT radiators: LT Supply (55/35°C)	114	467	0	0	0

In conclusion, it can be ascertained that the MD2 measure or, in other words, the minimum renovation requirements mandated by the Dutch building decree, prove to be sufficient for the terraced house built before 1945 for transitioning to lower supply temperatures (MT and LT levels) from DH system considering energy efficiency and thermal comfort criteria. These findings can be extrapolated qualitatively to recommend minimum renovation interventions for intermediate terraced houses built after 1945 when connected to a DH system with a lower temperature supply.

The study on reference dwellings in the Netherlands (Rijksdienst voor Ondernemend, 2023) provides the current insulation levels of such dwellings across various construction years, as illustrated in Table 3.5. It can be observed that the case study dwelling's insulation levels before renovations (Table 3.3) closely align with the median insulation values of terraced houses built before 1945. Moreover, by implementing moderate renovation measures, MD2 would upgrade the houses to the insulation level closer to dwellings constructed in 1975-1991. Therefore, it can be inferred that dwellings built before 1975 may require MD2 measures without changing their radiators for MT supply, and by changing to LT radiators, they can also be prepared for LT supply. On the other hand, dwellings built after 1975 may already have a certain level of readiness for MT supply, although basic intervention would be required for LT supply.

TABLE 3.5 Table 3.5 Renovation recommendations for intermediate terraced houses in different construction years. The table also includes median insulation values and the state of the dwellings in the five construction periods (Rijksdienst voor Ondernemend, 2023).

Component	<1945	1946-1964	1965-1974	1975-1991	>1991
External Wall	1.92	1.92	1.67	0.68	0.37-0.21
	Uninsulated: 70% of the homes	Uninsulated: 62% of the homes	Uninsulated: 35% of the homes	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Ground Floor	2.4	2.4	2.3	1.28	0.36-0.27
	Uninsulated: 70% of the homes	Uninsulated: 85% of the homes	Uninsulated: 62% of the homes	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Roof	0.84	1.12	0.97	0.68	0.37-0.16
	Uninsulated: 30% slopping roof, 50% flat roof	Uninsulated: 48% slopping roof, 68% flat roof	Uninsulated: 31% slopping roof, 68% flat roof	Mostly insulated	Insulated to meet at least Rc: 2.5 m^2K/W
Windows	2.9	2.9	2.9	2.9	1.8
	16%: single glazing, 59%: double glazing, 16% HR++ glass	16%: single glazing, 54%: double glazing, 23% HR++ glass	56%: double glazing, 29% HR++ glass	8%: single glazing, 64%: double glazing, 21% HR++ glass	Mostly HR++
Ventilation system	Natural ventilation: 89% homes, Mechanical ventilation:11% homes	Natural ventilation: 89% homes, Mechanical ventilation:11% homes	Natural ventilation: 73% homes, Mechanical ventilation:27% homes	Natural ventilation: 41% homes, Mechanical ventilation:57% homes, Balanced: 2% homes	Mostly mechanical ventilation and balanced ventilation
Infiltration	Some houses are airtight	Some houses are airtight	Some houses are airtight	All houses are airtight	All houses are airtight
Recommendations for a minimum level of renovation intervention required					
MT supply (70/50 °C)	Moderate renovations with MD2 measure without changing existing radiators			Could be ready for MT supply	
LT Supply (55/35 °C)	Moderate renovations with MD2 measure with LT radiators			Basic: LT radiators	Basic: LT radiators

3.4.2 Implications and limitations of the proposed approach

The proposed two-step approach developed in this study has implications and limitations that must be considered when used to select renovations for heating a dwelling with LTH through DH systems. This approach aims to identify technically desirable solutions from a diverse renovation solution space that can potentially prepare the dwelling for utilising LTH supplied by the DH systems. Even though this study analysed a limited number of measures, the method could still help filter out suitable solutions when the solution space is extensive. This approach provides stakeholders with a systematic method to assess the necessity of renovations for using LTH and reduces the number of viable solutions to select from, thus alleviating decision paralysis. However, a comprehensive validation through stakeholders involved in the decision-making process is required to validate this theory.

The novelty of this method lies in its criteria for testing the readiness of a dwelling for LTH, which is essential in narrowing down the renovation options before the decision-making stage. Energy efficiency and thermal comfort were identified as essential non-compensatory criteria, serving as filtering criteria for reducing renovation options. Nevertheless, for actual decision-making, it is essential to evaluate the feasibility and environmental impact of narrowed renovation options, which was beyond the scope of this study.

Additionally, for developing relevant renovation scenarios, it is essential to consider the feasibility and practicality of the alternative solutions based on the constructional limitations of the dwelling in context. For instance, the selection of post-cavity insulation as a renovation measure would depend on the cavity's presence and width, based on the construction year of the dwelling.

Since the current study focused on intermediate terraced houses, the recommendations may not directly apply to other dwelling types in the Netherlands. However, a recent study by Cornelisse et al. (2021) determined that houses with similar building characteristics and compactness ratios can be grouped. As a result, other housing types with similar compactness ratios and characteristics to the case study dwelling might have similar energy performance and recommendations for renovation options for being lower-temperature ready. However, a comprehensive study is necessary to test this hypothesis. Finally, it is essential to mention that the proposed two-step approach works well for analysing one or a few houses. Consequently, additional adjustments to the method might be required for analysing a large number of dwellings at the district level or housing corporations with a considerable portfolio, thus suggesting future research opportunities.

3.5 Conclusions

This study presented a two-step approach for identifying the renovation intervention required for existing dwellings in the Netherlands to enable them to use LTH from DH systems. The approach was structured to assess the dwelling's potential to be heated in its existing condition with lower supply temperatures from DH systems. On the other hand, if this was not possible, then to develop and evaluate alternative renovation solutions to make the dwelling lower-temperature ready.

The approach was applied to a typical intermediate terraced house built before 1945 to test its applicability. The renovation problem entailed determining minimum renovation requirements for utilising LTH from the DH system. The objective of the renovation was to prepare the dwelling for MT(70/50°C) and LT(55/35°C) supply compared to existing HT (90/70°C) from DH systems. This study proposed a definition for evaluating the readiness of a dwelling to be heated with a lower supply temperature that corresponds to an improvement in thermal comfort and energy efficiency relative to the current situation of the dwelling with an HT supply. As a result, energy efficiency and thermal comfort were considered as non-compensatory criteria, meaning that both criteria must be satisfied without any trade-offs. The KPI used to evaluate energy efficiency was annual space heating demand, while for thermal comfort, occupied hours below the lower limit of 20% PPD was used as an indication of thermal discomfort and calculated according to the ATL method. A calibrated simulation model was developed and used to evaluate the performances of the dwelling in its existing condition with HT supply and under MT and LT supply levels.

Consequently, the approach proposed six renovation scenarios based on different intervention levels (basic, moderate and deep) for MT and LT supply temperature transition goals. Depending on the definition of the intervention level, each scenario consisted of renovation strategies and subsequent renovation measures. The main findings from the application of the two-step approach on the selected case study dwelling are as follows:

- Intermediate terraced houses constructed before 1945 require energy renovations to enable heating with MT and LT supply.
- The basic renovation strategy, which involved the replacement of existing radiator systems with ones that provide higher heat output, was insufficient to prepare

the case study dwelling to be heated with a lower temperature supply from the DH system.

- The moderate intervention level, with the measure that upgrades the building envelope to meet the minimum insulation levels mandated by the Dutch building decree (Wall: 0.71 W/m^{2}K, Floor: 0.38 W/m^{2}K, Roof: 0.47 W/m^{2}K and Windows: 1.5 W/m^{2}K), along with reduced infiltration and LT radiators, serves a dual purpose of preparing the dwelling for both MT (70/50°C) and LT (55/35°C) supply transition goals.

- When applied with MT supply, this measure achieves a 33% reduction in space heating demand and a 42% decrease in the occupied cold hours. Conversely, when LT supply is utilised, the same measure results in a 34% reduction in space heating demand and a 37% reduction in occupied cold hours.

- Deep renovation strategies can further reduce the space heating demand and occupied cold hours, although it is essential to note that these deep renovation measures may introduce a risk of summer overheating, which must be included in future analyses.

Finally, the proposed two-step approach has significant implications as it has the potential to systematically streamline the decision-making process for selecting renovations for heating dwellings with LTH through DH systems by reducing the number of renovation options. These reduced options can then further be analysed in the decision-making stage by evaluating their performances on economic and environmental criteria with a life cycle perspective. In this manner, the method could reduce stakeholders' decision paralysis, although it must be thoroughly confirmed through stakeholder analysis. Additionally, this study is limited to only a single dwelling type, and further research is essential for evaluating and analysing its application in different dwelling types.

A 3.1 Characteristics of the case study dwelling before and after renovations

The case study dwelling is an intermediate terraced house built in 1938. As a part of the "LT Ready project" by TU Delft (van den Brom & van den Ham, n.d.), the house was renovated in 2020 with a focus on building envelope and ventilation systems. Table A.3.1 illustrates the building characteristics before and after renovations.

TABLE A. 3.1 Building characteristics data of the case study dwelling before and after renovations. The case study dwelling was renovated as a part of the LT-ready project.

Component	Subtype	Unit	Characteristics	
			Before Renovations	After Renovations
Wall	Cavity wall	U-Value [W/m²K]	1.45	0.46
	Interior Wall	U-Value [W/m²K]	2.40	2.35
	Separation wall	U-Value [W/m²K]	1.40	1.40
Floor	Ground Floor	U-Value [W/m²K]	1.45	0.27
	Separation Floor	U-Value [W/m²K]	1.45	1.5
Roof	-	U-Value [W/m²K]	0.58	0.22
Glazing	-	U-Value [W/m²K]	Double glazing unit: 2.4	HR++ : 1.1
Infiltration	-	h^{-1}	0.4	0.2
Ventilation system	-	-	Natural ventilation system	Balanced mechanical ventilation system with heat recovery
Ventilation rate	Ground Floor	h^{-1}	1.28	0.385
	First Floor	h^{-1}	1.21	0.361

A.3.2 Input parameters for simulation model

The entire dwelling was modelled in DesignBuilder® V7.0 as different thermal zones. The exterior envelope surface area of the dwelling is 94 m^2, while the total window area is 19 m^2. Table A.3.2 provides input parameters for the ground and first floor of the case study dwelling after renovations.

TABLE A. 3.2 Overview of input parameters for making simulation model for the renovated condition of the case study dwelling.

Parameters	Ground Floor				First Floor				
Space	Entrance Foyer, staircase	Kitchen	Living Room	Toilet	Corridor and stair-case	Bedroom 1	Bedroom 2	Bedroom 3	Bath-room
Area [m^2]	6.09	6.37	18.40	0.85	2.90	11.41	6.59	6.02	1.13
Height [m]	2.45 for the ground floor				2.25 for the first floor				
Volume[m^3]	14.85	15.52	44.84	2.06	8.48	25.54	14.76	13.48	2.54
Heating	No	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Radiator Type	-	Type 21	Type 21 Type10	-	-	Type 11	Type 11	Type 10	Type 10
Radiator dimensions (length X breadth) [m]	-	0.6 X 0.9	1.9 x 0.4 0.5 x 0.9	-	-	1.9 X 0.5	1.9 x 0.4	0.6 X 0.9	0.6 X 0.9
Heating capacity at 90°C [W]	-	1458	2637	-	-	1805	1444	702	702
Heating Schedule	-	8:00-23:00	8:00-23:00	-	-	8:00-23:00	8:00-23:00	8:00-23:00	8:00-23:00
Heating set-point [°C]	-	20	20	-	-	20	20	20	20
Heating Set-back [°C]	-	18	18	-	-	18	18	18	18
Air change rate [1/h]	1.28 for the ground floor				1.21 for the first floor				
Infiltration rate [1/h]	0.4 for the ground floor				0.4 for the first floor				
Internal gains (occupants + lighting + equipment) [W/m^2]	4.80 for the entire dwelling								

A.3.3 Simulation model calibration

The uncalibrated DesignBuilder® model was calibrated using the monitored indoor air temperature of the living room in the renovated dwelling condition between November-December 2020. The weather file from the De Bilt weather station was adjusted for 2020 climate conditions for calibration. For calibration, the coefficient of variation of root means square error (CV(RMSE)) statistical index recommended by the ASHRAE guidelines was employed (Ruiz & Bandera, 2017). The CV(RMSE) calibration index calculates the variation of error between the simulated and measured data, indicating the similarity between the simulated and measured data. The index is calculated using equation A.3.1, where the value of calibrated hourly model must be less than 0.3 (Ruiz & Bandera, 2017).

TOC

$$CV(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^{n} (m_i - s_i)^2}{n - p}} \qquad (A.3.3)$$

where $\bar{m}$ is the mean of measured data, m_i is the measured data and s_i is the simulated data for the hourly data point i, n is the number of measured data points, and the value of p is considered 1.

A one-week monitoring dataset (13/12-19/12) with a relatively consistent trend of the living room's indoor air temperature was selected for model calibration. The simulated indoor air temperature was then compared to the monitored data using the calibration index. Next, the model was adjusted iteratively by modifying the input parameters. The achieved CV(RMSE) value of the calibrated model was 0.06, which was below the recommended threshold of 0.3 for hourly calibration. After the model was calibrated with the renovated conditions of the case study dwelling, the building envelope characteristics were reverted to the condition before renovations, as mentioned in Table A.3.1. Figure A.3.1 illustrates the simulated and monitored indoor air temperature of the calibrated living room model graphically.

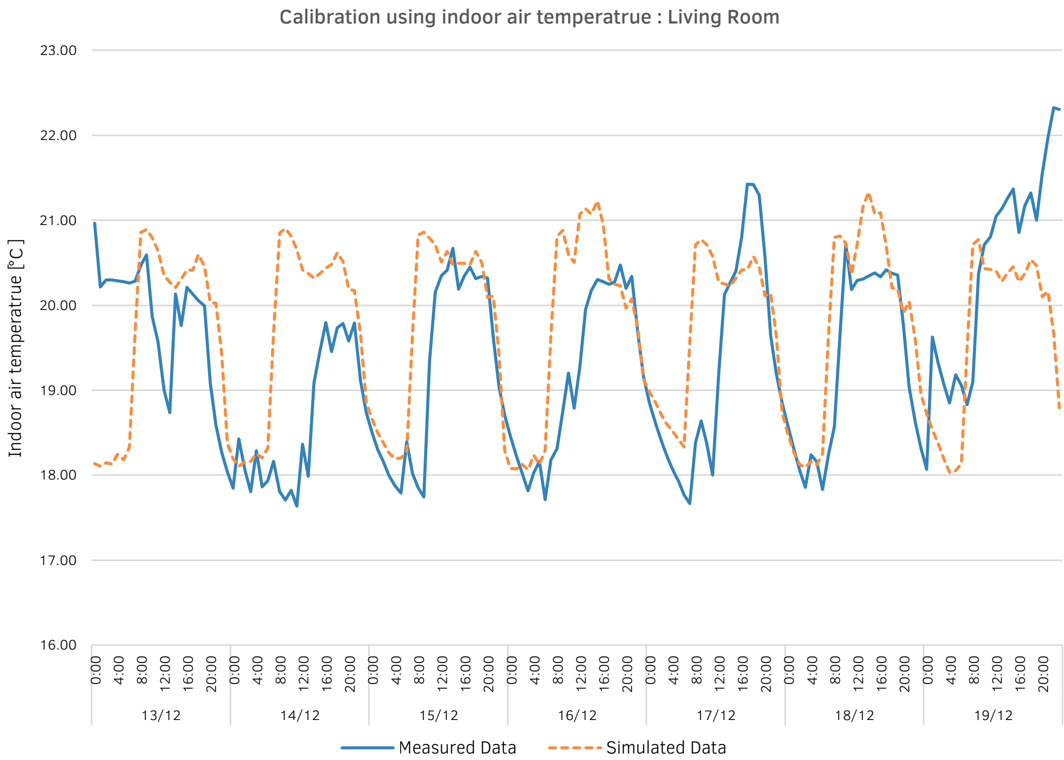


FIG. A. 3.1 Comparison between simulated and monitored indoor air temperature of the living room after calibration.

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4 Evaluating building-level parameters for lower-temperature heating readiness

A sampling-based approach to addressing the heterogeneity of Dutch housing stock

First published as: Wahi, P., Konstantinou, T., Visscher, H., & Tenpierik, M. J. (2024). Evaluating building-level parameters for lower-temperature heating readiness: A sampling-based approach to addressing the heterogeneity of Dutch housing stock. Energy and Buildings, 322, 114703. https://doi.org/10.1016/j.enbuild.2024.114703

Aside from layout changes and minor textual changes to improve readability, this paper has not been amended for uptake in this dissertation.

ABSTRACT

The Dutch government aims to eliminate natural gas for residential heating in 1.5 million homes by 2030. One strategy is connecting existing dwellings to lower-temperature DH systems, although these dwellings might require energy renovations. The heterogeneous dwelling stock causes varying renovation needs that complicate the energy transition. The present study addresses this issue by assessing the building-level parameters affecting the readiness of the Dutch terraced-intermediate and apartment types for lower-temperature heating (LTH) supplied by DH systems. A sampling-based approach was employed to capture variability within these dwelling types, addressing the limitations of archetype-based methods. The findings suggest a sample size of 1300 to represent the variations in these dwelling types. Parametric simulations and machine learning methods were used to identify significant building-level parameters for medium-temperature (MT: 70/50°C) and low-temperature (LT: 55/35°C) supply levels. These include heating setpoints (desired indoor temperature) and ventilation-related parameters (ventilation system type and air infiltration rate), followed by fabric-related parameters (roof, glazing, wall, ground, and door insulation) and geometric properties (orientation, compactness ratio, and window-to-wall ratio). Additionally, radiator oversizing also impacts LTH readiness. These results broadly apply to the studied dwelling types, although feature importance varies by supply temperature and dwelling type. The findings can guide stakeholders in assessing current conditions and prioritising renovation measures, aiding the development of targeted renovation solutions. Encompassing the representative variations within studied dwelling types enhances the robustness of the results. However, incorporating more refined data could improve the accuracy of the findings, better supporting the energy transition of these dwellings.

KEYWORDS Energy Transition, Heating Decarbonisation, Energy Renovations, Parametric Simulations, Machine Learning

4.1 Introduction

The built environment is currently responsible for 30% of global energy consumption (Delmastro & Chen, 2023), with 15% of this energy being used for space heating and hot water (Briens & Martinez-Gordon, 2023). In 2022, fossil fuels accounted for 60% of the heating energy demand, resulting in direct CO_2 emissions of 2400 megatonnes (Briens & Martinez-Gordon, 2023). Therefore, it is imperative to explore fossil-free approaches for decarbonising the building heating sector. The Dutch government has set an ambitious target to eliminate the use of natural gas for domestic heating in 1.5 million existing homes by 2030 (Dutch Ministry of Economic Affairs and Climate, 2019). For this transition, lower-temperature DH systems are emerging as a viable solution to provide sustainable heat to densely populated areas (Doračić et al., 2020; Persson et al., 2019; Zach et al., 2019). Unlike traditional DH systems, these operate with supply temperatures below 75°C, allowing for the integration of various sustainable heat sources, such as geothermal, aqua thermal, residual heat from industry, data centres, supermarkets, and solar thermal plants, as alternatives to natural gas (Averfalk et al., 2017; Harrestrup & Svendsen, 2015). Additionally, lower supply temperatures improve the efficiency of heat distribution networks (Averfalk et al., 2017; Brand & Svendsen, 2013) and enhance thermal comfort at the building level (Ovchinnikov, Borodiņecs, & Millers, 2017; Wang et al., 2016). Currently, only 6.4% of

Dutch homes are connected to DH systems (Centraal Bureau voor de Stastiek, 2022; Koster et al., 2022), although it is estimated that by 2050, nearly 50% of sustainable heat will be supplied through them (Beckman & van den Beukel, 2019). In due course, many existing dwellings will be connected to lower-temperature DH systems.

The transition of existing dwellings to these lower-temperature DH systems often requires energy renovations (Harrestrup & Svendsen, 2015; Pakere et al., 2021; Wahi et al., 2023b), which involves complex decision-making due to the involvement of multiple stakeholders with conflicting objectives (Gade et al., 2018; Jafari & Valentin, 2018; Serrano-Jiménez et al., 2021). This complexity is further compounded by the heterogeneity of the dwelling stock, resulting in varying renovation needs that require individual assessments and customised solutions (Baldini et al., 2020; Eriksson & Johansson, 2021; Husiev et al., 2023). Nevertheless, developing assessment models for the entire stock at the individual dwelling level is challenging due to the limited data availability and the computational resources required to analyse them (Álvarez-Sanz et al., 2024; Booth et al., 2012; De Jaeger et al., 2020; Li et al., 2018; Mastrucci et al., 2017). Consequently, studies typically employ reference or archetype buildings to represent the national stock (Ballarini et al., 2014; Li et al., 2018; Pristerà et al., 2023). These archetypes are developed through statistical analyses and the clustering of common building features such as construction period, type, size, HVAC systems and occupant profiles within specific building categories (Aksoezen et al., 2015; Ballarini et al., 2014; Li et al., 2018; Mata et al., 2014). While these archetypes are beneficial for estimating energy-saving potential and assessing the cost-effectiveness of renovation measures at a policy level (Li et al., 2018; Mauro et al., 2015), they introduce uncertainties due to the averaging of variations within dwelling types (Aksoezen et al., 2015; Baldini et al., 2020). As a consequence, these uncertainties may result in a performance gap between the expected outcomes, based on archetypes, and the actual performance of individual dwellings (Baldini et al., 2020; Brøgger et al., 2019).

A systematic review conducted by the authors (Wahi et al., 2023a) found that current scientific literature relies on archetypes, or specific cases, for evaluating the renovation measures needed for LTH in residential buildings. As a result, analysis of variations due to building characteristics within the dwelling types is not taken into account when assessing the readiness of the dwelling stock for LTH, highlighting a significant knowledge gap. This gap is particularly crucial for stakeholders such as municipalities and housing corporations who manage diverse portfolios and require insights to determine which dwellings are prepared for LTH, those which necessitate renovations for LTH implementation, and where priorities should be established. These challenges correspond to the information barrier impeding energy renovation projects (Jensen et al., 2013, 2018).

In this context, recent studies have conducted extensive measurement campaigns encompassing the diversity of the dwelling stock. For instance, the study conducted by Østergaard et al. (2018) analysed survey data from 1,645 single-family houses (SFH) and apartments in Denmark to evaluate the oversizing of radiators and their suitability with low-temperature supply from DH systems. Similarly, Pothof et al. (2023) measured 220 existing dwellings that were representative of the Dutch dwelling stock with natural gas heating systems. These dwellings were examined to determine the minimum supply temperature required without any renovations under design conditions, as well as to assess their suitability for lower supply temperatures. While these studies provide valuable insights, they encounter limitations due to uncertainties from manual data entry and measurement errors. Moreover, such comprehensive approaches, though ideal, are expensive and time-intensive (Najafi et al., 2021). To address this, several researchers propose a statistical sampling-based approach (Brown et al., 2014; De Jaeger et al., 2021; Liang & Shen, 2012; Mauro et al., 2015). Compared to the traditional archetype-based method, representative samples that reflect the variations in the dwelling types can be generated and facilitate quicker evaluations than extensive measurements or surveys of dwellings.

4.1.1 Research gap and aim of the study

Existing dwellings in the Netherlands require energy renovations to use LTH from DH systems. However, the heterogeneous nature of the dwelling stock complicates the decision-making process concerning the selection of the appropriate renovation solutions. Current research reveals specific gaps in understanding the requirements for transitioning these dwellings to LTH. Firstly, most studies rely on archetype-based approaches, which are inadequate for addressing the variations within dwelling types. Consequently, these approaches create information barriers for stakeholders, as they are limited in providing detailed insights into diverse dwellings. Secondly, while direct measurement and surveying of buildings offer detailed information, they are resource-intensive and time-consuming, making them impractical for large-scale assessments.

Given these challenges and gaps identified in the existing knowledge base, the primary objective of this study is to evaluate how the diversity within the dwelling stock can be incorporated into the assessment of LTH readiness in the Netherlands. By acknowledging the heterogeneity of dwellings, this study aims to provide a nuanced analysis of building-level parameters that influence LTH readiness. To achieve this, the study employed the sampling-based approach. This approach offers a robust framework to strategise suitable energy renovations for preparing Dutch dwellings for LTH supplied by DH systems.

4.1.2 Related studies on sampling-based approach

Previous applications of the sampling-based approach have demonstrated its utility in energy renovation research. For instance, according to Liang and Shen (2012), surveying and measuring energy consumption is not always feasible for all the buildings in an area. Therefore, they proposed a sampling-based approach to generate representative data and concluded that simulations based on such data could yield valuable insights, provided that an appropriate sample size is used. Further, Brown et al. (2014) utilised statistically representative samples derived from comprehensive survey data collected across Sweden's building stock. A sample of 1400 multi-family homes (MFH) and single-family homes (SFH) were analysed to assess the embodied global warming potential of renovation measures that reduce operational energy consumption.

Furthermore, an approach for investigating the cost-optimality of energy renovations in the presence of variations within a building category is proposed by Mauro et al. (2015). The authors introduced a methodological framework called SLABE that leveraged statistical and probabilistic methods for generating representative samples of a dwelling type (referred to as reference building samples) instead of the single archetype (referred to as a reference building). Moreover, a comprehensive review by Mastrucci et al. (2017) on the lifecycle assessment of building stock identified the convenience of modelling representative samples, compared to a building-by-building approach, in capturing the broad variability of the building stock. Additionally, Baldini et al. (2020) assessed building samples to investigate energy-efficient and cost-effective renovation measures for a DH area in Denmark, which were tailored to diverse building characteristics instead of archetypes. Their study ascertained that the heterogeneous approach could provide valuable insights that might have been overlooked in an archetype-based approach.

Further, Jaeger et al. (2021) discussed the limitations of the archetype-based approach for Urban building energy modelling (UBEM). They proposed an approach to characterise the buildings in a UBEM through probability density functions (PDFs) defined for key parameters. As per the authors, the PDFs can be statistically defined, including the renovation probability for estimating the possible building values, thus generating realistic variations for existing dwelling stock. In recent studies (Ali et al., 2024; Álvarez-Sanz et al., 2024), the authors utilised sample-based approaches to generate represented data and train machine learning models to predict energy consumption and identify the essential features that can assist in prioritising renovation strategies.

4.1.3 Methodology and outline

While the literature suggests that sampling-based approaches could provide a more feasible solution to address heterogeneity, these approaches have not yet been applied to assess the diversity of dwellings in the Netherlands concerning their readiness for LTH. Therefore, to address the research aim, the methodology employed consists of two components: 1) determining the appropriate sample size to adequately represent the variations in dwelling type, and 2) identifying the significance of building-level parameters in assessing the readiness of a dwelling for LTH, while accounting for the variations. This approach will be applied to terraced-intermediate and apartment dwelling types, which constitute a substantial portion of SFH and MFH in the Netherlands. Section 4.2 presents these selected dwelling types and discusses their representation in the national building stock. Following this, Section 4.3 outlines the methodological framework, detailing the parametric simulation workflow, the generation and identification of appropriate sample size, dataset labelling and the application of supervised machine learning in predicting a dwelling's readiness for LTH. In this study, the LTH refers to heat supplied at Medium Temperature (MT: 70/50°C) and Low Temperature (LT: 55/35°C) levels compared to the High Temperature (HT: 90/70°C) supply. Sections 4.4 and 4.5 describe the results and provide insights into the appropriate sample size required to represent variations in dwelling types. They also discuss the relative importance of the input features extracted from the machine learning model. Finally, Section 4.6 summarises the study's findings and limitations.

The novelty of this study lies in two main aspects: 1) a sampling-based approach in generating a dataset representing the variations found in SFH and MFH in the Netherlands. Such datasets can be utilised in future research endeavours aiming to explore solutions for the energy transition of existing residential stock, 2) the identification of the parameters that significantly influence a dwelling's readiness for LTH while accounting for the variations within the dwelling type. The study argues that incorporating these variations ensures robustness in assessing the implications of these parameters. Moreover, these parameters can serve as a guide for strategising renovations aimed at preparing dwellings for LTH. Consequently, they can assist stakeholders with diverse portfolios in effectively selecting renovation strategies to decarbonise their portfolio by transitioning to LTH supplied by DH systems fuelled by sustainable heat sources.

4.2 Overview of dwelling types

The Dutch dwelling stock comprises a variety of typologies influenced by different construction years and distinctive architectural features. This stock is categorised into 16 types, segmented by four construction periods and four dwelling types, as depicted in Figure 4.1. The dwelling types are clustered into two main categories: SFH, which includes terraced-intermediate, corner and detached houses, and MFH, encompassing various apartment typologies (Cornelisse et al., 2021). The term ‘intermediate’ refers to a dwelling situated between two others, whereas the ‘corner house’ category comprises terraced houses located at the end of row houses and the semi-detached typology, commonly known in Dutch as “*twee onder een kap*” (two under one roof). The apartment category broadly includes maisonettes, walk-ups or porches, gallery and flat types. A more detailed sub-type of apartments, based on their position within the residential block, is provided in (Rijksdienst voor Ondernemend, 2023a).

The categorisation of construction periods reflects the diverse constructional practices and building regulations over the periods considered. For instance, dwellings built before the 1970s have poor energy performance, having been constructed prior to the adoption of thermal regulations (Pothof et al., 2023; Wahi et al., 2023a). In contrast, stricter building regulations to improve energy performance in the Netherlands were introduced in 1991 (Van Der Heijden et al., 2006). A recent housing survey in the Netherlands revealed that dwellings constructed before the 1980s typically have energy labels C or worse, indicating higher energy demands for such houses (Stuart-Fox et al., 2019). These dwellings may present challenges when connecting to DH systems with lower temperature supply (Harrestrup & Svendsen, 2015).

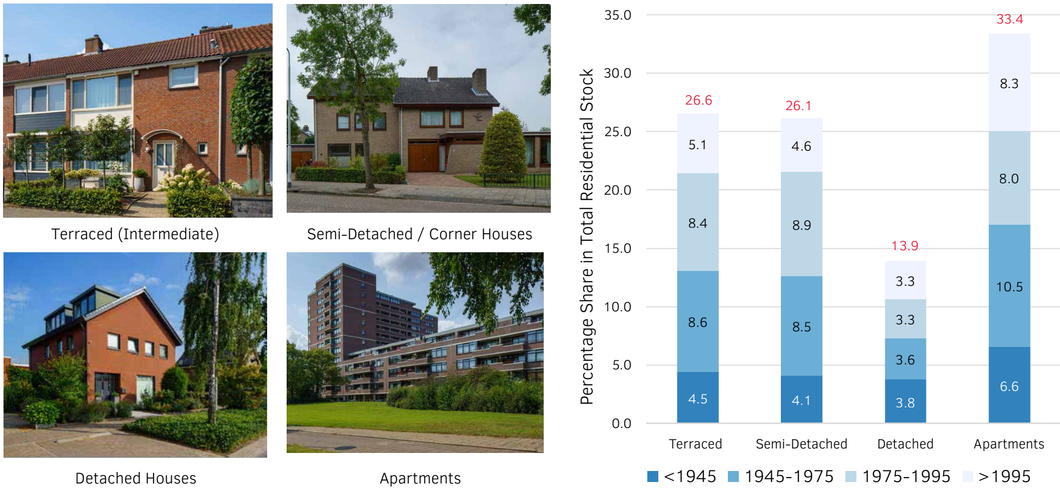

FIG. 4.1 Categorisation of housing stock. The Figure illustrates the categorisation of housing stock based on four dwelling types and their respective share in each construction year and in the total existing housing stock (Cornelisse et al., 2021; Rijksdienst voor Ondernemend, 2023b)

In addition, Figure 4.1 illustrates the distribution of dwelling types across each construction period and within the existing dwelling stock. Comprising 66%, SFHs constitute the majority of the stock, while MFHs make up the remainder. Due to time constraints, this study focuses explicitly on terraced intermediate houses, which represent 26.6% of the stock, and apartments, which account for 33.4%. By focusing on these two types, the study aims to examine a substantial portion of the dwelling stock, characterised by a diverse range of building characteristics, to identify the significant features that determine their suitability for LTH.

4.3 Materials and Methods

This section outlines the methodological steps for analysing variations within a specific dwelling type in the Netherlands, when aiming to assess the influence of building characteristics on the readiness of the dwellings to operate at lower temperature supplies from DH systems. The study first identified key building-level parameters, referred to as interest parameters, which affect both the variations within dwelling type and their readiness for LTH. A sampling procedure was employed to generate diverse samples in order to systematically assess these interest parameters, thus capturing the variations within the dwelling type. These samples were subsequently examined through a parametric workflow to simulate annual space heating demand and underheated hours when the dwellings were occupied. Notably, these output parameters are central to the LTH-readiness definition established in our previous work (Wahi et al., 2023b).

Identifying an appropriate sample size to represent these variations within the dwelling type is essential to this study. To accomplish this, the sample size was incrementally increased until the effects of the interest parameters on the two output parameters converged. The Standardised Rank Regression Coefficient (SRRC), a global sensitivity analysis (GSA) method, was used for this purpose. Subsequently, the identified sample size was used to generate representative samples, which were subjected to simulations at HT (90/70°C), MT (70/50°C) and LT (55/35°C) supply temperatures. Using the LTH-readiness definition, these samples were classified as either “ready” or “not ready” for both MT and LT supply temperatures.

In addition, the representative sample datasets with binary classifications, for MT and LT supply, were used to train the ensemble-based Random Forest (RF) classifier model. The RF models facilitated the extraction of the relative importance of the interest parameters for each dwelling type. This analysis underscores the significance of the building-level parameters in determining the readiness of the dwelling type for both MT and LT supply while also accounting for variations due to these parameters. Figure 4.2 visually describes the methodological steps applied to both terraced intermediate and apartment dwelling types, with corresponding sub-sections providing further explanation. Conversely, Figure A.4.1 in the appendix presents a detailed process workflow used in this study.

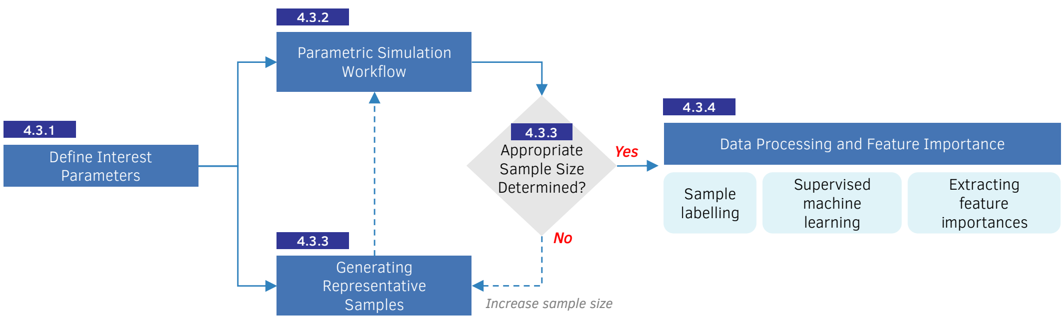

FIG. 4.2 Methodological steps applied to terraced intermediate and apartment dwelling types, with the corresponding sub-section providing further explanation.

4.3.1 Interest parameters

This section describes the identified dwelling characteristics that introduce variability within dwellings as well as affect their readiness for LTH. These variations, resulting from specific interest parameters, contribute to the heterogeneity of the dwelling stock. The parameters that characterise a dwelling can broadly be categorised into geometry, fabric, system and occupancy controls (Mauro et al., 2015; Oraiopoulos & Howard, 2022). Geometrical properties encompass the physical attributes of a dwelling, such as shape, orientation, floor area, window-to-wall ratio and position (particularly in apartment settings) (Pang et al., 2020). Fabric properties refer to the thermo-physical characteristics of both the opaque and transparent components of the building envelope (Álvarez-Sanz et al., 2024). System parameters are concerned with the heating, ventilation and air-conditioning (HVAC) systems and their operational management. Lastly, the occupancy parameters focus on the presence of occupants and their behavioural actions (Oraiopoulos & Howard, 2022).

The systematic literature review in our recent study (Wahi et al., 2023) identified the essential building characteristics that influence the potential for implementing LTH and the necessity for renovations. These characteristics include the compactness ratio, which represents the geometrical relationship between dwelling shape, position and surface area; thermal insulation of the building envelope; ventilation system and airtightness; and the capacity of the existing space heating system as per the supply temperature level. Additionally, indoor heating setpoints were indicated as a parameter reflecting the occupant's preference for indoor comfort. As a result, combining these studies, Table 4.1 illustrates the interest parameters that characterise a dwelling as well as impact its LTH readiness. These parameters are utilised to develop the simulation workflow, as described in the subsequent section, and the sampling procedure is used to generate samples by varying them, as detailed in section 4.3.3.

TOC

TABLE 4.1 Interest parameters that characterise a dwelling and have an impact on LTH readiness (Mauro et al., 2015; Oraiopoulos & Howard, 2022; Pang et al., 2020; Wahi et al., 2023a)

Category	Input Parameter	Units
Geometrical	Orientation	°
	Compactness-Ratio	-
	Window-to-Wall Ratio	-
	Position of Apartment*	-
Fabric	Ground Insulation, R	$m^2 \cdot K/W$
	External Wall Insulation, R	$m^2 \cdot K/W$
	Roof Insulation, R	$m^2 \cdot K/W$
	Glazing Insulation, U	$W/m^2 \cdot K$
	External Door Insulation, U	$W/m^2 \cdot K$
	Infiltration	$dm^3/s.m^2$
HVAC	Ventilation System	-
	Heating Capacity	W
Occupant and Control	Heating Setpoint	°C

**Only for apartment typology*

4.3.2 Parametric simulation

The interest parameters outlined in the previous section informed the development of the parametric simulation workflow, which is designed to process batches of samples produced by the sampling procedure (described in section 4.3.3). The workflow was developed within the Rhino-Grashopper v7 environment with Ladybug Honeybee tools v1.6, which facilitated the translation of Rhino geometry into a multi-zone building energy model. In addition, the samples from the sampling procedure in an Excel file were imported into the grasshopper environment, where an iterator using the Colibri plugin v2.0 was used to run through each sample. Each interest parameter interacted with a seed model that represented a typical geometry and internal layout of the dwelling type. Depending on the values of each interest parameter, the seed model was altered to represent a dwelling case, based on the sample. After generating all the samples, they were simulated in the cloud, and the results were recorded in an Excel output file. This section discusses the development of the seed model, model validation, and cloud computing integration, as shown in Figure 4.3. The Grasshopper and Python scripts developed are open-source and can be accessed through the open-source repository (Wahi et al., 2024).

Generating seed model

Geometry

The seed models illustrate the typical geometry and internal layout of terraced and apartment dwellings, as described in section 4.2. Further, the geometric model for the terraced dwelling was developed using typical plans obtained from (Alavirad et al., 2022; SenterNovem, 2006). These studies indicate that despite representing newer construction, existing dwellings generally share the same layout. Conversely, a typical layout of walk-up apartments (referred to as "*portiekwoning*" in Dutch) was used for the apartment typology. Such apartment types were widespread during the post-war period (Konstantinou et al., 2020; Oorschot et al., 2018; Steensma et al., 2016). The layouts used to generate these geometries can be found in Figure A.4.2 in the appendix.

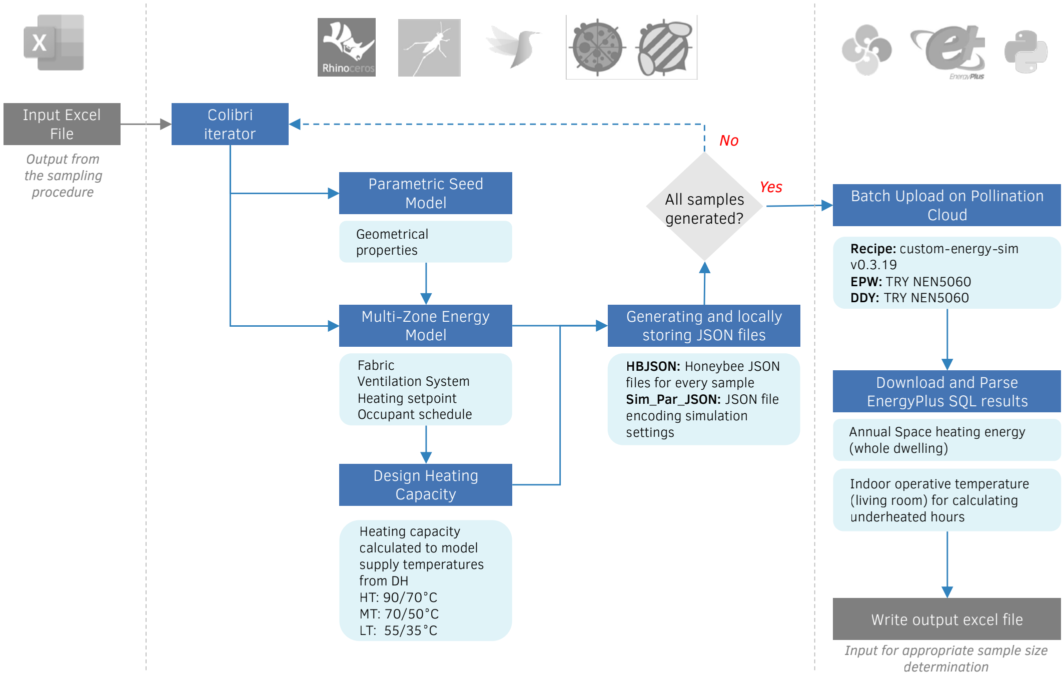

FIG. 4.3 The parametric simulation workflow to simulate the batch of samples.

Even though these models represent the standard geometry and layout of the dwellings, variations in dwelling size exist. These variations were incorporated using the compactness ratio parameter. According to the Dutch Technical Agreement (NTA8800) (2023), the compactness ratio is defined as the ratio between the heat loss envelope surface area (Als) and the total usable heated area (Ag). This ratio serves as a metric for assessing the impact of dwelling size on heat losses and heating demands. Within Dutch regulations, the compactness ratio (Als / Ag) plays an essential role in establishing benchmarks for new construction to achieve nearly zero energy standards (Alavirad et al., 2022; Rijksdienst voor Ondernemend Nederland, 2017) and in defining the insulation standards for existing dwellings (Rijksdienst voor Ondernemend Nederland, 2021).

In the parametric workflow, the sampled compactness ratio is utilised to proportionally adjust the length of the seed model to reflect the variation in the dwelling size. For both dwelling types, a geometric relationship was formulated between the compactness ratio and the length of the seed model while keeping the width and height fixed. Compared to a terraced house, this relationship for apartment typology also reflects its possible positions within the apartment block itself. Nevertheless, it should be noted that in some instances, the sampled compactness ratio may result in unrealistic lengths. Therefore, limits were imposed on the calculated length to mitigate this issue and prevent such samples. Appendix A.4.3 describes the geometric relationship and the corresponding calculations.

Fabric

Once the geometry of the seed model is adjusted to represent the sample, thermal insulation values are assigned to the ground floor, external wall, roof, glazing, and doors. Additionally, the airtightness of the building envelope is assigned as the infiltration rate. In the absence of measured values, the NTA8800 (2023) provides a calculation method to estimate the infiltration rate, taking into account different building types. The calculation method is illustrated in Equation 4.1, where Q_{v10} represents the calculated air infiltration rate, and $q_{v10;spec}$ represents the specific infiltration rate for a building type at a uniform pressure of 10 Pa. The dimensionless correction factor due to building type and position is denoted by f_{type}, while the correction factor due to construction year is represented by f_y.

$$Q_{v10} = f_{type} \times f_y \times q_{v10;spec} \left[\frac{dm^3}{s.m^2} \right] \tag{4.1}$$

TOC

HVAC and occupant control

Ventilation system

In the Netherlands, the three prevalent ventilation systems are A, C and D (Rijksdienst voor Ondernemend, 2023a). System A utilises a natural ventilation system through openings, whereas System C integrates mechanical extract with natural intake (van Bueren et al., 2012). System D, also referred to as a balanced ventilation system, features mechanical intake and extraction and is often combined with a heat recovery (HRV) system (van Bueren et al., 2012). Variants within systems C and D, such as demand-driven or CO_2-controlled, can also be found for specific ventilation needs.

The simulation workflow involves maintaining a minimum ventilation rate for each space as mandated by the Dutch building decree (Bouwbesluit, 2021). System A regulates this rate by operable apertures, with the control operation as per ISSO 32 (2010) guidelines. In contrast, the demand-driven variant of system C adjusts the ventilation based on the occupancy schedule. For modelling system D, the study adopts the approach suggested by Alavirad et al. (2022), where a reduced ventilation rate serves as a proxy for a balanced ventilation system equipped with HRV. This adjustment rate is based on the HRV system's typical efficiency of 90%. However, this study adopts a conservative estimate by reducing the ventilation rate to be maintained by 50%. Consequently, only half the fresh air requires treatment, while the HRV system recovers the other half. This simplification aids in modelling the ventilation systems without complex calculations, focusing primarily on the impact on space heating energy. Nevertheless, it does not account for the operational energy of the system itself and might lead to oversimplification.

Modelling lower supply temperatures from DH systems

When the supply temperature is lowered, the heating capacity of existing space heating systems, such as radiators, is also reduced (Ovchinnikov, Borodiņecs, & Strelets, 2017; Tunzi et al., 2016; Wahi et al., 2023b). In dwellings with a high heating demand due to heat losses, the reduced capacity of the space heating system may be insufficient to offset these losses, potentially causing thermal discomfort to the occupants. Therefore, in this study, design heating capacities are used as a proxy to simulate the effect of supply temperature. Thus, the heating capacities for heated zones are calculated based on steady-state heat loss from ventilation and transmission under design conditions of -10°C outside and 20°C inside, excluding solar and internal heat gains (ISSO, 2018). At this stage, the design heating capacity is considered the same as the theoretical heat loss without oversizing. The calculated heating capacity represents the design capacity of the individual zones in the HT supply, and can be reduced further depending on the lower supply temperature levels, which in this study are MT(70/50°C) and LT(55/35°C). This reduction is calculated using Equations 4.2 and 4.3 (Østergaard & Svendsen, 2016) to evaluate the LTH readiness.

$$\varnothing = \varnothing_0 \times \left(\frac{\Delta T}{\Delta T_0} \right)^n \tag{4.2}$$

$$\Delta T = \left(T_s - T_r \right) \left[\ln \left(\frac{T_s - T_i}{T_r - T_i} \right) \right]^{-1} \tag{4.3}$$

In these equations, $\varnothing$ and $\varnothing_0$ are the radiator heating capacity in watts and ΔT and ΔT_0 are the logarithmic mean temperature difference at the new and original temperature set, respectively. The radiator exponent n is fixed at 1.33. In addition, ΔT is calculated using the supply and return temperature (T_s and T_r , respectively) in °C and the indoor design temperature (T_i) is set to 20 °C.

Heating setpoints and occupant schedule

According to the study by Guerra-Santin and Silvester (2017) on Dutch household occupancy and heating profiles for building simulations, a consistent heating schedule for the entire week can simplify the simulation process. Consequently, this study applies a constant heating setpoint temperature to the living room and kitchen, while a two-degree heating setback is used in bedroom spaces. Cooling systems are not yet standard in Dutch dwellings, although a setpoint of 24 ˚C is used for cooling (Alavirad et al., 2022; ISSO, 2010). This study also assumes an average occupancy of three people, representing a typical nuclear family, with a combined equipment and lighting load of 4 W/m^2 (Alavirad et al., 2022).

Simulation outputs

The simulation models generated for each sample were simulated annually using the test reference year (TRY) recommended by NEN 5060 (Stichting Koninklijk Nederlands Normalisatie Instituut, 2021). Building on the LTH-ready criteria defined in our previous research (Wahi et al., 2023b), a sample qualifies as LTH-ready if it maintains or improves the space heating demand and reduces thermal discomfort at lower temperatures relative to the original HT supply. As a result, annual space heating energy normalised for the total heated area (kWh/m^2), serves as a key performance indicator (KPI) to assess space heating demand. Additionally, the study evaluates thermal discomfort by calculating the occupied cold hours below the 20% predicted percentage dissatisfied threshold, defined here as underheated hours, and based on the method proposed by Peeters et al. (2009).

While the space heating demand is calculated for the entire dwelling, underheated hours are evaluated specifically for the living room. Given that occupants spend the majority of their time in the living room, it can act as a proxy for assessing the thermal comfort of the entire dwelling in the presence of lower temperatures. This approach is supported by findings from our previous research (Wahi et al., 2023b). For determining occupied underheated hours, it is assumed that the living room is occupied for 5840 hours annually from 8:00 to 23:00.

4.3.2.2 Model validation

The models developed from the described workflow are contingent on the accuracy of the outcomes. Therefore, validating the outcome from the simulation workflow is essential. For this purpose, this study utilised the average properties of terraced and apartment dwellings from four construction periods, as provided by the study done by Cornelisse et al. (2021) on insulation standards for Dutch existing dwellings. In addition, the same study details the average space heating demand of these dwelling categories across different construction years. Since there is a lack of reference data for underheated hours, this study will use the average space heating demand for validation from (Cornelisse et al., 2021). A deviation of up to 20% is considered acceptable for validation, accounting for differences in assumptions and calculation methods. Further, Table 4.2 outlines the data used as input to validate the simulation workflow.

TABLE 4.2 Input data used for validating simulation workflow for terraced intermediate and apartment dwelling types (Cornelisse et al., 2021).

Input Parameter	Terraced Intermediate				Apartments				Units
	<1945	1945-1975	1975-1995	>1995	<1945	1945-1975	1975-1995	>1995	
Orientation[1]	0				0				°
Compactness-Ratio[1]	1.2				1.6	1.0	0.6	1.7	-
Window-to-Wall Ratio[1]	0.385				0.417				-
Position of Apartment[2]	-				I-R	C-I	I-I	C-G	-
Heated Floor Area[1]	142				64				m^2
Ground Insulation, R	0.77	0.57	1.16	2.68	0.56	0.48	1.16	2	$m^2 \cdot K/W$
External Wall Insulation, R	0.7	0.84	1.53	2.68	0.58	0.67	1.66	2.61	$m^2 \cdot K/W$
Roof Insulation, R	0.46	1.22	1.5	2.75	1	0.96	1.66	2.67	$m^2 \cdot K/W$
Glazing Insulation, U	2.96	2.73	2.82	2.1	3.11	2.87	2.91	2.16	$W/m^2 \cdot K$
External Door Insulation, U	3.36	3.31	3.33	3.27	3.32	3.30	3.32	3.28	$W/m^2 \cdot K$
Infiltration[3]	3	3	2.5	1.5	1.8	1.95	1.3	0.75	$dm^3/s.m^2$
Ventilation system	A		C		A		C		-
Heating setpoint[4]	20/16		20/18		20/16		20/18		°C
Space heating demand	170	145	110	80	180	150	100	75	kWh/m^2

1 From the seed model
2 I-R: Intermediate-Roof, C-I: Corner-Intermediate, I-I: Intermediate-Intermediate and C-G: Corner-Ground
3 Calculated using equation 4.1
4 Living room and kitchen with 20°C, bedrooms with 16°C for dwellings built before 1975 and 18°C for built after 1975

4.3.2.3 Cloud computing

One essential aspect of developing the workflow was accelerating the simulation process, allowing for rapid testing of various sample sizes. To achieve this, the study leveraged the Pollination cloud computing service for faster simulation (Pollination, n.d.). The multi-zone model of every sample incorporating the geometrical details, fabric, systems and controls was exported into a honeybee Json (HBjson) file format (Figure 4.3). These files were uploaded to the cloud server using the Pollination API and processed using the validated recipe “custom-energy-sim” v0.3.19. Upon completion of the simulations, the EnergyPlus outputs were retrieved as SQL files and parsed within the Grasshopper environment to compute normalised space heating energy demand and underheated hours.

4.3.3 Generating representative samples

As previously discussed, the heterogeneity of the dwelling stock introduces uncertainties regarding their readiness for LTH and the need for appropriate renovation options. Compared to the standard archetype, these uncertainties arise due to the inherent variations within each dwelling type (De Jaeger et al., 2021; Prataviera et al., 2022). To capture this diversity, samples that reflect these variations within specific dwelling types are generated. This section describes the systematic approach for creating these samples based on the interest parameters, as detailed in section 4.3.1. Additionally, it details the method used to determine the appropriate sample size required to represent the variability within the dwelling types.

4.3.3.1 Systematic sampling approach

Probabilistic sampling is a standard practice in conducting uncertainty and sensitivity analyses, as documented in the literature (Carpino et al., 2022; Menberg et al., 2016; Zhou et al., 2023). The uncertainties due to input parameters are typically characterised using ranges and PDFs defined at the individual building level. These uncertainties are incorporated through sample generation to evaluate their impact on the model outputs (Carpino et al., 2022; Pang et al., 2020; Van Hove et al., 2023). In contrast, this study extends the application of ranges and PDFs for interest parameters to cover the full spectrum of dwellings within the same type. Further, this approach allows the incorporation of inherent diversity among the same residential type, providing a broader analysis of variations within the dwelling stock.

A notable challenge in developing representative samples within a dwelling type is the potential creation of unrealistic combinations. For instance, samples might be configured with a balanced ventilation and heat recovery system alongside minimal insulation, combinations that are unlikely to exist in practice. To address this issue, the present study adopted a group sampling procedure with unequal proportion sampling, as discussed by Liang and Shen (2012). This approach involves classifying samples prior to actual sampling in order to enhance their representativeness. Consequently, a systematic multi-level sampling scheme was developed, where the sampling method initially selects the construction year category based on its discrete probability distribution. Further, this distribution is derived from the unequal proportion of the dwelling type across each construction year category. The PDFs and ranges of each interest parameter are subsequently varied according to the construction year class. After selecting the construction period, the sampling method employs the specific ranges and PDFs associated with that period to generate realistic samples.

Nevertheless, it is essential to note that the construction year category does not determine whether a house is ready to utilise LTH from DH systems (Pothof et al., 2023; Wahi et al., 2023a). Many dwellings, particularly those built before the Second World War, are likely to have undergone renovations or periodic maintenance (Rijksdienst voor Ondernemend, 2023a). Therefore, the ranges and PDFs developed for each interest parameter of terraced and apartment dwelling types across the four construction categories represent the current condition of the dwellings. Figure 4.4 illustrates the multi-level sampling approach. The distribution and ranges of interest parameters for four construction year categories are based on data from the 2018 National Housing Survey (Woon database) (Cornelisse et al., 2021; Rijksdienst voor Ondernemend, 2023a). The data is organised separately in Tables A.4.2 to A.4.11 for terraced-intermediate and apartment dwellings in Appendix A.4.4.

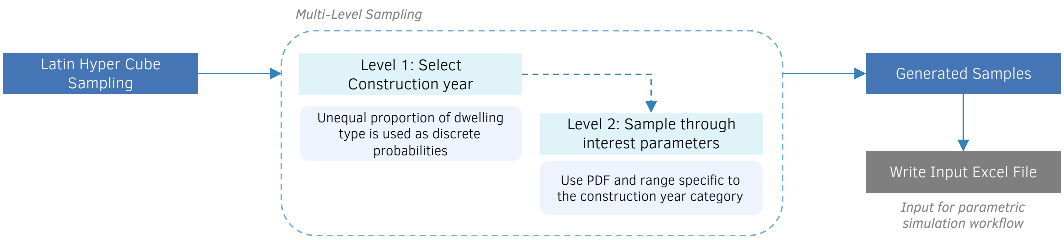

FIG. 4.4 Multi-level sampling scheme for generating representative samples for terraced-intermediate and apartment dwelling types.

Furthermore, the multi-level sampling approach utilises the Latin Hypercube Sampling (LHS) method to generate samples. The LHS method is widely used in building energy analysis as it can produce uniform and converging results with fewer samples (Carpino et al., 2022; Mauro et al., 2015; Pang et al., 2020). In this study, the multi-level sampling framework was implemented using Python v3.8.8 with libraries such as Pandas v2.0.3 (pandas development team, 2023) and SciPy v1.10.1 (Virtanen et al., 2020). The corresponding Python code is available in the open-source repository (Wahi et al., 2024). This code was used to generate a batch of samples, which were then exported as an Excel file. The exported samples were subsequently used in the simulation workflow to parametrically simulate each sample and report the outputs described in the previous section.

4.3.3.2 Identifying appropriate sample size

The reliability of samples to represent the variations depends on selecting an appropriate sample size (Mauro et al., 2015). A comprehensive review by Pang et al. (2020) on sensitivity analysis in building performance studies emphasises the importance of determining the right sample size to ensure reliable results while minimising computational costs. This review advocated assessing robustness and convergence over prior selection in order to determine sample size. Consequently, the present study employed GSA methods to identify the optimal sample size. The GSA approach allows for a thorough exploration of the entire input space by examining all possible combinations of input parameters, their interactions, and impacts on output parameters (Wei, 2013; Zhou et al., 2023). Additionally, these methods are categorised into screening-based, regression-based, variance decomposition and metamodel-based approaches (Ioannou & Itard, 2015; Menberg et al., 2016; Pang et al., 2020; Wei, 2013). This study utilised the SRRC method, a regression-based GSA technique. Compared to variance decomposition methods such as Sobol, SRRC can identify similar first-order interactions with fewer model evaluations, thus offering a computationally efficient alternative (Menberg et al., 2016; Saltelli et al., 2008).

Further, the SRRC method was implemented as a post-processing step where it calculated the ranked regression coefficients for the two output parameters: space heating demand and underheated hours. The magnitude of the SRRC reveals the sensitivity of each parameter, while the sign indicates its positive or negative relationship with the output. Absolute coefficient values were used to rank the interest parameters for both outputs separately. In this study, the sample size was incrementally increased until the ranks and absolute SRRC values stabilised. At this point, it was indicated that the sample size was sufficiently representative of the possible variations within the dwelling type, and further increases would not significantly affect parameter sensitivities.

Additionally, the coefficient of determination (R^2) was used to gauge how well the interest parameters explained the variance in the output parameters within the regression model, while also serving as a measure of the model's linearity (Pang et al., 2020). According to Saltelli, an R^2 value of 0.75 is considered acceptable for applying regression-based methods. If the R^2 is less than 0.75, rank-transformed methods such as SRRC are recommended (Saltelli et al., 2008). Furthermore, SRRC and R^2 values were calculated using the Open TURNS v1.21 (Baudin et al., 2015) library in Python.

4.3.4 Data processing and feature importance

4.3.4.1 Radiator oversizing

Once the appropriate sample size has been determined, a new batch of samples is generated and simulated for the three supply temperatures: HT(90/70°C), MT(70/50°C) and LT(55/35°C), following the procedures described in sections 4.3.3 and 4.3.2, respectively. As outlined in Section 4.3.2.1.3, heating capacities are utilised to study the effects of different supply temperatures. This assumes that the design heat losses, calculated for the HT supply without any overcapacity, represent the design heating capacity of each zone. However, in practice, installed radiator capacity often exceeds these design capacities, commonly referred to as radiator oversizing. Radiators are frequently oversized due to safety margins applied by practitioners and assumptions made during the design stage. This oversizing might also result from renovations that reduce heat losses or from selecting a larger radiator size than is needed from what is available in the market (Domestic Heat Distribution Systems: Evidence Gathering, 2021; Reguis et al., 2021; Tol, 2020). A survey of 515 UK homes revealed that radiators are, on average, oversized by a factor of 1.46, although the degree of oversizing varies widely, impacting the adoption of LTH (Domestic Heat Distribution Systems: Evidence Gathering, 2021). In the Netherlands, Pothof et al. (2023) established a relationship between the design supply temperature and the inverse of the oversizing factor (defined in their study as dimensionless design heat output) based on a survey of 220 Dutch dwellings. Given an oversizing factor, this relationship can help determine the extent to which supply temperatures can be lowered without compromising occupant comfort.

Further, oversized radiators can affect the thermal comfort of a dwelling at lower temperatures. Therefore, it is crucial to consider oversizing when assessing the LTH readiness of the representative samples. Accordingly, this study assumes an additional heating capacity, often considered by practitioners as a safety margin, to heat the dwelling from cold temperatures after a period without heating. This extra capacity is calculated as 20 times the heated floor area of the thermal zone and added to its design heat losses (due to transmission and ventilation) to determine the installed heating capacity of the specific thermal zone (Schalkoort & van den Engel, 2014). It is important to note that while this assumption is applied generically across all samples, installed radiator capacity can be higher than this estimate due to the factors described above. The heating capacities calculated with this approach are applied at the HT level and adjusted for MT or LT, as outlined in Section 4.3.2.1.3.

4.3.4.2 Labelling samples for LTH readiness

The simulated samples with assumed oversized heating capacity were evaluated using the LTH-ready definition described in Section 4.3.2.1.4. This evaluation aimed to label the samples as either “ready” or “not ready” for MT and LT supply. Figure 4.5 illustrates this labelling process. Subsequently, the labelled datasets were analysed using a supervised machine learning technique, the Random Forest (RF) classification algorithm.

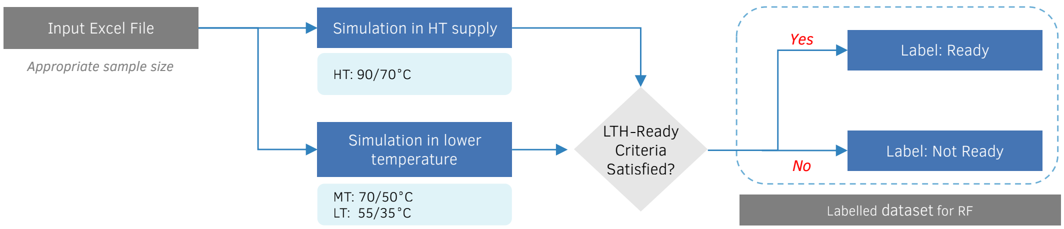

FIG. 4.5 Labelling process by applying LTH-ready criteria on MT and LT supply datasets. The labelled datasets were then used to train an RF.

4.3.5 Random forest classification

The RF algorithm is an ensemble-based machine-learning technique that addresses classification and regression problems by generating multiple decision trees during the training phase. Each tree is trained independently using different random samples generated through bootstrapping of the training data (Hussien et al., 2023; Najafi et al., 2021; Yao et al., 2023). This algorithm is widely used in building performance studies due to its ability to handle high-dimensional data and various input types, such as categorical and continuous parameters (Jaxa-Rozen & Kwakkel, 2018). Compared to other algorithms, RF models can provide good results without extensive hyperparameter tuning (Ahmad et al., 2017), and they allow for the extraction of feature importance, offering insights into the parameters that most influence the model’s predictions (Najafi et al., 2021).

Feature importance extraction from RF models has been utilised previously in studies focusing on energy performance and renovation for dwellings. For instance, Cheng and Ma (2016) used the RF regression model to identify parameters influencing the energy performance of residential buildings in New York City. Their study

TOC

investigated 171 features related to energy use intensity and identified the 20 most influential parameters. Further, Olu-Ajayi et al. (2022) employed an RF classifier model for feature selection from 23 input parameters. They selected the ten most impactful features for developing a machine learning regression model to forecast annual energy consumption in a large dataset of residential buildings. Additionally, Borragán et al. (2022) utilised classification algorithms to identify renovation plans and their associated costs for different residential types in the Flemish region of Herentals. Through RF classification, their study extracted the relative importance of building features that are significant in predicting the type of renovation.

In this study, an RF classification model was trained on the labelled dataset for the terraced and apartment dwelling types (outlined in section 4.3.4.2). Each dwelling type has two labelled datasets for MT and LT supply, resulting in a total of four RF classifier models. For model training, the features included interest parameters that caused variations within the dwelling type as well as affected their LTH readiness, with the readiness label serving as the target variable. A typical train-test split of 80:20 was used, where 80% of the data was used for training the RF model, and the remaining 20% was used for evaluating performance. The performance of the RF model was assessed using standard classification metrics such as accuracy, precision, recall and F1 scores (Ali et al., 2024; Borragán et al., 2022; Mosley, 2013; Najafi et al., 2021). These metrics provide various measures of model performance concerning correct predictions (True Positives and True Negatives) and classification errors (False Positives and False Negatives).

In the context of this study, True Positives and True Negatives represent the number of samples correctly predicted as “ready” or “not ready”, respectively, for a particular lower supply temperature. False Positives are samples incorrectly predicted as “ready” when they are not, while False Negatives are samples predicted as “not ready” when they actually are. Accuracy measures the overall correctness of the model in predicting LTH readiness. Meanwhile, precision measures the proportion of samples predicted as “ready” that were actually “ready,” with high precision indicating that the model’s “ready” predictions are usually correct. Recall measures the model’s ability to identify actual “ready” samples among all the ready samples, with high recall indicating that the model effectively captures most “ready” instances. Lastly, F1 scores provide a single metric that balances precision and recall.

After evaluating model performances, the feature importances for each dwelling type at both supply temperature levels were extracted. The relative importance of each parameter was examined to understand its contribution to the model’s predictions. This analysis provided a clear understanding of which building-level parameters are most influential in determining the readiness of each dwelling type for both MT and LT supply. Additionally, the analysis accounted for variations due to these parameters, offering a comprehensive view of their effects.

4.4 Results

4.4.1 Validation of the parametric simulation workflow

The parametric workflow was validated by generating and simulating models using the input data described in Table 4.2, derived from Cornelisse et al. (2021). For validation, the model generation adhered to the assumption in the study by Cornelisse et al. (2021) that the design heating capacities are equivalent to the design heat losses without oversizing. These calculated heating capacities for the thermal zones were considered for the HT supply. Figure 4.6 illustrates the validation results, comparing the benchmark and simulated space heating demand for terraced-intermediate houses and apartments across each construction category. Additionally, the position of the apartment indicates the effect of location. The graph demonstrates that, given the input data from Table 4.2, the models generated through the workflow can simulate within a 20% deviation from the benchmark performance. However, variations exist where the models either overestimate or underestimate the performance. These discrepancies are attributed to differences in assumptions and calculation methods. For instance, the benchmarks provided in the study by Cornelisse et al. (2021) were calculated using NTA8800, which employs steady-state calculation with correction factors, whereas the present study utilised dynamic simulation.

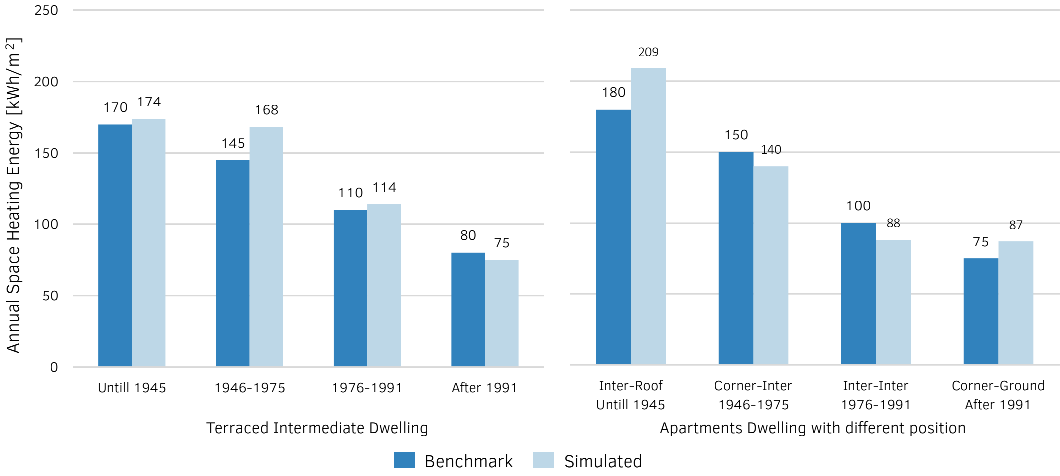

FIG. 4.6 Validation of the parametric simulation workflow by comparing benchmark data (Table 4.2) from the study of Cornelisse et al. (2021) with simulated model performance.

4.4.2 Determining the appropriate sample size

The validated simulation workflow was used to determine the appropriate sample size for both dwelling types. The simulated data from each sample size iteration was post-processed using the SRRC method to assess the sensitivity of the input parameters to the output parameters, specifically space heating demand and underheated hours. Additionally, the sample size was iteratively increased in multiples of 100 until the ranks and SRRC values stabilised, representing the appropriate sample size to capture variations in the dwelling type. This process was conducted separately for each dwelling type and the two supply temperatures (MT and LT).

Figures 4.7 and 4.8 illustrate the parameter ranking, absolute SRRC, and the R2 values for the two output parameters for terraced-intermediate and apartment dwellings, respectively, under the MT supply of 70/50°C. The SRRC ranks and absolute values were analysed together, as the ranks are sensitive to slight changes in the absolute SRRC values. For the terraced dwellings (Figure 4.7), the SRRC ranks for many parameters stabilised at 1000 samples for space heating demand. In contrast, for underheated hours, the ranks stabilised after 1200 samples. The sample size with comparatively higher R^2 for both outputs was chosen as it can better explain the variance in them. Therefore, a sample size of 1300 was selected.

TOC

A similar process was applied to the apartment dwelling type. Figure 4.8 shows that stabilisation of the ranks and SRRC values for many parameters were achieved at 1000 samples for space heating demand and 700 for underheated hours. Compared to the terraced-intermediate type, the apartment dwelling type exhibited a lower R^2 value, indicating higher non-linear effects, thereby justifying the use of the SRRC method. Nevertheless, the sample size with the highest R^2 again corresponded to 1300 samples. The same experiment was repeated with the LT supply, varying the sample size between 1000 and 1400, as shown in Figures A.4.3 and A.4.4 in Appendix A.4.4. It was found that for LT supply, the ranking, absolute SRRC, and R^2 values also converged at a sample size of 1300. Thus, it was concluded that a sample size of 1300 for terraced-intermediate and apartment types is appropriate for representing the variations due to the interest parameters within the dwelling types.

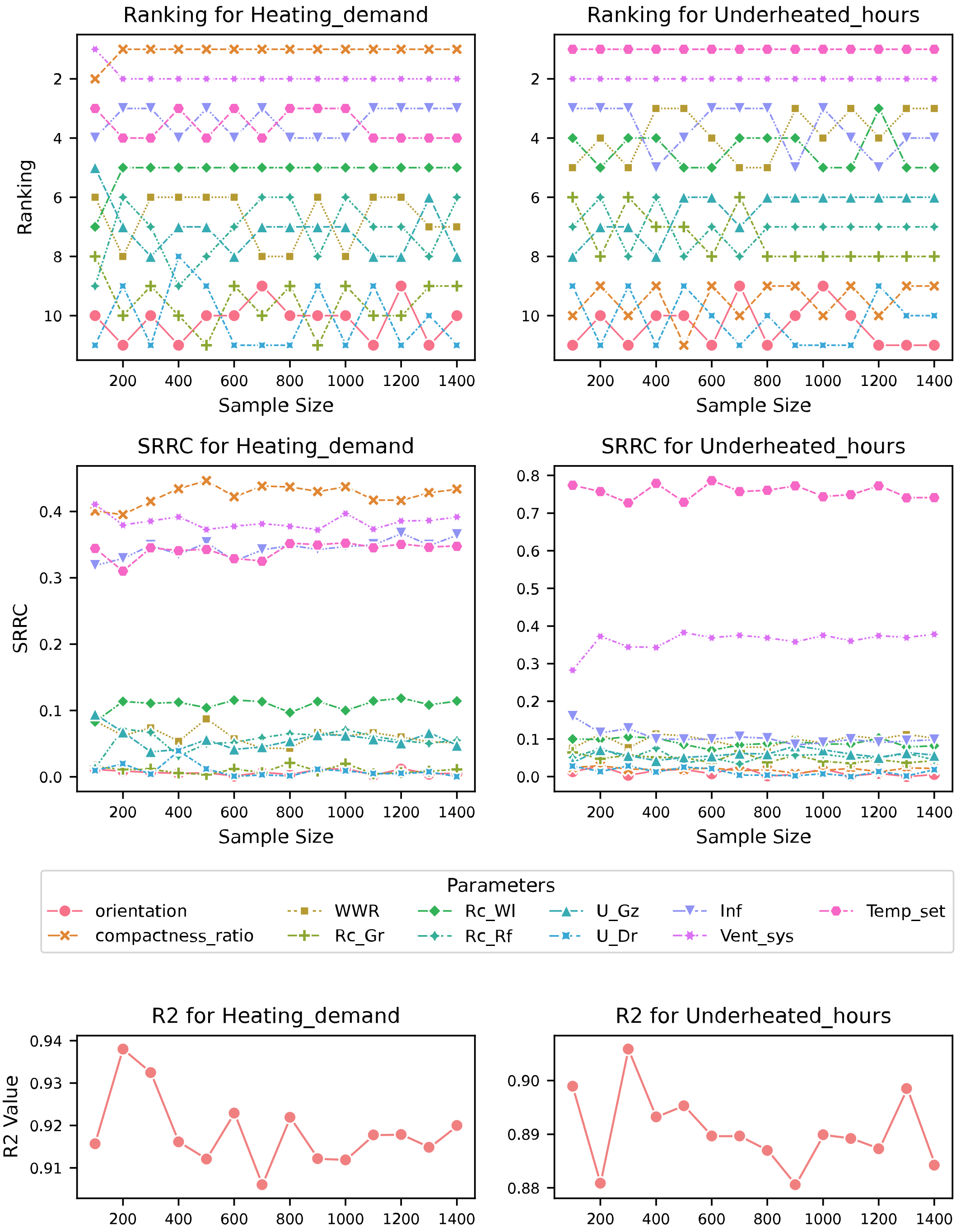

FIG. 4.7 Parameter ranking, SRRC absolute and R2 values of terraced-intermediate dwelling type for the two output parameters under MT supply of 70/50°C.

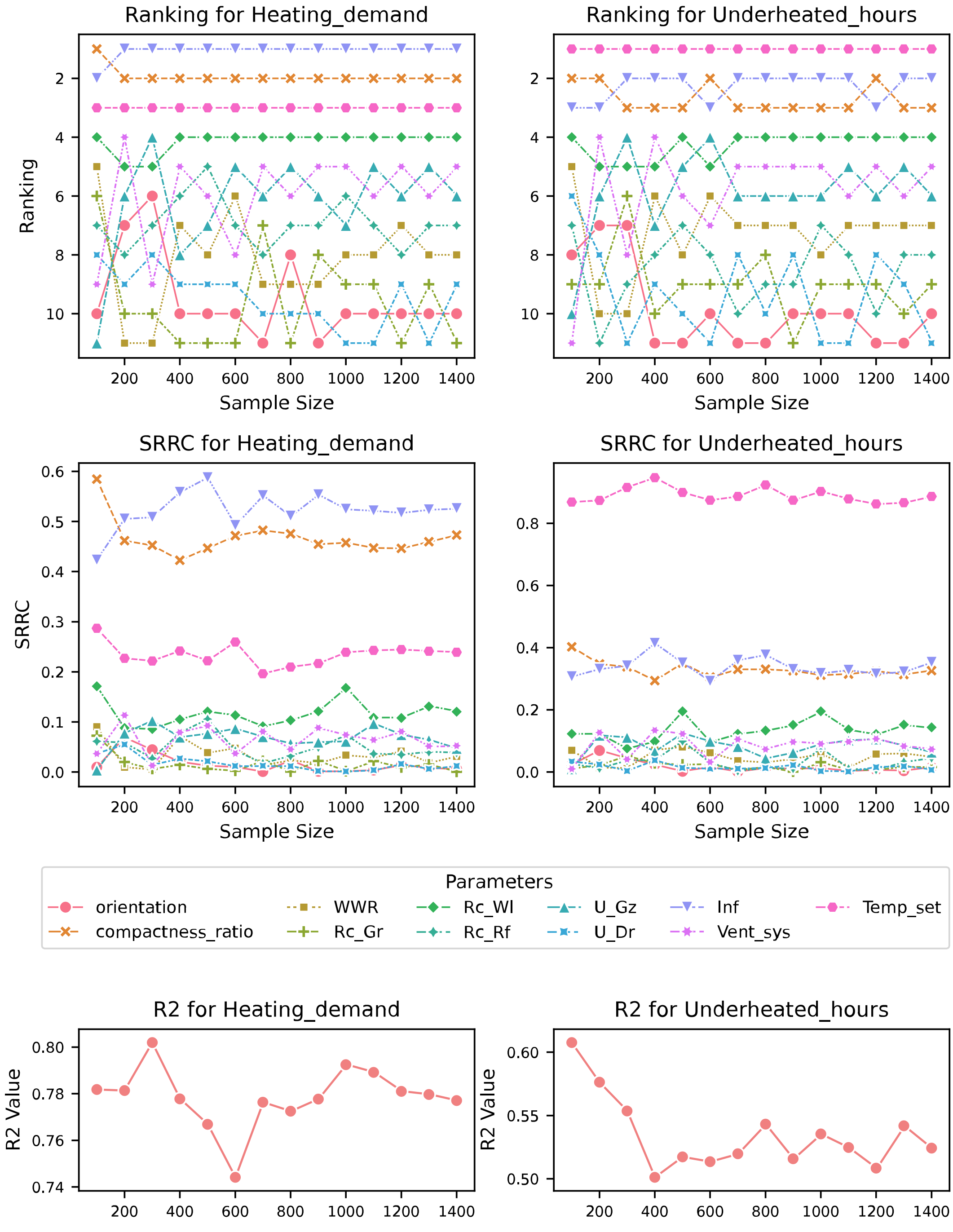

FIG. 4.8 Parameter ranking, SRRC absolute and R2 values of apartment dwelling type for the two output parameters under MT supply of 70/50°C.

TOC

4.4.3 Labelling for LTH-readiness of dwelling types

A new batch of 1300 samples was generated and subjected to annual simulations under HT, MT and LT supply. The generic assumption of radiator oversizing (outlined in section 4.3.4.1) was considered when calculating the design heating capacities under HT supply. The dataset with simulated outputs was labelled for LTH-readiness as described in section 3.4.2. Further, Figure 4.9 illustrates the distribution of terrace-intermediate and apartment types being LTH-ready under MT and LT supply.

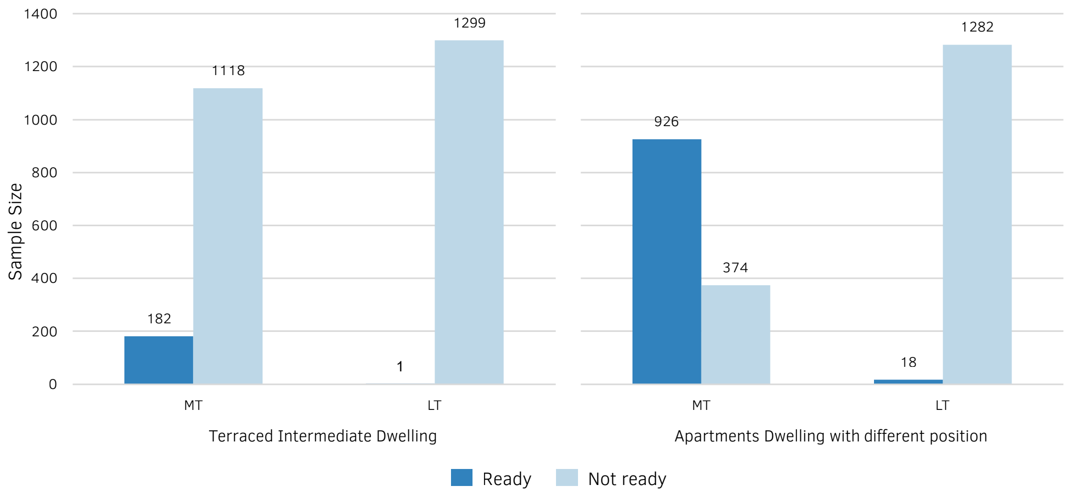

FIG. 4.9 Distribution of LTH-readiness of terraced-intermediate and apartment dwelling types for MT and LT supply.

The graph illustrates that, in the current state, approximately 14% of terraced-intermediate samples are ready to be heated with DH systems under MT supply. In contrast, 71% of apartment dwellings are suitable for MT supply. However, neither the apartment nor terraced-intermediate type is prepared for LT supply from DH systems. Specifically, only one terraced-intermediate sample was ready for LT supply, compared to 18 apartment samples. This indicates that the majority of terraced-intermediate dwelling types are not yet suitable for either MT or LT supply and would require energy renovations before being connected to DH systems under these temperature supply conditions. While apartment dwellings show significant readiness for MT supply, they nevertheless need adjustments to be suitable for LT supply from DH systems.

4.4.4 Classification models and feature importance

4.4.4.1 Data processing for model training

The RF classifier was utilised to train the models on the labelled datasets to predict the readiness of samples for both dwelling types for MT and LT supply. From these classification models, the relative importance of the features (interest parameters) used to predict the target variable (LTH-readiness label) was extracted. This ranking of feature importance aids in identifying the parameters that influence the readiness of the dwellings. However, as shown in Figure 4.9, the labelled dataset exhibits a significant class imbalance problem.

Class imbalance refers to datasets with an unequal proportion of positive and negative classes (Akosa, 2017; Kulkarni et al., 2020). This issue is commonly observed in scenarios such as fraud detection or medical diagnosis, where most of the instances correspond to the negative class (referred to as the majority class) compared to the positive class (referred to as the minority class) (Chen & Liaw, 2004; Kulkarni et al., 2020). The class imbalance problem impacts classification accuracy and can introduce bias into the trained model. Therefore, it is essential to address the imbalance in the dataset prior to using it for model training. One approach suggested in the literature is cost-sensitive learning, which assigns a higher cost to misclassifying the minority class during training (Akosa, 2017; Chen & Liaw, 2004). This study implemented the class weighting using the built-in functionality of the RF classifier available in the Scikit-learn v1.4.2 Python library (Pedregosa et al., 2011).

Moreover, the RF models for terrace-intermediate and apartment dwelling types were trained for MT supply by assigning weights to the respective minority and majority classes. In contrast, for both dwelling types, very few samples are ready under LT supply; thus, the data is deemed insufficient for training the models for it. As per the LTH ready criteria, a sample is considered ready if the space heating demand and underheated hours in the lower temperature supply are less than or equal to those in the HT supply. Specifically, for underheated hours, this means that a sample under LTH with even one more underheated hour than that of HT supply would be considered not ready for the lower supply temperature. This strict criterion might be too rigid in reality and requires an experimental investigation of the acceptable range of discomfort hours for a dwelling to be ready for LTH. Consequently, a necessary assumption was made to relax the underheated hours criterion by 15 hours for both dwelling types under LT supply conditions. These hours represent one occupied day in the living room between 8:00 – 23:00. The relaxed criteria resulted in 8% of terraced-intermediate and 33% of the apartment samples being ready for LT supply, which can now be used for training RF models with class-weighting.

4.4.4.2 Evaluation of trained models

Two training scenarios were employed to compare model performance: one using the original imbalanced dataset and the other using the cost-sensitive approach. The trained models were then evaluated using the test dataset, which was kept aside during the training phase. Despite the different training methods, the class distribution remained imbalanced. Therefore, balanced accuracy, which measures the average accuracy of the model for both minority and majority classes, was used. Additionally, precision, recall, and F1 scores were considered to evaluate the models' performance. Table 4.3 shows the performance of the trained models on the test dataset for two supply temperatures for terraced-intermediate and apartment dwelling types. The Table also compares the models trained for each supply temperature using the original imbalanced dataset and the cost-sensitive approach.

TABLE 4.3 Evaluation of the trained classification models on the test set. The models were trained using the original imbalanced dataset (RF) and cost-sensitive approach (RF_weighted) for MT and LT supply for both dwelling types.

Evaluation metrics	Terraced-Intermediate				Apartment			
	MT supply		LT supply*		MT supply		LT supply*	
	RF	RF_weighted	RF	RF_weighted	RF	RF_weighted	RF	RF_weighted
Balanced Accuracy	0.892	0.851	0.962	0.951	0.774	0.782	0.922	0.928
Precision	0.902	0.916	0.741	0.880	0.800	0.842	0.897	0.898
Recall	0.804	0.717	0.958	0.916	0.615	0.615	0.897	0.909
F1 Score	0.850	0.804	0.836	0.897	0.695	0.711	0.897	0.903

* model trained on relaxed underheated hours criteria

The RF model is preferred for terraced-intermediate dwellings under MT supply due to its higher balanced accuracy and recall score, despite the RF_weighted model exhibiting slightly better precision. This implies that the RF model is more effective at correctly identifying both "ready" and "not ready" cases, thus providing a robust assessment of readiness. However, it may generate a few false positives when compared to the RF_weighted model due to its slightly lower precision. The higher recall ensures that most dwellings that are actually ready for MT supply are correctly identified. Conversely, the RF_weighted model is favoured under LT supply due to its better balance between Precision and Recall, resulting in a higher F1 Score. This suggests that the RF_weighted model can more accurately identify actual ready cases while minimising false positives, leading to more reliable readiness predictions.

Further, for apartments, the RF_weighted model consistently outperforms the RF model. Under MT supply, the RF_weighted model shows higher balanced accuracy and precision. It is important to note that the minority class in this model is the negative class. Therefore, the precision and recall scores reflect the model's performance in predicting the "not ready" class. Even though the RF_weighted model surpasses the RF model in these metrics, its overall performance is lower than other models, suggesting the need for further hyperparameter tuning. Lastly, the RF_weighted model performs better across all metrics for apartments under LT supply, effectively identifying both "ready" and "not ready" cases.

4.4.4.3 Extracted feature importance

The relative importance of the features is presented in Table 4.4 in descending order of their contribution to the model's predictions for MT and LT supply in terraced-intermediate and apartment dwelling types, respectively. The Table highlights that building-level features affect the readiness differently for each dwelling type. Regarding specific supply temperatures, the parameters influencing readiness for MT and LT in terraced-intermediate types are similar, with some fluctuations. In contrast, feature importance rankings for apartments show variations, as detailed in Table 4.4. However, some general trends can be observed for the parameters affecting readiness for LTH in both dwelling types.

TABLE 4.4 Importance Ranking for terraced-intermediate and apartment dwelling type for readiness in MT and LT supply. The numbers represent the contribution of features in predicting LTH readiness.

Rank	Terraced-Intermediate				Apartment			
	MT		LT		MT		LT	
1	Heating Setpoint	0.326	Heating Setpoint	0.558	Infiltration	0.238	Heating Setpoint	0.465
2	Ventilation System	0.217	Ventilation System	0.228	Compact-ness-Ratio	0.174	Infiltration	0.250
3	Roof Insulation	0.062	Roof Insulation	0.035	Heating Setpoint	0.119	Roof Insulation	0.048
4	Glazing Insulation	0.059	Infiltration	0.032	External Wall Insulation	0.087	Compact-ness-Ratio	0.043
5	Infiltration	0.057	Glazing Insulation	0.031	Glazing Insulation	0.081	Ventilation System	0.040
6	Orientation	0.055	Orientation	0.028	Roof Insulation	0.075	Glazing Insulation	0.040
7	External Wall Insulation	0.053	External Wall Insulation	0.023	Ground Insulation	0.070	External Wall Insulation	0.034
8	Compact-ness-Ratio	0.051	External Door Insulation	0.019	External Door Insulation	0.058	Ground Insulation	0.029
9	Ground Insulation	0.050	Ground Insulation	0.018	Ventilation System	0.045	External Door Insulation	0.025
10	External Door Insulation	0.042	Compact-ness-Ratio	0.013	Orientation	0.032	Orientation	0.011
11	Window-to-Wall Ratio	0.022	Window-to-Wall Ratio	0.011	Window-to-Wall Ratio	0.016	Window-to-Wall Ratio	0.010

For instance, the heating setpoint is among the most influential parameters for both dwelling types, contributing 20-50% in the prediction of a sample's readiness for LTH. A lower heating setpoint could reduce space heating energy, although it might increase the number of underheated hours. Even though a higher temperature setpoint for heating could reduce uncomfortable hours due to underheating, it could increase space heating energy consumption. This highlights the crucial role of occupants and their heating preferences in dictating the readiness of the dwelling.

Following the heating setpoint, the parameters related to the ventilation heat losses significantly influence LTH readiness. Overall, it can be seen that ventilation systems are more impactful for terraced-intermediate dwellings, whereas, for apartments, infiltration is more influential. These findings align with other studies exploring the influential features affecting the prediction of heating demand from machine learning models. Ali et al. (2024) trained a machine learning model to predict the energy performance of the Irish building stock and found that the most influential characteristics for heating demand are air change rate and temperature setpoints for heating, followed by fabric-related parameters. Similarly, Álvarez-Sanz et al. (2024) identified infilteration as an influential parameter in space heating demand using machine learning algorithms. These results indicate the importance of curbing ventilation heat losses with efficient ventilation systems and reducing the infiltration rate to prepare the dwelling types for heating with lower supply temperatures.

In terms of building envelope insulation, except for apartments in MT supply, the dwelling types follow a similar pattern of influence. Roof and window insulations are the most influential, followed by wall insulation, with ground insulation and door insulation being consistently less influential. This aligns with the study by Borragán et al. (2022), who trained a random forest classifier model to predict renovation measures for different dwellings in the Flemish region of Herentals, Belgium. They also found that roof insulation had the highest influence, followed by window, wall, and ground-floor insulation.

Regarding geometric properties, the window-to-wall ratio does not significantly influence LTH readiness for either dwelling type. A possible reason could be the lack of variations during the sampling process. The window-to-wall ratio variable was fixed with the average ratio for each construction year and for both dwelling types, as per (Rijksdienst voor Ondernemend, 2023a). Compared to the terraced-intermediate type, the compactness ratio has a more substantial influence on apartments, as it also considers the dwelling's position, which determines the heat loss area and affects LTH readiness. Lastly, orientation is shown to have some effect on terraced dwellings but a minimal influence on apartments.

4.4.5 Effect of radiator oversizing on LTH readiness

As described in section 4.3.4.1, radiator oversizing might influence the readiness of dwellings for LTH. To investigate this, a separate analysis was conducted. The oversizing factor is calculated as the ratio of installed heating capacity to design heating output. In this study, the design heating output is determined by the steady-state heat loss under design conditions. However, the installed heating capacity can vary for each dwelling, making it difficult to determine without an on-site inspection. Nevertheless, a recent study by Pothof et al. (2023) provides insight into oversizing factors based on surveying and monitoring 220 dwellings representative of existing Dutch homes. Their study found that the oversizing factor ranges between 1.25 and 5 for the sample studied, varying with the dwelling types.

To assess the impact of the radiator oversizing on LTH suitability, four oversizing factors (1.25, 1.66, 2.5, 5) were used. The results were compared with the generic oversizing assumption described in section 4.3.4.1. A batch of 1300 samples was simulated under HT, MT, and LT supply conditions, incorporating these four oversizing factors. Further, these samples were evaluated using the LTH readiness definition to determine the increase in readiness for different oversizing factors.

Furthermore, Figure 4.10 illustrates the effect of oversizing factors on the readiness of terraced-intermediate and apartment dwelling types for LTH. The Figure shows that a higher oversizing factor generally corresponds to a higher level of readiness for lower temperature supply. Additionally, different oversizing factors indicate varying degrees of readiness, with apartments typically being more prepared for MT and LT supply. For terraced-intermediate dwellings, an oversizing factor in the range of 2.5 to 5 is required for over 50% of the samples to be ready for MT or LT supply. In contrast, apartments require a lower oversizing factor, between 1.25 and 2.5, to be prepared for LT supply, as they are already ready for MT supply. These results complement the findings by Pothof et al. (2023), suggesting that the oversizing factor is a significant parameter influencing LTH readiness. However, it is essential to investigate the uncertainties associated with the oversizing factor by incorporating data on installed heating capacity in national housing surveys.

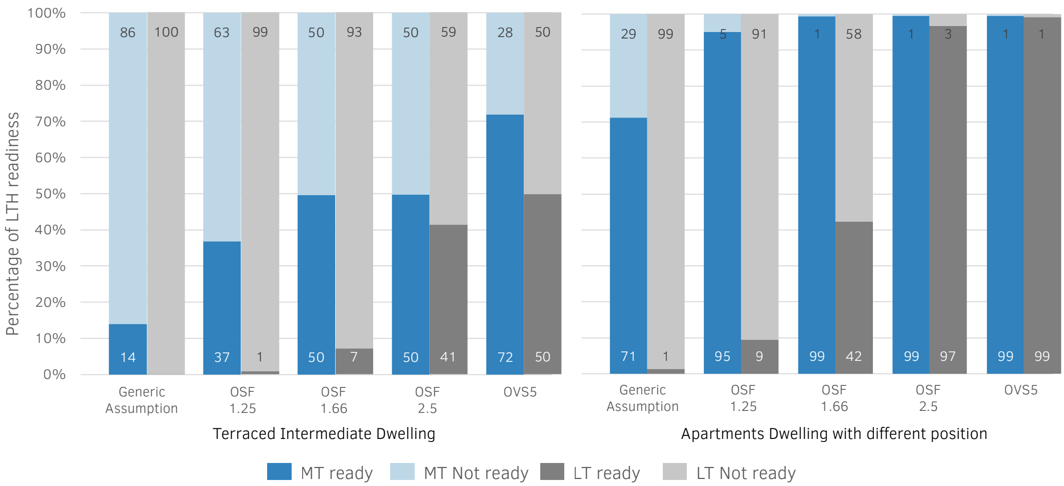

FIG. 4.10 The effect of different oversizing factors on the LTH readiness of the dwelling types.

4.5 Discussion

4.5.1 Sampling-based approach

This study identified the most influential factors affecting the LTH readiness of terraced-intermediate and apartment dwelling types. Unlike the traditional archetype-based approach, a sampling-based method was adopted to incorporate the possible variations in dwelling types due to parameters that not only characterise a dwelling but may also affect LTH readiness. Further, the study determined that a sample size of 1300 for both dwelling types could represent the possible variations due to building-level interest parameters. While a larger sample size can reduce uncertainties caused by variations in dwelling types, the determination of the sample size depends on the study's context, interest parameters, and available computational resources. Therefore, this determination must be made for each specific study and should not be generalised.

Currently, the study was limited to terraced-intermediate and apartment dwelling types, although the sampling-based method can be scaled to include other dwelling types, such as detached and semi-detached. Additionally, the multi-level sampling framework can be adjusted to sample through the entire building stock, thus providing opportunities to adapt the approach from the building to the dwelling stock level. However, a potential bottleneck in the methodology corresponds to the iterative generation of HBjson models from the parametric simulation workflow in the Grasshopper environment. The time taken to generate the Hbjson depends on the processing capacity of the local system, which directly affects the number of samples that could be studied. A possible solution would be to develop the simulation workflow through custom scripts on Python. This can be achieved by exploiting libraries such as Geomeppy to alter the geometrical aspects of the samples and Eppy for EnergyPlus simulations.

4.5.2 Implication of feature importance

Extracting feature importances from the trained models offers valuable insights into the factors influencing the model's predictions. These insights help to create an understanding of the key parameters determining the readiness of dwellings for LTH. According to Table 4.4, both dwelling types have different parameters affecting their readiness. However, there are some commonalities across both types.

In general, the findings of this study suggest that parameters related to occupancy have the most significant influence on a dwelling's readiness for LTH. This is followed by the impact of HVAC systems, building envelope insulation, and geometric properties. While these findings can be generalised to some extent at the dwelling stock level, they also reveal the specific impacts of different building-level parameters for each dwelling type. Therefore, to accurately assess a dwelling's readiness for LTH, it is essential to consider the relative importance identified for the particular dwelling type. However, it should be noted that these results are based on the specific data and variables studied. Incorporating additional variables and improvements in the data generation method can refine the importance rankings and enhance the overall analysis. In addition to these parameter influences, radiator oversizing has a significant impact on the readiness of the dwelling. Future studies should include this factor, along with associated uncertainties, for a more comprehensive analysis of LTH readiness in the Netherlands.

Regarding the practical implications, the influence of building-level parameters can guide the prioritisation of renovation measures to make dwellings LTH-ready. The selection of appropriate renovation measures would be based on additional decision-making criteria, such as carbon emissions, initial investment, life cycle cost, payback period, and hassle for the occupants. Nevertheless, the feature importance can be used to prioritise renovation strategies in order to develop targeted measures to make the dwelling LTH-ready. This can significantly help stakeholders to reduce decision-making struggles by alleviating the decision paralysis that occurs when selecting appropriate solutions from various available renovation options.

4.6 Conclusions

Transitioning existing dwellings in the Netherlands to LTH supplied by DH is essential for achieving the Dutch decarbonisation goals. Consequently, energy renovations might be required to prepare them to be heated with LTH. However, the heterogeneity of the housing stock poses significant challenges in determining the necessary energy renovations and selecting appropriate strategies. To address these challenges, this study provides a comprehensive assessment of building-level parameters that affect the readiness of Dutch dwellings, particularly terrace-intermediate and apartment dwelling types, for LTH from the DH system. By employing a sampling-based approach, representative samples were generated to capture the inherent variability within these dwelling types. This method addresses the limitations of traditional archetype-based approaches by incorporating a broader range of building-level parameters and variations, thereby offering a more robust framework for evaluating LTH readiness.

The findings revealed that a sample size of 1300 is adequate to incorporate the variations within the terraced-intermediate and apartment dwelling types. These samples were assessed for LTH readiness by comparing them to high-temperature (HT: 90/70°C) supply benchmarks and evaluating their suitability for medium-temperature (MT: 70/50°C) and low-temperature (LT: 55/35°C) supply. The results indicate significant differences in the readiness of these dwelling types for lower temperature supply conditions. Specifically, terraced-intermediate dwellings show limited readiness for both MT and LT supply. Conversely, while a considerable proportion of apartment dwellings are ready for MT supply, very few are suitable for LT supply, highlighting the varying levels of LTH readiness.

Moreover, the feature importance analysis from the RF classification models underscores the critical influence of building-level parameters. Key factors influencing LTH readiness include (in this order of importance) temperature setpoints for heating, ventilation-related parameters (ventilation system and infiltration), fabric-related parameters (roof, glazing, wall, ground, and door insulation), and geometric properties (orientation, compactness ratio, and window-to-wall ratio). To accurately assess a dwelling's readiness for LTH, it is crucial to consider the relative importance of these factors specific to the dwelling type. Additionally, radiator oversizing significantly impacts LTH readiness, suggesting that future studies should incorporate this factor and its associated uncertainties for a more comprehensive analysis of LTH readiness in the Netherlands.

These insights can guide stakeholders in inspecting the existing condition of the dwellings within their portfolio and prioritising renovation measures to make them LTH-ready. Understanding the influence of these parameters can help stakeholders develop targeted renovation measures, thereby reducing decision paralysis when selecting the appropriate renovation solutions. These findings are robust as they were derived by incorporating the representative variations within the studied dwelling types and can aid in preparing dwellings for LTH. However, it is essential to note that the results are based on the available data. Including more refined data could further improve the accuracy and nuance of the results, thereby better supporting the energy transition of the dwelling stock in the Netherlands.

Data availability

The dataset and corresponding code are available on 4TU.ResearchData and can be accessed through the following DOI: https://doi.org/10.4121/65afe08d-ee21-4531-9218-5f595cef7f69.v1.

Appendices

A.4.1 Detailed process workflow

Figure A.4.1 illustrates the detailed porcess followed in this study.

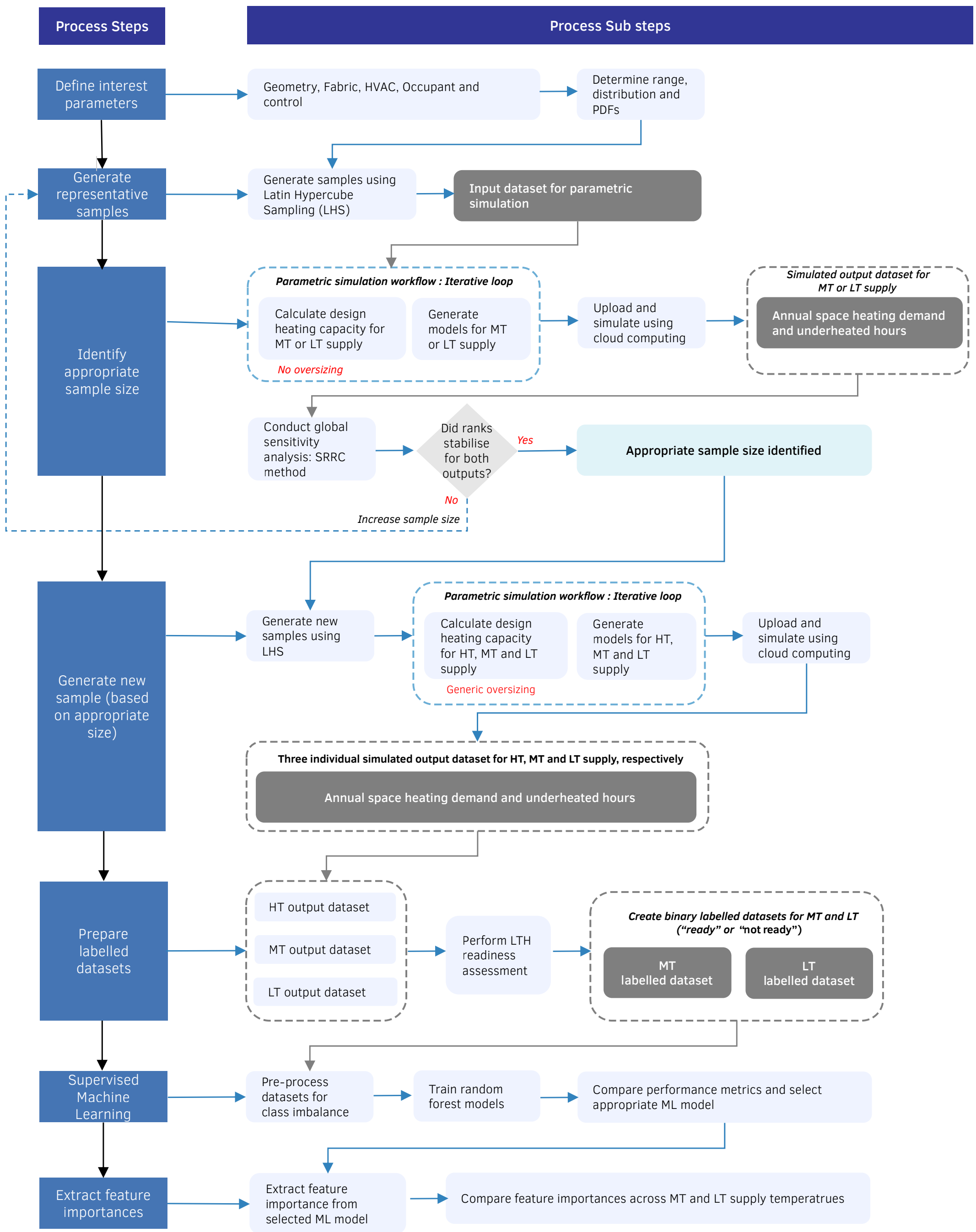

FIG. A. 4.1 Detailed process steps and sub-steps followed in this study.

A.4.2 Typical dwelling layouts

Figure A.4.2 presents the typical layouts for terraced-intermediate (Alavirad et al., 2022; SenterNovem, 2006) and apartment dwelling types (Oorschot et al., 2018). For terraced-intermediate dwellings, an overall height of 10.6 m and a floor-to-floor height of 2.7 m are considered. In contrast, a floor-to-floor height of 2.8 m is used for apartment dwellings.

FIG. A. 4.2 Typical dwelling layouts for terraced-intermediate and apartments (Alavirad et al., 2022; Oorschot et al., 2018; SenterNovem, 2006).

A.4.3 Geometrical relationship between length and compactness ratio

Terraced-Intermediate

The sampling procedure developed utilises the probabilities specified in Tables A.4.2 – A.4.5 to sample the compactness ratio (CR) for terraced-intermediate dwelling types. To represent the sampled CR, the seed model is scaled along its length while maintaining a fixed width of 5.4 meters and a height of 10.6 meters. Consequently, a geometrical relationship is established to calculate the new length (L) for the sampled CR, described in Equation A.4.1.

$$CR = \frac{3.89 \times L + 61.56 + 10.8\sqrt{24.01 + \left(\frac{L}{2}\right)^2}}{14.58 \times L} \tag{A.4.1}$$

According to Kafaei (2021) and Esposito et al. (2019), the length of a terraced dwelling typically ranges from 5 to 15 meters. Applying this range in Equation A.4.1 results in a compactness ratio between 0.99 and 1.9. These values align with the probabilities of the compactness ratio found in Tables A.4.2 – A.4.5, where higher probabilities correspond to a range of 1.0 to 2.0. However, houses built before 1975 may exhibit a compactness ratio exceeding 2.0. For the purposes of this study, a length range of 5 to 15 meters is used as a constraint. This constraint is applied during the sampling process, where the sampler first determines the compactness ratio and then calculates the length using Equation A.4.1. If the length falls within the 5 to 15 meter range, the sample is retained in the batch for further evaluation. This approach ensures that only relevant samples are included in the analysis.

Apartments

The sampling procedure for apartments also utilises the probabilities outlined in Tables A.4.7 – A.4.10 for different construction years. Similar to the terraced-intermediate type, a relationship is established between the compactness ratio (CR) and the length (L) of the apartment, with a fixed width of 6.74 meters and a height of 2.8 meters. However, individual apartments differ in their position within the apartment block, which impacts their external heat loss area. Consequently, the compactness ratio is calculated for six typical positions. Table A.4.1 illustrates the geometrical relationship between CR and L for each position, with conditions to avoid division by zero. For apartment types, to ensure realistic sampling, length limits were derived based on the average floor area for MFH types from the reference home study (Rijksdienst voor Ondernemend, 2023a). According to this study, the usable heated area for MFHs ranges from 25 to 150 m². Given the fixed width of 6.74 meters for the apartments, this corresponds to a length limit ranging from 3.7 to 22 meters.

TABLE A. 4.1 Specific geometric relationship between compactness ratio and length of the apartment for each position. The conditions ensure avoiding division by zero.

Position	Description	Relationship	Condition
1	Intermediate-Intermediate	$L = \frac{5.6}{CR}$	$CR > 0$
2	Corner – Intermediate	$L = \frac{5.6}{CR - 0.415}$	$CR > 0.415$
3	Intermediate - Ground	$L = \frac{5.6}{CR - 0.7}$	$CR > 0.7$
4	Intermediate - Roof	$L = \frac{5.6}{CR - 1}$	$CR > 1$
5	Corner - Ground	$L = \frac{5.6}{CR - 1.15}$	$CR > 1.15$
6	Corner - Roof	$L = \frac{5.6}{CR - 1.415}$	$CR > 1.415$

A.4.4 Multi-level sampling

Terraced-Intermediate

Table A.4.2 shows the discrete probabilities for terraced-intermediate dwelling types across different construction year categories. These probabilities represent unequal proportions and are derived from the study by Cornelisse et al. (2021). The sampler first selects a construction year category based on these probabilities, which determines the probability density functions (PDFs) and ranges for the interest parameters. Tables A.4.3 to A.4.6 illustrate the PDFs and parameter ranges for each construction year category.

TABLE A. 4.2 Discrete probabilities for construction year category for terraced-intermediate dwelling type (Cornelisse et al., 2021).

Parameter	Type	Distribution	Range	Probabilities
Construction Year	Discrete	Categorical	Until 1945	0.172
			1945-1975	0.309
			1975-1995	0.338
			After 1995	0.181

TABLE A. 4.3 PDFs and Ranges for the interest parameters for the construction year category “until1945” for terraced-intermediate type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.000	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.000		[0.5, 1.0)	
				1.0 – 1.5	0.412		[1.0, 1.5)	
				1.5 – 2.0	0.451		[1.5, 2.0)	
				2.0 – 2.5	0.113		[2.0, 2.5)	
				2.5 – 3.0	0.017		[2.5, 3.0)	
				3.0 – 3.5	0.008		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Window – wall Ratio[2]	Discrete	Fixed	31	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.15, 5.04, 0.77]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[0.19, 2.53, 0.7]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Roof Insulation[2], R	Continuous	Triangle	[0.22, 2.53, 1.24]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1.4, 5.1, 2.96]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.36]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	Infilteration[2]	Continuous	Triangle	[0.15, 5.04, 0.77]	Triangle PDF[3, 4]	-	-	$dm^3/s.m^2$
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.866, 0.129, 0.005]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin.
[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.4 PDFs and Ranges for the interest parameters for the construction year category “1945-1975” terraced-intermediate type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.000	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.000		[0.5, 1.0)	
				1.0 – 1.5	0.582		[1.0, 1.5)	
				1.5 – 2.0	0.374		[1.5, 2.0)	
				2.0 – 2.5	0.042		[2.0, 2.5)	
				2.5 – 3.0	0.001		[2.5, 3.0)	
				3.0 – 3.5	0.001		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Window – wall Ratio[2]	Discrete	Fixed	36	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.15, 5.48, 0.57]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[0.19, 3.5, 0.84]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Roof Insulation[2], R	Continuous	Triangle	[0.22, 3.78, 1.22]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1.56, 5.59, 2.73]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.31]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	Infilteration[2]	Continuous	Triangle	[0.7, 3, 3]	Triangle PDF[3, 4]	-	-	$dm^3/s.m^2$
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.791, 0.207, 0.002]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin.
[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.5 PDFs and Ranges for the interest parameters for the construction year category "1975-1995" terraced-intermediate type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.000	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.007		[0.5, 1.0)	
				1.0 – 1.5	0.697		[1.0, 1.5)	
				1.5 – 2.0	0.268		[1.5, 2.0)	
				2.0 – 2.5	0.028		[2.0, 2.5)	
				2.5 – 3.0	0.000		[2.5, 3.0)	
				3.0 – 3.5	0.000		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Window – wall Ratio[2]	Discrete	Fixed	31	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.52, 5.38, 1.16]	Triangle PDF[3]	-	-	m^2·K/W
	External Wall Insulation[2], R	Continuous	Triangle	[0.8, 2.71, 1.53]	Triangle PDF[3]	-	-	m^2·K/W
	Roof Insulation[2], R	Continuous	Triangle	[0.44, 3.78, 1.5]	Triangle PDF[3]	-	-	m^2·K/W
	Window Insulaiton[2], U	Continous	Triangle	[1.8, 5.62, 2.82]	Triangle PDF[3]	-	-	W/m^2·K
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.33]	Triangle PDF[3]	-	-	W/m^2·K
	Infilteration[2]	Continuous	Triangle	[0.7, 2.5, 2]	Triangle PDF[3, 4]	-	-	$dm^3/s.m^2$
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.364, 0.621, 0.015]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin.
[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.6 PDFs and Ranges for the interest parameters for the construction year category "after 1995" terraced-intermediate type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.000	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.000		[0.5, 1.0)	
				1.0 – 1.5	0.658		[1.0, 1.5)	
				1.5 – 2.0	0.303		[1.5, 2.0)	
				2.0 – 2.5	0.032		[2.0, 2.5)	
				2.5 – 3.0	0.007		[2.5, 3.0)	
				3.0 – 3.5	0.000		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Window – wall Ratio[2]	Discrete	Fixed	29	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[1.7, 6, 2.68]	Triangle PDF[3]	-	-	$m^2·K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[1.51, 7, 2.68]	Triangle PDF[3]	-	-	$m^2·K/W$
	Roof Insulation[2], R	Continuous	Triangle	[2, 9, 2.75]	Triangle PDF[3]	-	-	$m^2·K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1, 3.31, 2.1]	Triangle PDF[3]	-	-	$W/m^2·K$
	External Door Insulation[2], U	Continuous	Triangle	[1, 3.4, 3.27]	Triangle PDF[3]	-	-	$W/m^2·K$
	Infilteration[2]	Continuous	Triangle	[0.7, 1.5, 1]	Triangle PDF[3, 4]	-	-	$dm^3/s.m^2$
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.005, 0.832, 0.163]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

[*] Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin.
[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

Apartments

Table A.4.7 shows the discrete probabilities for apartment dwelling types across different construction year categories. These probabilities represent unequal proportions and are derived from the study by Cornelisse et al. (2021). The sampler first selects a construction year category based on these probabilities, which determines the probability density functions (PDFs) and ranges for the interest parameters. Tables A.4.8 to A.4.11 illustrate the PDFs and parameter ranges for each construction year category.

TABLE A. 4.7 Discrete probabilities for construction year category for apartment dwelling type (Cornelisse et al., 2021)

Parameter	Type	Distribution	Range	Probabilities
Construction Year	Discrete	Categorical	Until 1945	0.1870
			1945-1975	0.3004
			1975-1995	0.2464
			After 1995	0.2662

TABLE A. 4.8 PDFs and Ranges for the interest parameters for the construction year category "until 1945" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.029	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.273		[0.5, 1.0)	
				1.0 – 1.5	0.270		[1.0, 1.5)	
				1.5 – 2.0	0.322		[1.5, 2.0)	
				2.0 – 2.5	0.089		[2.0, 2.5)	
				2.5 – 3.0	0.011		[2.5, 3.0)	
				3.0 – 3.5	0.005		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Position of Apartment	Discrete	Uniform	[1, 2, 3, 4, 5, 6]	-	-	-	-
	Window–wall Ratio[2]	Discrete	Fixed	32	-	-	-	%

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TABLE A. 4.8 PDFs and Ranges for the interest parameters for the construction year category "until 1945" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.15, 3.50, 0.56]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[0.19, 3.50, 0.58]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Roof Insulation[2], R	Continuous	Triangle	[0.22, 3.78, 1]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1.63, 6.2, 3.11]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	External Door Insulation[2], U	Continuous	Triangle	[2.29, 3.4, 3.32]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	Infilteration[3]	Discrete	-	1: Intermediate-Intermediate	Based on the sampled position of the apartment	Triangle PDF[3, 4]	[0.35, 1.5, 1.5]	$dm^3/s.m^2$
				2: Corner-Intermediate			[0.455, 1.95, 1.95]	
				3: Intermediate - Ground			[0.35, 1.5, 1.5]	
				4: Intermediate-Roof			[0.42, 1.8, 1.8]	
				5: Corner-Ground			[0.455, 1.95, 1.95]	
				6: Corner - Roof			[0.49, 2.1, 2.1]	
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.758, 0.227, 0.015]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin. For infiltration, the position of the apartment is selected first, followed by the corresponding infiltration range from which a value is then sampled

[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.9 PDFs and Ranges for the interest parameters for the construction year category "1945-1975" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.068	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.367		[0.5, 1.0)	
				1.0 – 1.5	0.214		[1.0, 1.5)	
				1.5 – 2.0	0.274		[1.5, 2.0)	
				2.0 – 2.5	0.063		[2.0, 2.5)	
				2.5 – 3.0	0.008		[2.5, 3.0)	
				3.0 – 3.5	0.007		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Position of Apartment	Discrete	Uniform	[1, 2, 3, 4, 5, 6]	-	-	-	-
	Window–wall Ratio[2]	Discrete	Fixed	40	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.15, 4.15, 0.48]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[0.19, 4.18, 0.67]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Roof Insulation[2], R	Continuous	Triangle	[0.22, 2, 0.96]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1.4, 5.96, 2.87]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.3]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	Infilteration[3]	Discrete	-	1: Intermediate-Intermediate	Based on the sampled position of the apartment	Triangle PDF[3, 4]	[0.35, 1.5, 1.5]	$dm^3/s.m^2$
				2: Corner-Intermediate			[0.455, 1.95, 1.95]	
				3: Intermediate - Ground			[0.35, 1.5, 1.5]	
				4: Intermediate-Roof			[0.42, 1.8, 1.8]	
				5: Corner-Ground			[0.455, 1.95, 1.95]	
				6: Corner - Roof			[0.42, 2.1, 2.1]	

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TOC

TABLE A. 4.9 PDFs and Ranges for the interest parameters for the construction year category "1945-1975" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.528, 0.460, 0.012]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin. For infiltration, the position of the apartment is selected first, followed by the corresponding infiltration range from which a value is then sampled

[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.10 PDFs and Ranges for the interest parameters for the construction year category "1975 - 1995" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.154	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.355		[0.5, 1.0)	
				1.0 – 1.5	0.175		[1.0, 1.5)	
				1.5 – 2.0	0.231		[1.5, 2.0)	
				2.0 – 2.5	0.043		[2.0, 2.5)	
				2.5 – 3.0	0.041		[2.5, 3.0)	
				3.0 – 3.5	0.000		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Position of Apartment	Discrete	Uniform	[1, 2, 3, 4, 5, 6]	-	-	-	-
	Window–wall Ratio[2]	Discrete	Fixed	38	-	-	-	%

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TABLE A. 4.10 PDFs and Ranges for the interest parameters for the construction year category “1975 - 1995” apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.82, 4.59, 2]	Triangle PDF[3]	-	-	m^2·K/W
	External Wall Insulation[2], R	Continuous	Triangle	[1.69, 5.69, 2.61]	Triangle PDF[3]	-	-	m^2·K/W
	Roof Insulation[2], R	Continuous	Triangle	[2.5, 3.5, 2.67]	Triangle PDF[3]	-	-	m^2·K/W
	Window Insulaiton[2], U	Continous	Triangle	[1., 4.1, 2.16]	Triangle PDF[3]	-	-	W/m^2·K
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.28]	Triangle PDF[3]	-	-	W/m^2·K
	Infilteration[3]	Discrete	-	1: Intermediate-Intermediate	Based on the sampled position of the apartment	Triangle PDF[3, 4]	[0.35, 0.75, 0.50]	$dm^3/s.m^2$
				2: Corner-Intermediate			[0.455, 0.98, 0.65]	
				3: Intermediate - Ground			[0.35, 0.75, 0.50]	
				4: Intermediate-Roof			[0.42, 0.9, 0.6]	
				5: Corner-Ground			[0.455, 0.975, 0.65]	
				6: Corner - Roof			[0.49, 1.05, 0.7]	
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.014, 0.781, 0.196]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin. For infiltration, the position of the apartment is selected first, followed by the corresponding infiltration range from which a value is then sampled

[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

TABLE A. 4.11 PDFs and Ranges for the interest parameters for the construction year category “after 1995” apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
Geometrical	Orientation	Discrete	Uniform	[0, 45, 90, 135, 180, 225, 270, 315]	-	-	-	°
	Compactness Ratio[1]	Discrete	Categorical	0.0 – 0.5	0.154	Uniform	[0.0, 0.5)	-
				0.5 – 1.0	0.355		[0.5, 1.0)	
				1.0 – 1.5	0.175		[1.0, 1.5)	
				1.5 – 2.0	0.231		[1.5, 2.0)	
				2.0 – 2.5	0.043		[2.0, 2.5)	
				2.5 – 3.0	0.041		[2.5, 3.0)	
				3.0 – 3.5	0.000		[3.0, 3.5)	
				3.5 – 4.0	0.000		[3.5, 4.0)	
	Position of Apartment	Discrete	Uniform	[1, 2, 3, 4, 5, 6]	-	-	-	-
	Window–wall Ratio[2]	Discrete	Fixed	38	-	-	-	%
Fabric	Ground Insulation[2], R	Continuous	Triangle	[0.82, 4.59, 2]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	External Wall Insulation[2], R	Continuous	Triangle	[1.69, 5.69, 2.61]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Roof Insulation[2], R	Continuous	Triangle	[2.5, 3.5, 2.67]	Triangle PDF[3]	-	-	$m^2 \cdot K/W$
	Window Insulaiton[2], U	Continous	Triangle	[1., 4.1, 2.16]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	External Door Insulation[2], U	Continuous	Triangle	[2, 3.4, 3.28]	Triangle PDF[3]	-	-	$W/m^2 \cdot K$
	Infilteration[3]	Discrete	-	1: Intermediate-Intermediate	Based on the sampled position of the apartment	Triangle PDF[3, 4]	[0.35, 0.75, 0.50]	$dm^3/s.m^2$
				2: Corner-Intermediate			[0.455, 0.98, 0.65]	
				3: Intermediate - Ground			[0.35, 0.75, 0.50]	
				4: Intermediate-Roof			[0.42, 0.9, 0.6]	
				5: Corner-Ground			[0.455, 0.975, 0.65]	
				6: Corner - Roof			[0.49, 1.05, 0.7]	

>>>

TABLE A. 4.11 PDFs and Ranges for the interest parameters for the construction year category "after 1995" apartment type.

Category	Parameter	Type	Distribution	Range	Probabilities	Distribution*	Range*	Unit
HVAC	Ventilation system[2]	Discrete	Categorical	[A, C, D]	[0.014, 0.781, 0.196]	-	-	-
Occupant and Control	Heating setpoint	Discrete	Uniform	[18, 19, 20, 21]	-	-	-	°C

* Sub-level data: After selecting a bin for the compactness ratio based on its probabilities, a value is sampled uniformly from the range of the chosen bin. For infiltration, the position of the apartment is selected first, followed by the corresponding infiltration range from which a value is then sampled

[1] Sourced from (Rijksdienst voor Ondernemend, 2023a), [2] Sourced from (Cornelisse et al., 2021), [3] Triangle distribution with [lower limit, upper limit, mode], [4] Calculated using equation 1 (Nederlandse technische afspraak 8800:2023, 2023) in section 4.3.2.1.2.

A.4.4 Appropriate sampling size in LT(55/35°C) supply

Figures A.4.3 and A.4.4 illustrate the parameter ranking, absolute SRRC, and R^2 values for the two output parameters for terraced-intermediate and apartment dwellings, respectively, under an LT supply of 55/35°C. From both graphs, it can be observed that convergence reached around 1300 samples, with the R^2 value being the highest.

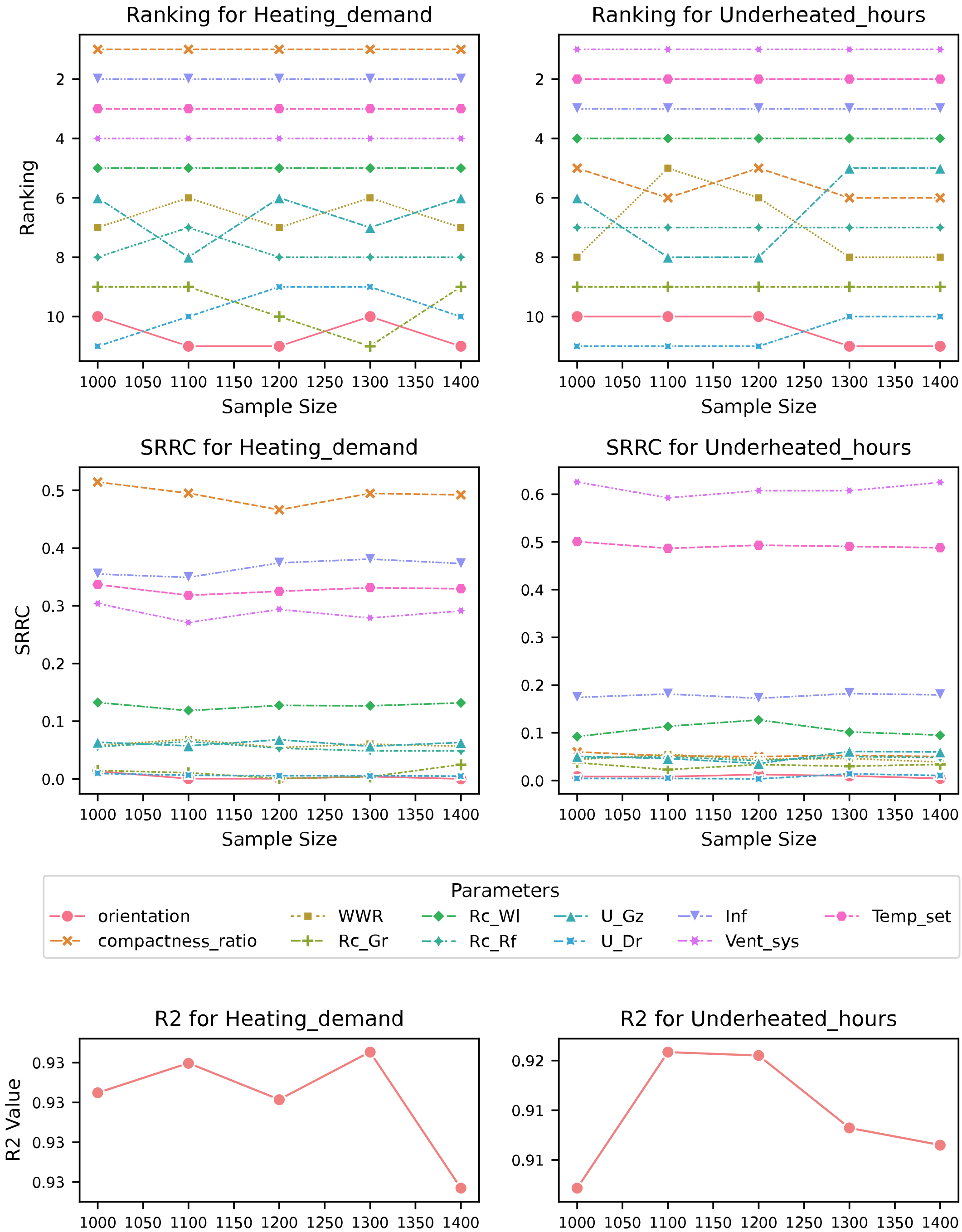

FIG. A. 4.3 Parameter ranking, SRRC absolute and R2 values of terraced-intermediate dwelling type for the two output parameters under LT supply of 55/35°C.

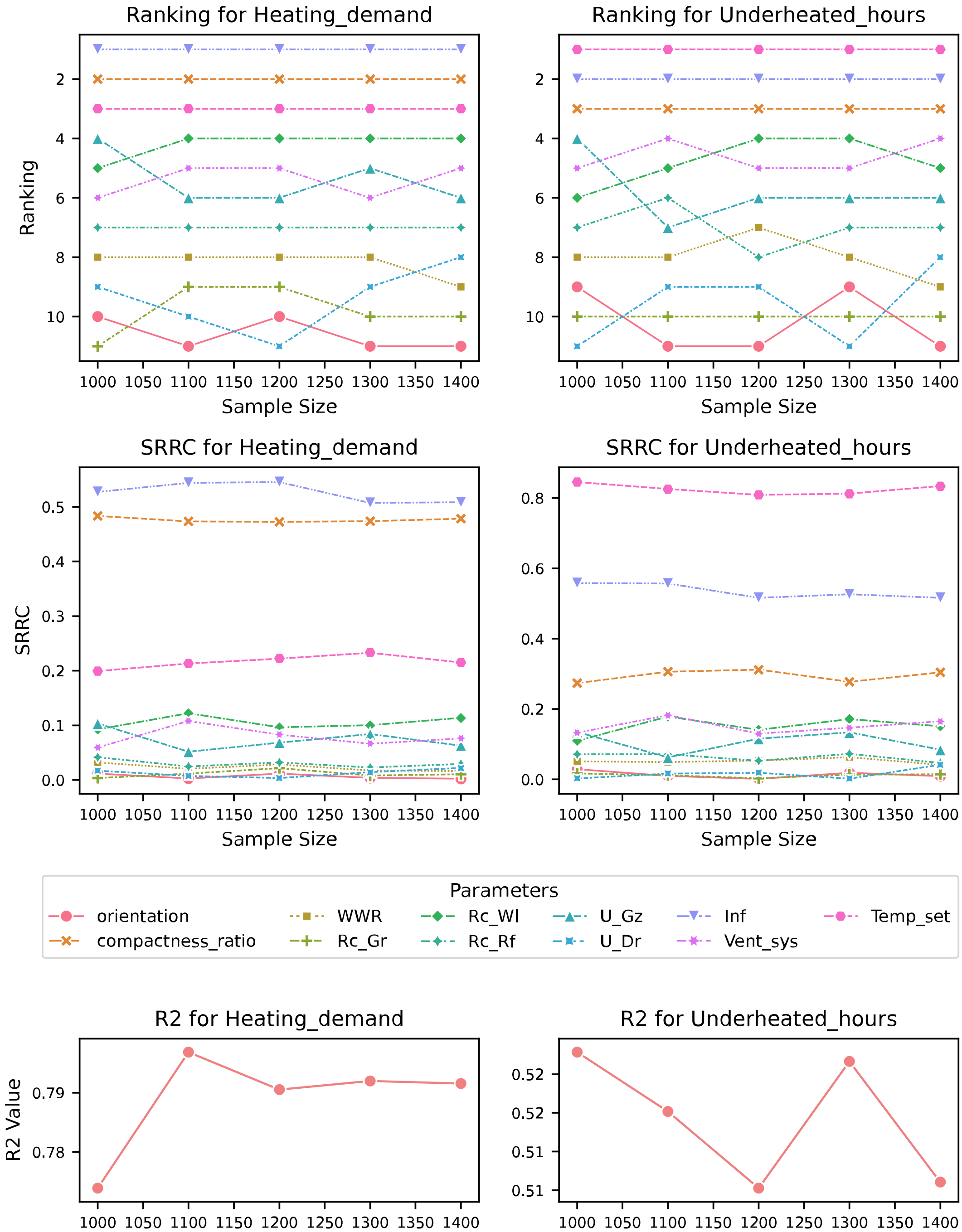

FIG. A. 4.4 Parameter ranking, SRRC absolute and R2 values of apartment dwelling type for the two output parameters under LT supply of 55/35°C.

TOC

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5 Preparing for Lower-Temperature Heating

A Multi-Criteria Decision-Making Framework for Energy Renovations of Existing Dutch Dwellings

Submitted as: Wahi, P., Koster, V., Tenpierik, M. J., Visscher, H & Konstantinou, T. (2025). Preparing for Lower-Temperature Heating: A Multi-Criteria Decision-Making Framework for Energy Renovations of Existing Dutch Dwellings. Energy Reports, 2025

This chapter is under review at the time of writing this manuscript.

ABSTRACT

Transitioning existing dwellings to lower temperature heating (LTH) is crucial for achieving the Dutch goal of making 1.5 million homes gas-free 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 a 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 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.

KEYWORDS Energy Transition, Heating Decarbonisation, Energy Renovations, Parametric Simulations, Multi-Criteria Decision-Making, Pair-wise comparison, TOPSIS

5.1 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 & 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 & Svendsen, 2013; Harrestrup & Svendsen, 2015). Additionally, at the building level, LTH can enhance thermal comfort and indoor environmental quality (Eijdems et al., 1999; Ovchinnikov et al., 2017; Q. 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 HT supply of more than 75°C (Østergaard & 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 & 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 modifications aimed at lowering heating demands and facilitating the readiness of dwellings for LTH using sustainable energy sources (Asdrubali & 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 & 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 & Ramachandran, 2004; Siksnelyte-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 & 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).

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 (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 5.2 elaborates on this process, identifying essential decision-making aspects for framework development. Subsequently, Section 5.3 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 5.4 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 5.5 discusses the implications of the proposed framework in supporting decision-making for LTH, drawing on insights gained from the case study application. Finally, Section 5.6 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 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.

5.2 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 & Hartmann, 2022; Jafari & Valentin, 2018; Rosenfeld & 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 & Hartmann, 2022; Laguna Salvadó et al., 2022). As noted by 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 & Hartmann, 2022; Cajot et al., 2017; Pohekar & Ramachandran, 2004; Si et al., 2016). Moreover, integrating these varied preferences to evaluate and rank different solutions further complicates the decision-making process (Amorocho & 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 et al. (2016) in an extensive review of 46 existing decision-support tools. The following subsections describe the decision-making aspects in detail.

5.2.1 Incorporating stakeholder's interests

In decision-making scenarios involving energy renovations, numerous actors or stakeholders participate who frequently have direct interests and the capability to influence outcomes (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 & 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 & Hartmann, 2022; Kylili et al., 2016; Lu et al., 2007; Pramangioulis et al., 2019; Sen & Yang, 1998). The majority of the research emphasises a holistic sustainability assessment, incorporating technical, social, economic and environmental objectives as primary renovation goals (Amorocho & Hartmann, 2022; Khadra et al., 2020; Serrano-Jiménez et al., 2021; Si et al., 2016; J. J. Wang et al., 2009; Zavadskas et al., 2008). As the number and complexity of decision-making criteria increase, organising and logically presenting

TOC

them becomes essential. Therefore, a decision tree is often employed, where objectives are arranged hierarchically and lead to specific criteria (Amorocho & 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 & Hartmann, 2022; Jafari & 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.

5.2.2 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; J. J. 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 & Polatidis, 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 & Yang, 1998).

5.2.3 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 & 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 & 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 & 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).

5.2.4 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 & Ramachandran, 2004; Sen & 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 Realité (ÉLECTRE) (Cajot et al., 2017; Kumar et al., 2017; Pohekar & 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 & 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 Figure 5.1 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.

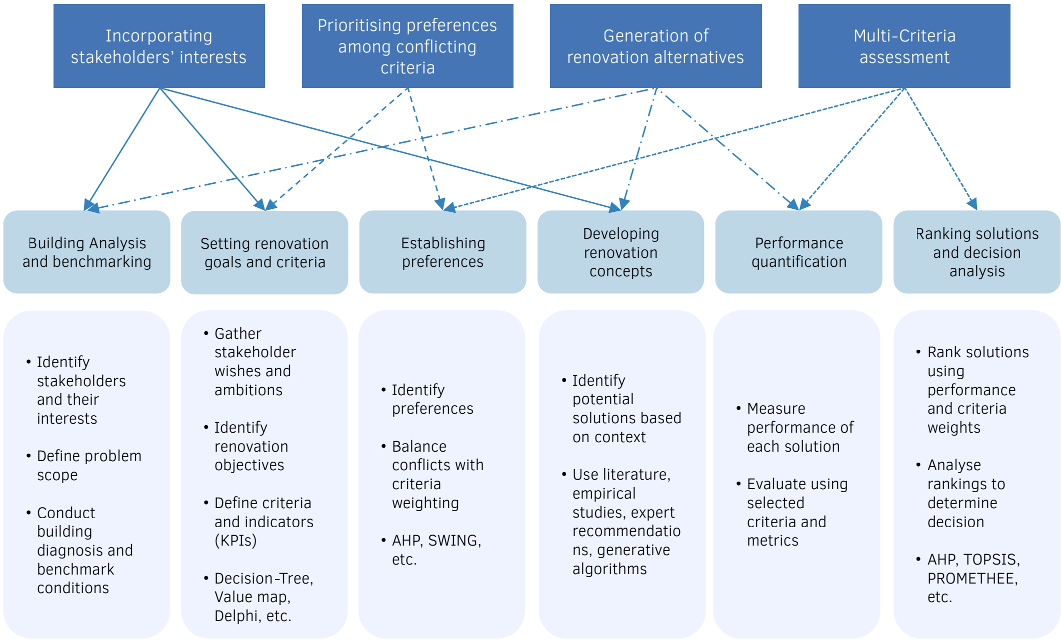

FIG. 5.1 Generalised decision-making steps derived from literature mapped to the specific decision-making aspect.

5.3 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. Figure 5.2 illustrates the developed decision-making framework.

5.3.1 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 (Amorocho & 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).

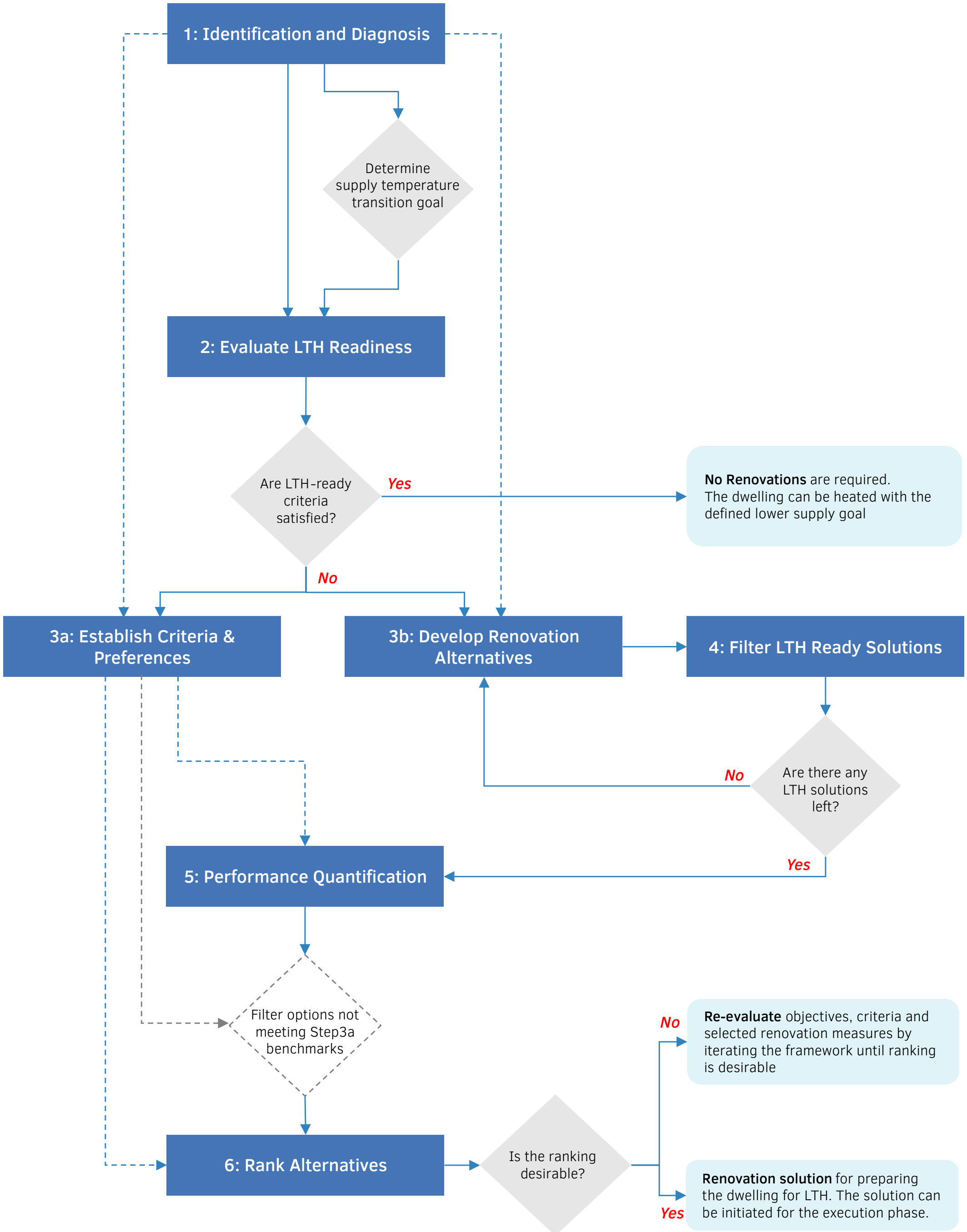

FIG. 5.2 Proposed decision support framework for selecting renovations to prepare dwellings for LTH.

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 (Amorocho & Hartmann, 2022; Ferreira et al., 2013; Konstantinou & 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. (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.5.1). 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 Honeybee plugins for energy simulations, as outlined in our previous study (Wahi, Konstantinou, et al., 2024b). This benchmarking is crucial for evaluating the LTH readiness of the dwelling and determining the need for renovation, as discussed in the subsequent step.

5.3.2 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/m^2) 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.

5.3.3 Step3a: 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 5.1 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).

TABLE 5.1 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 (Amorocho & Hartmann, 2022; Khadra et al., 2020; Nielsen et al., 2016; Si et al., 2016; Wahi et al., 2023a; J. J. Wang et al., 2009)

Sustainability Pillars	Objectives	Criteria
Environmental	To minimise the operational and primary energy demand	Space heating demand[1]
		Annual net energy consumption
		Total Primary energy consumption
		Renewable energy generation
		Energy savings
	To reduce environmental impact due to direct and indirect embodied emissions	Global warming potential
		Estimation of embodied energy
		Estimation of carbon emissions
Economic	To improve affordability	Total investment costs
		Available local and national subsidies
	To optimise cost-benefits	Rent increment
		Payback period
		Life cycle costs
Social	To improve indoor comfort	Thermal comfort[1]
		Visual comfort/daylight
		Acoustical Comfort
		Indoor air quality
	To improve social acceptability	Aesthetics
		Renovation duration
		Energy Costs

[1] *Space heating demand and thermal comfort as non-negotiable criteria for evaluating LTH readiness*

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 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 (m^3), 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 crietria 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 (Amorocho & Hartmann, 2022; Lu et al., 2007; Pohekar & Ramachandran, 2004; Sen & Yang, 1998; Si et al., 2016; Tae-Woo et al., 2018; J. J. Wang et al., 2009), can be followed for conducting the pairwise comparisons:

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

5.3.4 Step3b: Developing renovation alternatives

In this stage, all potential renovation solutions for a given dwelling context are developed. As described in Section 5.1, 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, Konstantinou, et al., 2024b). 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. Figure 5.3 illustrates the sub-framework to organise the solutions as well as the relative importance of the 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).

5.3.5 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 5.3.2), 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.

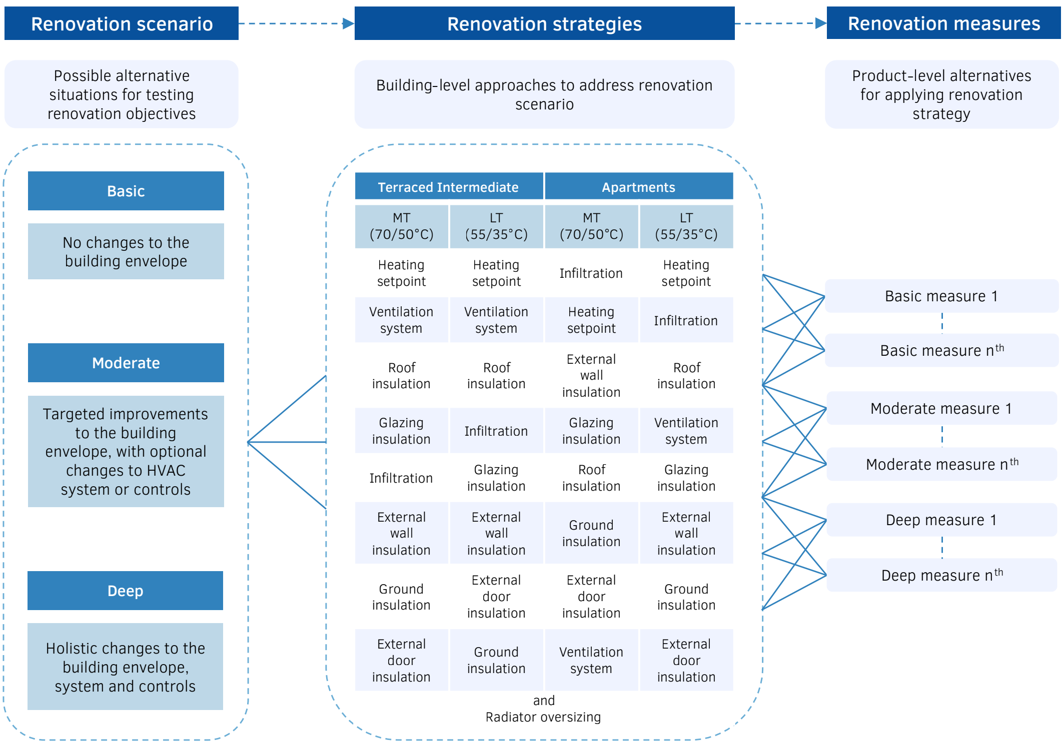

FIG. 5.3 Sub-Framework for Generating and Organising the Renovation Solution Space. The feature importance list is used to examine the dwelling, identify areas of improvement, and develop targeted strategies according to the required level of intervention. These strategies are then translated into specific product-level measures (Wahi et al., 2023b; Wahi, Konstantinou, et al., 2024a). The feature importance was determined in our previous study (Wahi, Konstantinou, et al., 2024b).

5.3.6 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.

5.3.7 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 (Siksnelyte-Butkiene et al., 2021). This method, proposed by 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 5.2.4, various authors (Amorocho & Hartmann, 2022; Hwang & Yoon, 1981; Kamari et al., 2018; Lu et al., 2007; Moghtadernejad et al., 2018; Sen & Yang, 1998) have employed the method, following these typical steps:

- Establish a decision matrix with the alternatives and their performance for each decision criterion.
- Normalise the decision matrix to convert varying criteria into dimensionless values.
- Construct the weighted normalised decision matrix using the weights for each criterion obtained in Step 3a.
- Determine the Positive Ideal Solutions (PIS) and Negative Ideal Solutions (NIS).
- Calculate the Euclidean distance of alternatives from both negative and positive ideal solutions.
- Calculate the relative closeness index for each alternative to the positive ideal solution.
- 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.

TOC

5.4 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. Figure 5.4 illustrates the apartment complex located in the Noord-Holland province of the Netherlands.

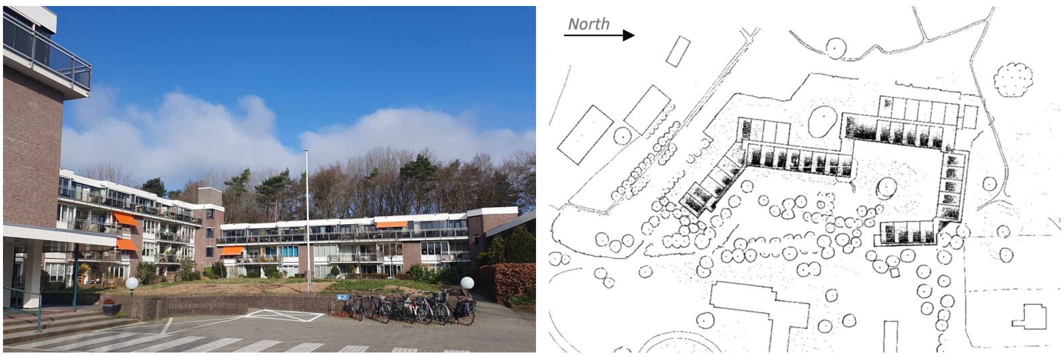

FIG. 5.4 The apartment complex, built in the 1980s, selected to demonstrate the application of the proposed framework.

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.

5.4.1 Identification and diagnosis

5.4.1.1 Case study description

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 m^2 and 76 m^2 floor area, respectively. The typical floor plans of the apartments can be found in Appendix A.5.2. The complex varies from two to four stories, with most apartments primarily oriented east-west, as depicted in Figure 5.4 (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 55-45°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.

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 5.2 displays the insulation values of the building fabric prior to renovations.

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.

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

TABLE 5.2 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		$m^2 \cdot K/W$
External Wall Insulation[2], R	0.69		$m^2 \cdot K/W$
Roof Insulation[2], R	2.5		$m^2 \cdot K/W$
Glazing Insulation[2], U	1.8		$W/m^2 \cdot K$
External Door Insulation[2], U	3.4		$W/m^2 \cdot K$
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 (2023)
[4] Adjusted during calibration

5.4.1.2 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.5.3).

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 to 23:00, totalling 5840 hours annually. Table 5.2 presents the input data used to simulate the benchmark performance of the selected apartments parametrically. Additionally, Table 5.3 showcases the benchmark performance results under HT supply, highlighting both the space heating demand and thermal discomfort hours.

5.4.2 Evaluate LTH readiness

The apartment complex has been renovated with a collective air-to-water heat pump that provides a 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 5.3 compares their performance under this LT supply to the benchmark performance established in Step 1 (Section 5.4.1). 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.

TABLE 5.3 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

5.4.3 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 5.4 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.

TABLE 5.4 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
			C3	Energy Index[1]	[-]	≤ 1.4	Minimum
	O2	To reduce environmental impact	C4	Share of renewable energy generation[1]	%	>0	Maximum
			C5	Energy savings (gas)[1]	Average m^3 per year	>0	Maximum
Economic	O3	To reduce investment costs	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
			C9	Payback period[3]	Years	< 20 years	Minimum
Social	O5	To improve indoor comfort[1]	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 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*

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.

5.4.4 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 5.3.4, 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 Figure 5.3, 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. 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 5.2) 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 Rc: 2.1 m^2K/W, windows U: 2.2 W/m^2K), although they could benefit from further upgrades. In contrast, walls (Rc: 1.4 m^2K/W) and ground insulation (Rc:2.6 m^2K/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 5.5. 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 (Figure 5.5). Consequently, additional solutions with moderate and deep intervention levels were developed.

TABLE 5.5 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, R	Wall, R	Floor, R	Infil-tration	Glaz-ing, U	Door, U	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
Moderate	**A1**	-	1.69	-	1.5	-	-	-	-	-	LED lighting
	A2	5.84	1.69	-	1.2	-	-	-	-	-	PV panel LED lighting
	A3	5.84	1.69	-	1.2	-	-	-	Heat pump PV	-	
	A4	5.84	1.69	-	1.2	-	-	-	Heat pump PVT	-	
	A5 , A5R	-	6.3	-	1.2	-	-	-	Heat pump PVT	Existing radiators Or Replaced with a ra-diator with a higher heating power	PV panel LED lighting
	A6, A6R	-	6.3	-	1.2	-	-	Balanced ventilation with heat recovery (MVHR)			
	A7, A7R	-	6.3	-	1	1	-	-			
	A8, A8R	-	6.3	-	1	1	-	Balanced ventilation with heat recovery (MVHR)			

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TABLE 5.5 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, R	Wall, R	Floor, R	Infil-tration	Glaz-ing, U	Door, U	Ventilation system	Heat generation	Heat distribution	Other
		m^2K/W	m^2K/W	m^2K/W	$dm^3/s.m^2$	W/m^2K	W/m^2K				
Deep	**A9**	5.84	1.69	-	0.7	1	-	-	Heat pump PVT	Replaced with a radiator with a higher heating power	PV panel LED lighting
	A10	5.84	1.69	-	0.7	1	-	Balanced ventilation with heat recovery (MVHR)			
	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)			
	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)			

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. Figure 5.5 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, Koster, et al., 2024).

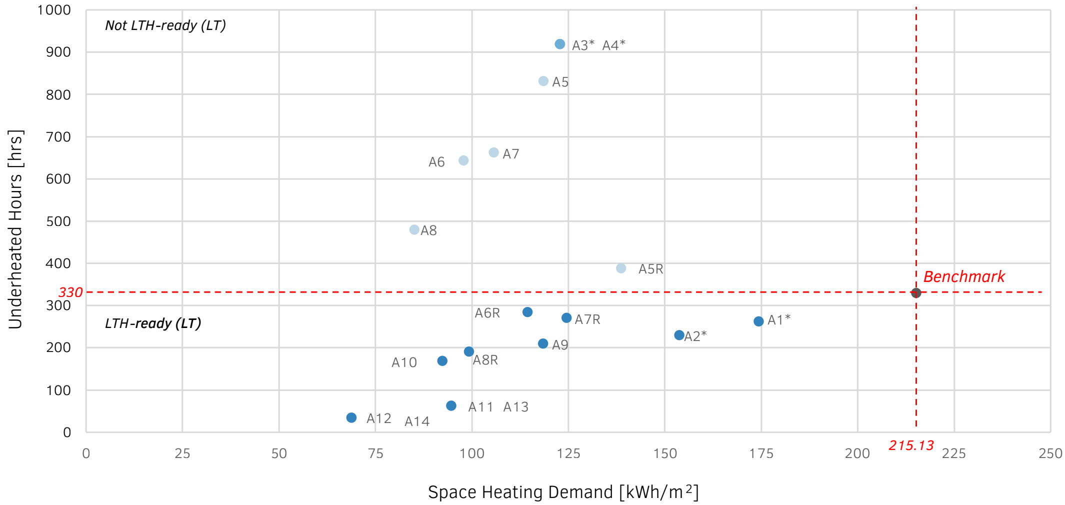

FIG. 5.5 Filtered Solutions for LTH Readiness. Of 14 solutions, nine could prepare the apartment complex for heating with LT supply (55/35°C). An asterisk (*) indicates alternatives proposed in the project plan, while "R" denotes alternatives with upgraded radiators.

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.

5.4.5 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 5.4.3), as illustrated in Table 5.6. 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

TOC

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 (Kostenkentallen) provided by the Netherlands Enterprise Agency (RVO, n.d.-a). 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 efficiency and occupant comfort. These criteria were extracted from the project plan and remained the same as A4 for other alternatives. Appendix A.5.4 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 5.4. 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.

TABLE 5.6 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.

	Environmental					Economic				Social			
	O1			O2		O3		O4		O5	O6	O7	
	To upgrade the apartment complex to 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**	**0**	**131.00k**	**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

5.4.6 Ranking alternatives using TOPSIS

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 5.4.3, equal weights were assigned to the decision criteria, making the evaluation based on the alternatives' performance rather than stakeholder preferences. Figure 5.6 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 5.4.4, none of the originally proposed alternatives (A1-A4) can prepare the apartment complex for heating with LT supply. Figure 5.6 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 is 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.

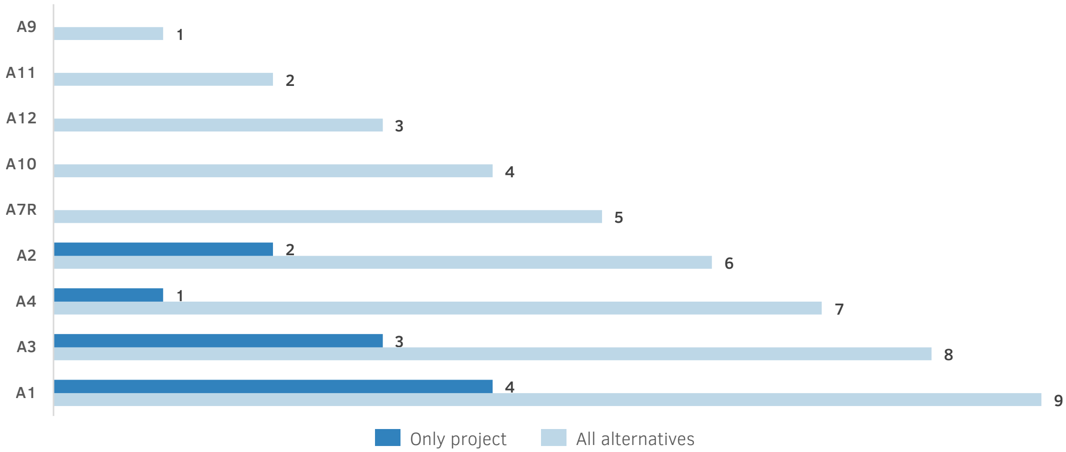

FIG. 5.6 TOPSIS Ranking of Renovation Alternatives. This graph displays the rankings for the four initially proposed alternatives and their rankings alongside five additional proposed solutions.

5.5 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.

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

As indicated in Table 5.6, 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.

5.5.2 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 5.1, 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, Konstantinou, et al., 2024b), 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.

5.6 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:

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

- Filtering feasible solutions that can specifically make the dwelling LTH ready.
- Quantifying these solutions against the decision criteria and further filter out non-feasible solutions.
- 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.

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.

Data availability

The data pertaining to the study is available on 4TU.ResearchData and can be accessed through the following DOI: https://doi.org/10.4121/87bd0b32-cf06-4f9a-9e02-d7842f5b3947.v1

A.5.1 Checklist for collecting data

TABLE A. 5.1 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
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 10Pa or 50Pa. 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.)	

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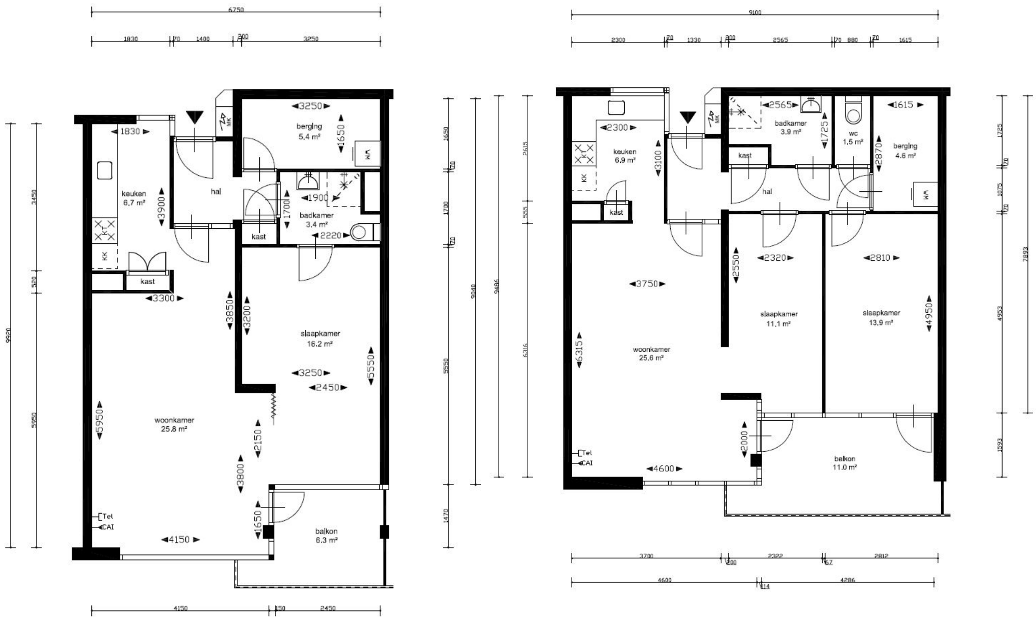
TABLE A. 5.1 A one-page datasheet was developed as a checklist to gather information about the dwelling(s) for LTH renovation.

Parameters	Availability	Description	Remarks
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.	

TOC

A.5.2 Typical floor plans



One-bedroom apartment type **Two-bedroom apartment type**

FIG. A. 5.1 Typical one-bedroom and two-bedroom apartment type.

A.5.3 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 5.4.1.2, 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 m^2) compared to the original floorplan dimensions (63 m^2).

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.5.2 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. 5.2 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.5.4 Performance quantification

A.5.4.1 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 Equation A.5.1 (Majcen et al., 2013; Paula van den Brom, 2020). Here, Q_{total} represents the total theoretical primary energy consumption in MJ, A_{floor} is the total usable floor of the dwelling, and A_{loss} is external heat loss surface area in m^2. The total primary energy consumption includes the energy required for space heating demand (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 Equation A.5.2. Table A.5.3 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.5.4, to determine the corresponding energy label (RVO, n.d.-b, 2024).

$$EI = \frac{Q_{total}}{\left(155 \times A_{floor}\right) + \left(106 \times A_{loss}\right) + 9560} \tag{A.5.1}$$

$$Q_{total} = Q_{SHD} + Q_{DHW} + Q_{lighting} + Q_{AUX} - Q_{PV} \tag{A.4.2}$$

TABLE A. 5.3 Data source used for calculating EI.

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

TABLE A. 5.4 Relationship between energy label and energy index (RVO, n.d.-b, 2024).

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
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.5.4.2 Calculation of Energy savings in gas (C5)

The gas energy savings in m^3 can be calculated using Equation A.5.3. 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 MJ/m^3. The change in energy demand (ΔQ_{SHD}) is calculated in kWh/m² from simulations, and a conversion factor of 3.6 is used to convert kWh to MJ.

$$savings(gas) = \frac{\Delta Q_{SHD} \times A_{floor} \times 3.6}{\eta \times CV_{gas}} \qquad \text{(A.5.3)}$$

A.5.4.3 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 Equations A.5.4 and A.5.5, respectively. In Equation A.5.4, i corresponds to the apartment position number as illustrated in Table A.5.5, along with the distribution of 108 apartments across the six positions.

$$Label\ step\ factor(LSF) = \frac{\sum_{i=1}^{6}(label\ step\ change_i \times number\ of\ units_i)}{108} \qquad \text{(A.5.4)}$$

$$Investment\ per\ label\ step\ per\ unit = \frac{Investment\ cost\ per\ alternative}{LSF} \qquad \text{(A.5.5)}$$

TABLE A. 5.5 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	29
5	Corner-ground	5
6	Corner-roof	9
		108 units

A.5.4.4 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 Equation A.5.6, 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

$$global\ costs = IC + OC + RC + MC \tag{A.5.6}$$

A.5.4.4.1 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, n.d.-a). These databases include common energy-efficient measures and associated costs, covering components, labour, and installation expenses. Table A.5.6 illustrates the costs extracted from the database used in this study.

TABLE A. 5.6 Investment costs for different components extracted from the cost database (RVO, n.d.-a) and project report.

Component	Description	Code from database	Insulation Value		Total Investment costs (€)
			RC [m^2K/W]	U [W/m^2K]	
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.5.4.4.2 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 Equation A.5.7. In this equation, OC_a represents the annual recurring costs, and df is the discount factor used to calculate the NPV of the OC (in €).

$$OC_{NPV} = df \times OC_a \tag{A.5.7}$$

Annual recurring operating costs (OC_a*)*

The annual recurring operating costs (in €) can be calculated using Equation A.5.8. 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 A.5.7 details the average variable and fixed costs from 2022, excluding VAT, used in this study (Centraal Bureau voor de Stastistiek, 2023).

$$OC_a = \left[\left(\frac{Total\ annual\ energy\ demand}{performance\ factor} \right) \times cost_{var} \right] + cost_{fixed} - tax\ reduction \quad \text{(A.5.8)}$$

TABLE A. 5.7 Average Variable and fixed costs from 2022 (Centraal Bureau voor de Staststiek, 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 equation A.5.9 (Fuller & Petersen, 1995; Hamdy et al., 2013). In this equation, r_e represents the real interest rate, which accounts for the inflation rate, and n_y is the calculation period, set at 30 years for this study.

$$df = \frac{1-(1+r_e)^{-n_y}}{r_e} \quad \text{(A.5.9)}$$

The real interest rate (r_e) can be calculated using Equation A.5.10 (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 & 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 Equation A.5.11, 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%.

$$r_e = \frac{r-e}{1+e} \quad \text{(A.5.10)}$$

$$e = \left(\frac{CPI_{2021}}{CPI_{2012}} \right)^{-t} - 1 \quad \text{(A.5.11)}$$

A.5.4.4.3 Maintenance costs

The annual recurring maintenance costs (MC) are calculated using Equation A.5.12 (Fabrycky & Blanchard, 1991), where the MC are a fraction (M_{rate}) of the IC. The M_{rate} values were determined according to Annex D of EN15459-1:2017 (NEN, 2017) and are discounted to account for future costs.

$$MC = IC \times M_{rate} \times df \quad \text{(A.5.12)}$$

A.5.4.4.4 Replacement costs

The replacement costs are calculated using Equation A.5.13, as suggested by 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 Equation A.5.10, and c is the life span of the component.

$$RC_k = IC_k \times (1+r_e)^{\frac{-c}{2}} \quad \text{(A.5.13)}$$

A.5.4.5 Simple payback period (C9)

The simple payback period is calculated without discounting future costs, using Equation A.5.14. 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 Equation A.5.3, and then multiplying this amount by the variable energy price, as specified in Table A.5.7.

$$SPB = \frac{Investment\ \cos ts}{Annual\ savings} \quad (A.5.14)$$

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6 Validation of the Decision-Support Framework

6.1 Introduction

The previous chapter introduced the decision support framework and demonstrated it through a case study involving a multi-family housing (MFH) type. The framework's application to the case study yielded optimal solutions similar to those initially made by the decision-makers. This suggests that the framework could be valuable in practical, real-world scenarios. Nevertheless, assessing the framework with stakeholders is essential to enhance its usability. Therefore, this chapter details the validation of the proposed decision-support framework (as detailed in Chapter 5) through a workshop with the stakeholders involved in the case study project. Section 6.2 describes the methodology used to develop the validation workshop. Section 6.3 presents and discusses the workshop results, focusing on validating the framework's usability in supporting decision-making. Section 6.4 summarises the findings, while Section 6.5 presents the limitations of the study and provides recommendations for future research.

6.2 Materials and Methods

The framework is designed to aid the decision-making process in selecting renovation solutions that enable dwellings to utilise LTH-based systems. To ensure its practical utility, it is essential to validate the usability of the framework in aiding stakeholders during this process. Therefore, this study proposes a workshop-based approach to validate the framework through stakeholder participation. According to Storvang et al. (2018, Chapter 7), workshops are effective for exploring shared topics through interactive, participatory environments and can validate data from other sources, such as interviews. This study adopts the general approach for organising a workshop as described by Storvang et al. (2018), which includes four phases: diagnosis, planning, facilitation, and analysis. Figure 6.1 illustrates these stages and their description. The subsequent sections will expand on these phases in the context of validating the decision support framework.

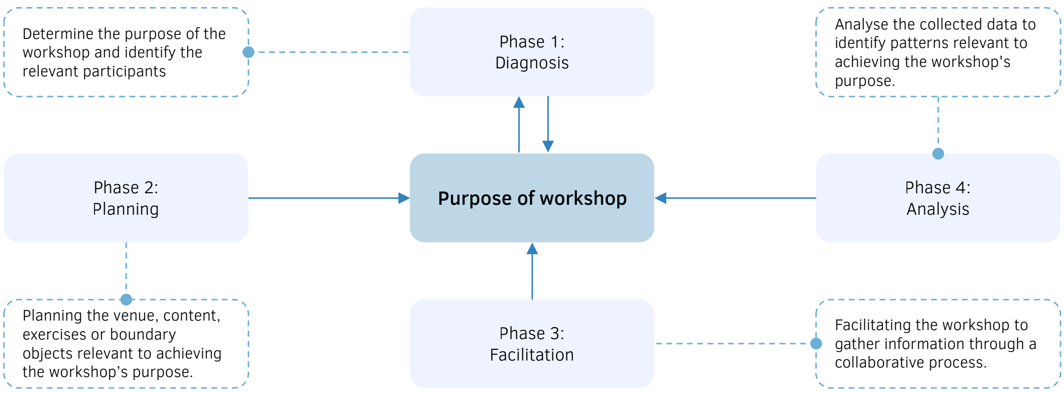

FIG. 6.1 Framework to develop the workshop for validating the decision support framework. Adapted from (Storvang et al., 2018).

6.2.1 Diagnosis

This phase involves defining the purpose of the workshop, which will guide the planning and facilitation stages. The data gathered during the workshop will be analysed to address the objectives set during the diagnosis phase, making this step central to the workshop. Additionally, this stage involves identifying the participants for the workshop. Since the primary purpose of the workshop is to validate the decision support framework, it is necessary to determine which aspects need validation. Therefore, this section will first outline the validation aspects, followed by identifying the stakeholder profiles for participation in the workshop.

6.2.1.1 Purpose of the workshop

The primary objective of the workshop is to validate the usability of the decision-support framework. According to Gass (1983) and Borenstein (1998), in operational research, validating a Decision Support System (DSS) involves ensuring that it reasonably reflects real-world conditions while providing credible insights. Consequently, for this study, validation entails presenting the developed framework, demonstrating its application, and comparing its outcomes with actual decisions made by stakeholders. Furthermore, in the application of the framework, as detailed in Chapter 5, stakeholders' preferences were not included, and equal weights were applied to all decision criteria. However, in practice, there are conflicting preferences among different stakeholders. Therefore, it is crucial to elicit and incorporate these preferences through criteria weighting, discuss how they affect the ranking of alternatives, and reflect stakeholders' preferences. Additionally, it is essential to assess their perceptions of the framework's effectiveness in supporting decision-making and gather suggestions for future improvements. Table 6.1 outlines these validation aspects addressing the purpose of the workshop.

TABLE 6.1 The specific aspects used to validate the developed framework for its usability in supporting decision-making.

Validation Aspect	Objective
Role of Stakeholders in the decision-making process	To identify and understand the involvement of participants within the proposed framework. This helps assess whether the framework accurately captures the roles of decision-makers.
Representation of real-world decision-making process	To evaluate if participants find the framework adequate to represent real-world conditions and provide credible insights.
Incorporation of stakeholders' preferences	To determine if the framework can capture and integrate stakeholders' preferences, incorporating them effectively into the decision-making process.
Effectiveness in supporting decision-making and further development	To assess if participants find the framework effective in aiding decision-making and to gather their suggestions for improvements to address any limitations.

6.2.1.2 Stakeholder identification

Energy renovations are inherently complex, involving various stakeholders with often conflicting perspectives (D'Oca et al., 2018; Husiev et al., 2023; Jafari & Valentin, 2018; Serrano-Jiménez et al., 2021). IEA Annex 75 defines stakeholders as "*any person or entity with an interest or concern in the value proposition*" (Konstantinou & Haase, 2023). These stakeholders can be categorised into Public, Market, and Demand actors, each playing different roles and exerting varying levels of influence on the development and implementation of renovations at the district level (Avelino & Wittmayer, 2016; Konstantinou & Haase, 2023). Table 6.2 summarises the stakeholders typically involved in renovations and sustainable heating transitions identified through literature (Kamari et al., 2019; Koster et al., 2022; Regionale Energie Strategie, n.d.; Wiegerinck, 2020). It also details their potential interests and influence.

TABLE 6.2 Different types of stakeholders involved in renovations and heating transition. (Kamari et al., 2019; Konstantinou & Haase, 2023; Koster et al., 2022; Regionale Energie Strategie, n.d.; Wiegerinck, 2020).

Actors	Stakeholder	Description	Interests	Influence	Scale of decision
Policy	National Government	– Governs the regulation and oversight of the heating sector. – Responsible for creating laws and policies that local governments implement.	– The entire heating sector. – Fostering innovation towards sustainable energy sources.	– Influences legislation (e.g., Warmtewet).	Decisions on the National level
	Regional	– Energy regions comprise municipalities, provinces and energy distributors. – Decentralising energy transition	– Planning for generating, distributing, utilising, and storing sustainable energy tailored to specific energy regions	– Influence strategy implementation at the local level.	Decision on the Energy Region level
	Municipality	– Public entity representing local citizens – Plans and designates areas for new energy systems. – Handles permits.	– Developing affordable, reliable, and sustainable energy solutions. – Ensuring tariff transparency.	– Manages permits and planning processes. – Promotes subsidies and funding	Decision on Local and Neighbourhood level
Market	District Heating Companies	– Responsible for energy production, distribution, and system operation. – Develop new district heating (DH) areas. – Installs heat delivery systems, offers services, and handles billing.	– Maintaining a balanced and stable heat load. – Achieving return on investment. – Ensuring heat sales security.	– If monopoly, they can decide which area receives the connection	Decide on connections or network
	Construction companies, designers, manufacturers, financial companies, consultants	– Participate in renovation projects.	– Being involved early in the renovation process. – Alleviating burdens for demand actors.	– Advises demand actors on specific decisions.	-

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TABLE 6.2 Different types of stakeholders involved in renovations and heating transition. (Kamari et al., 2019; Konstantinou & Haase, 2023; Koster et al., 2022; Regionale Energie Strategie, n.d.; Wiegerinck, 2020).

Actors	Stakeholder	Description	Interests	Influence	Scale of decision
Demand	Housing associations	– Major consumers that manage multiple end users. – Oversee large portfolios of residences.	– Securing affordable heating. – Reliability of heat for occupants/tenants – Maintaining comfortable and healthy indoor environments. – Prefer one-time costs over recurring connection costs.	– Influenced by local government policies and market actors. – Large portfolios can influence the business case of heating transition. – Occupants/Tenants collectively can influence renovations.	Decide for portfolio
	Building owners	– Owners but are not direct consumers.			
	Individual owners	– Only one organisation or household. – Own heat contract with DH or own heat pump – Can be the owner and user	– Renovation depends on disposable income and personal preferences. – Seeking reliable and affordable heating. – Balancing lower energy costs with comfort.	– Only influence if a consumer owns the building – Less influence on tenants – Less influence on the planning process.	Decide on their individual properties.

The validation workshop focuses on a single case involving an MFH type. It explicitly targets stakeholders from both the market and demand levels, represented by energy transition consultants specialising in residential renovations and the housing corporation that manages the apartment complex. According to Konstantinou and Haase (2023), demand actors are usually considered the primary decision-makers. Therefore, involving individuals from these stakeholder groups who have significantly influenced the decision-making process to renovate the selected case study is essential. Due to the lack of direct contact with the housing corporation, the energy transition consultants were approached to identify suitable participants for the workshop. Invitations were sent out, and five people agreed to participate, with four attending the workshop.

6.2.2 Planning

In this phase, the actual logistics of the workshop were planned, focusing on three key areas: the venue, the content, and the boundary objects.

Venue

This involves selecting the time, place, and location for the workshop. It is recommended that a neutral space be chosen that is conducive to facilitation. In this study, the office space regularly used by the stakeholders of the case study project was chosen.

Content

This entails designing the workshop structure to validate the framework outlined in Section 6.2.1.1. It involves identifying specific exercises or activities needed to address each validation aspect, such as presenting the framework and its results, eliciting preferences, and conducting open interview questions.

Boundary objects

Boundary objects are an essential part of conducting any workshop. As per Storvang & Clarke (2014), these could be drawings, models, prototypes, computer animations or any artefact that can initiate dialogue among the stakeholders. Additionally, boundary objects designed to cater for the purpose of the workshop can help the stakeholders to utilise their tacit knowledge, which otherwise is difficult to tap.

The workshop was divided into four question rounds, each addressing a specific validation aspect, as detailed in Table 6.3. A set of open or five-point ranking-based questions was prepared for each aspect, supplemented by various boundary objects to facilitate stakeholders' input. Figure 6.2 illustrates the boundary objects created to understand the role of stakeholders in the decision-making process. Figure 6.3 presents the paper handouts of the pairwise comparison prepared for eliciting preferences. The decision criteria in the pairwise comparison were the ones identified from the project during the application of the framework (Chapter 5).

TABLE 6.3 The workshop structure with the description of activities, questions, and boundary objects that address specific validation aspects.

**	Validation Aspect	Activity	Questions	Boundary objects	Time
1	Role of Stakeholders in the decision-making process	– Present a simplified version of the framework and provide it as a handout. – Initiate discussion using open-ended questions, allowing participants to mark or write on the handouts.	1. Can you describe your role in the process of selecting renovations? 2. In which steps are you involved?	A3 handouts of the simplified version of the framework (Figure 6.2).	15 mins
2	Representation of real-world decision-making process	– Demonstrate the application of the framework to the case study. – Ask participants to complete rating-based questions and explain their reasoning.	3. The framework accurately represents your decision-making process for the case study.* 4. The application of the framework provided a thorough analysis of the case study.*	Presentation deck to demonstrate the application of the framework. The questionnaire with ranking statements	20 mins
3.	Incorporation of stakeholders' preferences	– Distribute handouts for pairwise comparison and explain the process. – Calculate the criteria weights based on their input, incorporate them, and determine the new ranking of alternatives. – Present the updated ranking and ask participants to complete additional rating questions, explaining their reasons.	5. How do you trade-off different interests when assessing renovation scenarios for decision-making? 6. The preferences were incorporated in an effective manner* 7. Do you agree with the proposed solutions after incorporating preferences?	A3 handouts for pairwise comparisons (Figure 6.3) Slides for presenting new ranking. The questionnaire with ranking statements	25 mins 5 mins break to calculate the new rankings
4.	Effectiveness in supporting decisions and further suggestions	– Initiate discussion using open-ended questions	8. Is this framework helpful for your next project? 9. What changes do you suggest making the framework usable for your future project?		20 mins

five-point rating question: Strongly Disagree, Disagree, Neutral, Agree, Strongly Agree

***Question rounds*

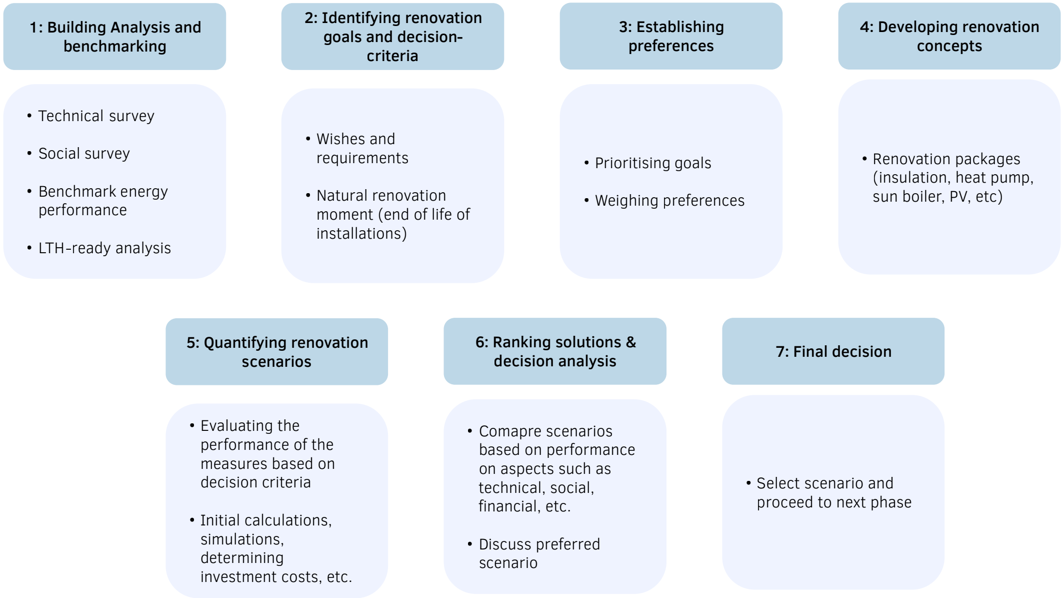

FIG. 6.2 Generic framework used as a boundary object for the workshop.

In addition to planning the workshop, careful consideration was given to managing the data collected before and after the workshop. Since the study involved human subjects, approval from the Human Ethics Research Committee (HREC) was obtained for collecting, storing, and processing personal and sensitive data. Furthermore, potential risks associated with recognising the participants were identified and minimised. Participants were informed of possible risks, and informed consent forms were developed and approved by HREC. The HREC approval and the consent forms, written in Dutch, can be found in the data repository (Wahi et al., 2024).

6.2.3 Facilitation

The planning of the workshop was executed in this stage. Given the limited availability of the participants, a detailed schedule was created, as shown in Table 6.3. The workshop was structured to incorporate some flexibility, with the content plus an additional 15 minutes for introductions and concluding rounds, totalling 100 minutes. The total time allocated for the workshop was 120 minutes, providing 20 extra minutes to accommodate any unforeseen delays or adjustments.

6.2.4 Analysis

This is the final phase of the workshop, where the gathered data is processed and analysed to achieve the workshop's primary objective. This data comprised written handouts and audio recordings. Since the data was in Dutch, it was translated and transcribed. Summaries in English were also shared with the participants for approval during the analysis. Anonymised summarises of the participants' responses could be found in the data repository (Wahi et al., 2024). The workshop results were triangulated with the case study project report and the framework's application, as discussed in the previous chapter, to draw conclusions and validate the framework.

Environmental

		Extremly important	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extremly important		Score	
Space heating demand	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C2		Energy Label
Space heating demand	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C3		Energy-Index
Space heating demand	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Share of renewable energy generation
Space heating demand	C1	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energy Savings (gas)
Energy Label	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C3		Energy-Index
Energy Label	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Share of renewable energy generation
Energy Label	C2	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energy Savings (gas)
Energy Label	C3	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C4		Share of renewable energy generation
Energy Label	C3	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energy Savings (gas)
Share of renewable energy generation	C4	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C5		Energy Savings (gas)

Economic

		Extremly important	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extremly important		Score	
Investment costs	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C7		Investment per label step per unit
Investment costs	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C8		Life cycle costs (LCC 30 years)
Investment costs	C6	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9		Simple payback period
Investment per label step per unit	C7	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C8		Life cycle costs (LCC 30 years)
Investment per label step per unit	C7	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9		Simple payback period
Life cycle costs (LCC 30 year)	C8	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C9		Simple payback period

Social

		Extremly important	Very strong to extreme importance	Very strong importance	Strong to very strong importance	Strong importance	Moderate to strong importance	Moderate importance	Equal to moderate importance	Equal importance	Equal to moderate importance	Moderate importance	Moderate to strong importance	Strong importance	Strong to very strong importance	Very strong importance	Very strong to extreme importance	Extremly important		Score	
Thermal comfort	C10	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C11		Renovation nuisance
Thermal comfort	C10	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C12		Energy cost savings
Thermal comfort	C10	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C13		Rent increment
Renovation nuisance	C11	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C12		Energy cost savings
Renovation nuisance	C11	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C13		Rent increment
Energy cost savings	C12	9	8	7	6	5	4	3	2	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	C13		Rent increment

How important is the criterion on the left compared to the criterion on the right?

Role : ________________________________

FIG. 6.3 Pairwise comparison handouts to capture preferences.

6.3 Results and Discussions

6.3.1 Role of stakeholders in the decision-making process

At the start of the workshop, the simplified decision support framework, illustrated in Figure 6.2, was presented to the participants. Following this, they described their roles within the decision-making process. Participants noted that their influence on decision-making changes throughout the project phases. Some may begin as advisors and later become decision-makers or authorisers, and vice versa, often blurring the line between these roles. Table 6.4 summarises the responses of the participants involved in the validation workshop.

TABLE 6.4 Participants' responses concerning their role in the decision-making process.

Participant	Organisation	Role	Response
1	Energy Transition Consultant	Project leader	Prepares decisions with the project team, gathers information, researches possibilities, and coordinates with stakeholders (resident consultant, asset manager, regional manager, technical manager) to inform and involve them in decision-making.
2	Social Housing Corporation	Programme manager	Manages the sustainability programme of the social housing corporation. Acts as an advisor during renovation scenario development and a decision-maker during the scenario selection. Leads decision documents and coordinates closely with decision-makers and the steering group.
3	Energy Transition Consultant	Programme manager	Oversees quality control of project plans, ensures adherence to agreements, participates in decision preparation, and is present during final decision-making.
4	Energy Transition Consultant	Project leader	Involved in project content and preparation, supports the programme manager, participates in the steering group, and collaborates with participants 1, 2, and 3 to maintain project quality.

Participants were then asked to reflect on the simplified decision support framework and identify the steps at which they recognised their roles within the framework's phases. Table 6.5 summarises the participants' involvement per framework step based on written and oral data collected during the workshop. All participants were somewhat involved in all the steps of the decision framework. The project team, including project leaders and programme managers, carries out the first six steps of the process. The final decision, made in the last step, involves the steering group, who are advised by programme managers, who, in turn, are guided by project leaders.

TABLE 6.5 Stakeholder involvement in the decision-making process for selecting renovation solutions.

	Decision-making steps	Response
1	Building analysis and bench-marking	The main stakeholders involved are project leaders and programme managers. Project leaders, supervised by programme managers, collect information for building analysis by outsourcing inspections or conduct-ing them themselves.
2	Identifying renovation goals and decision criteria	Programme managers are involved and are informed by project leaders. The decision parameters are determined during annual policy meetings.
3	Establishing preferences	The main stakeholders involved are programme managers, who are informed by project leaders. Preferences are policy-based.
4	Developing renovation con-cepts	Project leaders develop multiple renovation concepts, with programme managers advising on the renovation approach and conducting quality control. Ultimately, programme managers are responsible for the final choice of renovation option.
5	Quantifying renovation sce-nario	Project leaders are involved under the supervision of programme managers. Quantifying specific decision criteria can be outsourced to third-party experts.
6	Ranking solutions and decision analysis	Both project leaders and programme managers collaborate closely on decision analysis. Project leaders suggest preferred scenarios based on development and quantification, while programme managers ensure qual-ity control and fine-tuning.
7	Final decision	The final decision-making authority lies with the steering group, with programme managers acting as advisors to the group.

During the discussion, participant 2 suggested switching Step 2 (Identification of Renovation Goals and Criteria) with Step 1 (Building Analysis and Benchmarking). According to the participant, Step 2 is the starting point of the overarching programme, and the goals and decision parameters are based on the organisation's policy determined annually. In contrast, Step 1 is project-specific, and the relevant decision criteria are added when needed during project development.

6.3.2 Representation of real-world decision-making process

In this round, the decision support framework was presented and demonstrated through the case study. The presentation included the results of the case study application, as described in Chapter 5. Following the presentation, participants were asked to provide their perspectives on whether the framework accurately represented their decision-making process for the case study. The participants largely agreed that the framework did reflect their decision-making processes. For instance, Participant 1 highlighted the similarities between the presented framework and their current practice of providing advice (called Energy Advice report) in the early stages of the project. They noted that this preliminary investigation is essential as it forms the basis for developing a project plan, including various “what if” scenarios with all associated risks and control measures.

Similarly, Participant 2 recognised the consideration of realistic assumptions in the framework application, particularly the higher heating setpoints preferred by older residents for LT-ready assessment. They were also intrigued by the ranking system (TOPSIS method) and the quantification of the decision-making criteria considered. On the other hand, Participant 3 acknowledged the framework’s accuracy, although they emphasised the importance of practical human insights in evaluating theoretically viable solutions. For instance, they mentioned that they would not insulate ceilings or floors if there were no complaints. Even if insulating would theoretically improve performance, practical considerations take precedence.

Furthermore, participants also “agreed” that the framework application provided a thorough decision analysis, especially regarding environmental aspects. Participant 1 appreciated the inclusion of realistic building-level properties, such as insulation values, for analysis. However, all participants pointed out the limitations of incorporating social factors into the data-driven framework, such as inconvenience to tenants or renovating them in their presence. Participants 3 and 4 acknowledged that while the framework considers social factors, it is challenging to account for them entirely. This is because extracting insights from conversations with residents is inherently difficult. Nonetheless, Participant 3 suggested that this gap could be addressed through the expertise and experience of decision-makers.

6.3.3 Incorporating stakeholder preferences

6.3.3.1 Considering trade-offs between different interests for decision-making

Participants were asked how they consider trade-offs for different factors when comparing renovation scenarios in their decision-making process. Participant 2 highlighted the complexity of balancing various interests, including those of residents and previous agreements with them, real estate strategy, and changing policies and regulations related to sustainability. They emphasised their personal preference for considering long-term goals for operating the building in their decision-making. They also noted the importance of a “no-regret” philosophy

TOC

involving a thorough cost-benefit analysis when selecting solutions. Additionally, they discussed the significance of financial considerations, stating that they cannot afford to make risky investments with social housing funds. Therefore, they prefer reliable solutions that align with market standards, such as insulation, instead of high-risk innovative solutions.

Conversely, Participant 1 highlighted the value of considering local problems that can be encountered. For instance, they mentioned the problem of electricity grid congestion for connecting heat pumps, mentioning that in some areas, this is not an option for the next 20 years. According to them, having this knowledge beforehand can already inform them to reject renovation scenarios, even if they are theoretically good. Participant 3 explained that they consider net heating demand and resident comfort when choosing between scenarios within the financial budget. For analysing energy performance, Participants 2 and 3 prefer the standards on heating demand and insulation (in Dutch: Standaard and Streefwaarden) over the energy label. According to Participant 3, energy labels are only considered for rent increases, although they do not pay much attention to them.

The participants provided their preferences for various criteria when comparing renovation solutions for decision-making. Some of these criteria were also found in the project report, as illustrated in Table 5.4 in Chapter 5. These criteria were organised into environmental, economic, and social categories. However, while participants acknowledged these criteria, their relative significance was unclear. To address this, pairwise comparisons were conducted with the participants, as discussed in the subsequent section.

6.3.3.2 Pairwise comparison results

To incorporate stakeholder preferences into the decision-making process, they were asked to perform individual pairwise comparisons across environmental, economic, and social categories of decision criteria. The participants completed the handouts illustrated in Figure 6.3, followed by a 5-minute break. During this break, the scores from the pairwise comparisons were entered into an Excel tool to calculate the criteria weights. An essential step in the pairwise comparison method is to calculate the consistency ratio (CR) to evaluate the robustness of the weights from individual participants (Si et al., 2016; Tae-Woo et al., 2018). A standard threshold for the CR is 10%, although this can be higher if less precision is required (Saaty & Katz, 1990).

The CR is calculated as the ratio of inconsistencies from the participants (consistency index (CI)) and a randomly generated consistency index (RCI) (Tae-Woo et al., 2018). The CR analysis revealed that not all participants provided consistent answers. At a CR of 13%, 2 out of 4 stakeholders gave consistent answers. However, all criteria weights would be considered consistent at a CR of 25%. It is important to note that these inconsistencies affect the reliability of the weighted decision analysis ranking results. Therefore, it is recommended that the pairwise comparison answers be revised if the CR exceeds the threshold. Due to time constraints during the workshop, these inconsistencies were accepted without further discussion.

Once the individual pairwise comparisons were completed, the results were averaged for each criterion. These averages were then divided by the total sum of the average weights (300%) and converted into percentages to ensure that the sum of all weights equals 100%. Table 6.6 illustrates the individual, average, and balanced criteria weights used for the TOPSIS ranking. The data repository (Wahi et al., 2024) contains the pairwise comparison results from each participant.

TABLE 6.6 Final balanced criteria weights from individual pairwise comparison.

	Environmental					Economic				Social			
	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13
	Space heating demand	Energy label	Energy Index	Share of renew-able energy	Energy savings (gas)	Invest-ment costs	Invest-ment per label step per unit	Life cycle costs	Payback period	Thermal comfort	Reno-vation nuisance	Energy cost savings	Rent incre-ment
Participant 1	34%	18%	14%	10%	25%	46%	23%	16%	16%	42%	10%	41%	7%
Participant 2	31%	3%	3%	22%	40%	29%	10%	56%	5%	26%	10%	58%	6%
Participant 3	44%	7%	4%	12%	33%	15%	8%	39%	39%	37%	12%	32%	20%
Participant 4	45%	7%	3%	15%	30%	41%	4%	45%	11%	35%	6%	41%	17%
Average criteria weight	38.5%	8.8%	6.0%	14.8%	32.0%	32.8%	11.3%	39.0%	17.8%	35.0%	9.5%	43%	12.5%
Balanced criteria weight	12.8%	2.9%	2%	4.9%	10.7%	10.9%	3.8%	12.9%	5.9%	11.7%	3.2%	14.3%	4.1%

From the aggregated preferences of each participant, it can be observed that criteria related to energy savings (C12 and C5), financial considerations (C8 and C6), energy demand (C1), and resident comfort (C10) are given high priority. Additionally, within the framework, C1 and C10 are considered non-negotiable criteria for assessing LTH readiness. The preference elicitation also highlighted the low priority of the energy label and energy index, as discussed by participants (Section 6.3.3.1). While filling out the handout, some participants found the pairwise comparison for the social category challenging and discussed the implications of prioritising one aspect over another from the tenants' perspective.

6.3.3.3 Ranking alternatives with preferences

The balanced criteria weights were incorporated into the decision analysis to examine the impact of participants' preferences on the ranking of alternatives. Figures 6.4a and 6.4b illustrate how these preferences affect the ranking of the originally proposed alternatives (A1-A4) and the new solutions generated (A7R, A9-A12). These figures also include the rankings with equal criteria weights for comparison. Table 5.5 in Chapter 5 details these renovation solutions.

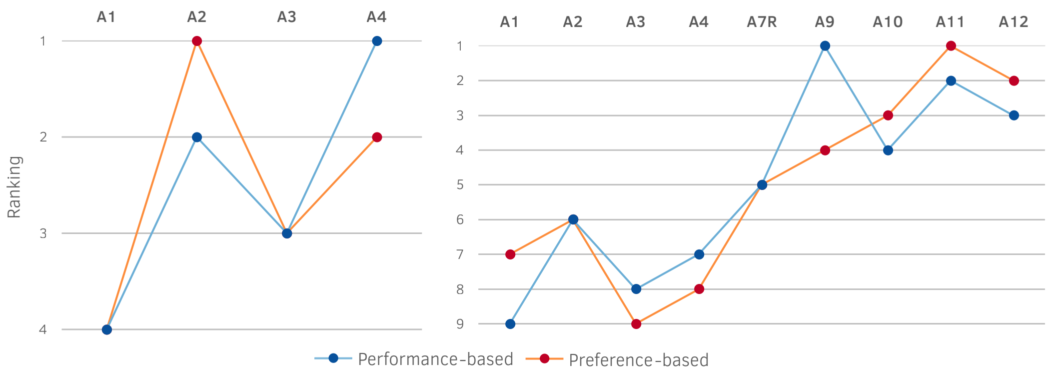

FIG. 6.4 Ranking of solutions based on two sets of criteria weights: equal criteria weights (performance-based) and participant-provided criteria weights (preference-based). 4a) The left panel shows the rankings of the originally proposed solutions. 4b) The right panel illustrates the rankings of both newly developed and original renovation solutions.

From the originally proposed solutions (A1-A4), the renovation alternative A4, which includes roof and cavity wall insulation, improved airtightness, a collective air-water heat pump, and PVT collectors, was chosen for the case study. When equal criteria weighting is considered, the TOPSIS method also identified A4 as the most optimal scenario. However, Figure 6.4a shows that incorporating the participants' preferences changes the most optimal renovation solution from A4 to A2. This solution is similar to A4, with a difference in a gas boiler instead of a heat pump and no renewable energy generation.

TOC

Upon further discussion about the effect of participants' preferences on this shift, it emerged that some participants based their preferences on current policies in 2024, as opposed to those during the case study in 2018. For instance, while the project's main objective was to improve the energy label, participants currently prioritise insulation standards to lower heating demands. This shift is reflected in the higher weights for C1 (heating demand) compared to C2 (energy label).

Additionally, some participants incorporated personal preferences instead of policy-driven ones, contributing to the shift in rankings. There were also discrepancies between stated importance and elicited preferences. For example, discussions highlighted that renovation inconvenience (C11) to tenants is a significant criterion, although this is not reflected in the criteria weights shown in Table 6.6. Lastly, the high CR value indicates that the consistency of the criteria weights is questionable, further affecting the ranking of alternatives.

Furthermore, Figure 4b illustrates the ranking of all the solutions, including the original and newly developed ones, based on balanced criteria weights. Even though A2 was considered the most optimal alternative after incorporating preferences, it only ranks sixth compared to the additional renovation alternatives. A noticeable shift in the optimal alternative occurs when comparing the equal weight rankings of all the solutions (A1-A4, A7R, A9-A12) to the balanced weights rankings. Compared to A9 in the performance-based ranking, A11 emerges as the most optimal after considering the preferences.

From the participant's perspective, the newly developed solutions through the framework application can theoretically prepare the apartment complex LT supply. However, concerns were raised regarding their feasibility in practice. For example, questions about replacing existing radiators and introducing balanced ventilation systems were highlighted. While these measures are necessary to achieve LT readiness for the case, they would also cause inconvenience to the tenants, as they need to be able to remain in their homes during renovations. Additionally, replacing functional components (existing radiators) must be reconsidered from a sustainability and material efficiency perspective.

According to Participant 2, financial considerations often limit the implementation of LT-ready measures for all homes. Therefore, a stepped approach is recommended, beginning with investments in building envelope insulation, which is considered a no-regret solution. Since technologies like heat pumps are continually evolving, it is advisable to focus on these no-regret solutions first. Additionally, given the current uncertainties in the heat network, Participant 2 suggested preparing the dwellings for LTH regardless of whether the future supply system is a heat pump or district heating.

6.3.3.4 Participants' view on eliciting preferences

The participants agreed that their preferences were represented both from a policy and personal perspective. They found the pairwise comparison method promising and supportive of the decision-making process, highlighting its potential to facilitate better-informed decisions. Participants noted that this method offers a quick and analytical approach to decision-making. This leads to more concise and targeted discussions, especially in the early stages of a project, thereby speeding up the overall process.

The participants considered the preference elicitation and incorporation to rank the alternatives as a novelty. This was in contrast to their existing decision-making process, which relies on a mix of gut feelings selectively supported by quantified data on a few decision parameters. The proposed framework provides an analytical backup to those gut feelings. Participants found this approach both interesting and helpful. They also mentioned that it could serve as a reflective tool to evaluate policies from previous years.

6.3.4 Effectiveness in supporting decision

6.3.4.1 Usability

In this final round, participants were asked if the framework could support decision-making in their next project. The participants unanimously agreed on the usability of the general framework. One participant suggested using the framework to reflect on and improve their own processes. Another proposed using the equal weights decision analysis to benchmark their policy. They also suggested involving the steering group and project team for input on the pairwise comparison for decision analysis with their preferences and comparing these two as a reflective tool for their policy. This approach was seen as a valuable opportunity to kickstart the project with focused discussions and support the development of the project strategy.

The workshop's success was evident, as no major issues arose during the decision analysis. The results of the pairwise comparison for criteria weights and TOPSIS for ranking were obtained and presented quickly and easily. This led to the conclusion that the framework's usability was validated for this case study. Another implicit validation of the framework's usability was the participants' invitation to conduct this workshop again for another group of stakeholders within their company, who could also benefit from this decision support framework.

6.3.4.2 Further development

The participants provided several suggestions to improve the framework. The first suggestion is introducing feedback loops at different stages, especially after the final decision stage. This stems from the fact that practical implementation of renovation solutions often leads to changes. Participants questioned whether to restart the process or follow specific steps when these changes occur. The second suggestion was to switch framework step 1 (building analysis and benchmarking) with step 2 (identifying decision parameters). This would improve the framework and follow a natural process, as step 2 is programme-related while step 1 is project-related. The third suggestion was to include an element in the decision support tool to filter out non-feasible renovation scenarios based on project specifics. For example, ensuring that tenants can stay in their homes would eliminate several renovation options. Finally, the fourth suggestion was to introduce a step for risk assessment before or parallel to the building analysis and benchmarking. Since decision criteria alone cannot make risk factors explicit, a thorough risk analysis could highlight potential issues more clearly.

6.4 Conclusions

The workshop aimed to validate the usability of the decision-support framework developed to assist stakeholders in selecting renovation solutions for LTH. This validation sought to ensure that the framework is applicable in real-world contexts, incorporates stakeholder preferences, and supports the decision-making process effectively. During the workshop, the framework's application to the case study was demonstrated. Preferences were elicited via pairwise comparisons and incorporated into rank evaluations, and participants' opinions were gathered through open-ended and rating-based questions to capture perspectives on the usability of the framework.

The workshop involved four expert stakeholders related to the case study: two project leaders, a programme manager from the energy transition consultants, and a programme manager from the social housing corporation. The project leaders gather information, coordinate with other stakeholders, and advise programme managers and, indirectly, the steering group with decisions. In contrast, programme managers ensure quality adherence to agreements, oversee decision preparation and work closely with decision-makers to reach a consensus. The findings reveal that participants were involved in all steps of the decision-support framework, assuming varying roles such as informants or advisors, decision-makers or authorisers. Consequently, this makes them suitable for validating the decision-support framework.

Participants affirmed that the framework accurately represented their decision-making processes, describing it as clear, concise, and structured. They agreed that the framework provided a thorough analysis of the case study by considering realistic inputs and assumptions for LT-ready assessment and other environmental criteria. However, while they agreed with the proposed solutions and their ranking from an LT readiness perspective, they questioned the feasibility of these solutions in practice. The participants highlighted the need for a more in-depth analysis of the local context (such as availability of heat grid or electricity grid congestion), social factors (e.g., renovating occupied building and associated inconvenience), practical considerations (such as available space for new installations) and material efficiency (replacing existing functional components). Incorporating these factors into the framework could enhance its accuracy.

The pairwise comparison method for eliciting stakeholder preferences was well-received. The incorporation of their preferences led to a shift in the optimal solution (A2) compared to the originally decided solution (A4) by the project. Thus, it underscored the importance of integrating stakeholder perspectives into decision-making. However, inconsistencies in the criteria weights, indicated by the high consistency ratio (CR), suggest that additional time and follow-up sessions may be necessary to refine and validate these weights.

Participants considered the framework valuable for several reasons. Unlike the current intuition-based process, the framework offers a structured and analytical basis for decision-making. However, they suggested incorporating human-based insights to navigate the complex decision-making process, which can sometimes be difficult for a logical model or framework to capture. Additionally, participants valued the framework's ability to reflect both policy-driven and personal preferences, allowing for a more comprehensive evaluation of renovation options. They also saw potential in using the framework as a reflective tool to evaluate past policies and decisions, further highlighting its utility.

Participants provided several suggestions for improvement. One recommendation was to focus on effective investments by prioritising no-regret solutions, such as building envelope insulation, over evolving technology-based solutions. They also suggested incorporating feedback loops to reflect the iterative nature of the decision-making process, reordering steps 1 (identification and benchmarking) and 2 (identification of goals and criteria), filtering out non-feasible solutions based on specific project constraints, and incorporating risk assessment as part of decision-making. In conclusion, the decision support framework demonstrated significant potential in supporting the decision-making process for selecting renovation solutions for making dwellings ready to be heated with LTH. The insights and suggestions stakeholders provide offer valuable directions for further refinement and application of the framework in real-world contexts.

6.5 Limitations and Recommendations

Despite the valuable insights from the validation studies, several limitations must be acknowledged. The workshop involved a limited number of participants, which may not fully represent all stakeholder perspectives. Additionally, the validation was based on a single case study. While the results are promising, multiple case studies with different stakeholder groups are needed to strengthen the findings. Future studies should apply the framework to ongoing projects to better capture its decision-support function.

Furthermore, only 1 out of 4 participants provided consistent criteria weights, and due to time constraints, these inconsistencies were not further discussed. Since these inconsistencies impact the final rankings, future studies must address this aspect when applying the decision support framework. The findings also revealed that some participants based their pairwise comparisons on personal rather than policy preferences, potentially influencing the results. This ambiguity could have affected the ranking outcomes. Therefore, it is essential for future research to clearly state the perspective from which participants should complete the pairwise comparison to ensure more accurate and relevant results.

Another limitation relates to the interdependencies of the decision-making criteria. Some criteria considered for preference elicitation, such as C1-C3, C5, and C12, are interrelated. According to Si et al. (2016), criteria must be independent to avoid overlapping and double counting during analysis. However, achieving independent criteria in the context of sustainable renovations is challenging (Si et al., 2016). To address this, future studies can explore criteria weighting techniques such as the Analytical Network Process (ANP) (Lei et al., 2023; Tae-Woo et al., 2018; Taherdoost

& Madanchian, 2023) or Decision Making Trial and Evaluation Laboratory (DEMATEL) scales (Schulze-González et al., 2023). Combining these techniques with the pairwise comparison method could better account for dependencies between criteria and improve decision-making.

Data availability

The data pertaining to the study is available on 4TU.ResearchData and can be accessed through the following DOI: https://doi.org/10.4121/d7548774-f2db-45e0-8c43-5dcda63c888c.v1

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7 Conclusions

7.1 Introduction

The Netherlands has set ambitious targets to transition 1.5 million homes by 2030 and 7.7 million homes by 2050 to natural gas-free heating as part of its broader strategy to decarbonise the built environment. This transition is vital for mitigating greenhouse gas (GHG) emissions, combating climate change, addressing seismic risks associated with natural gas extraction and enhancing energy security. District heating (DH) systems with lower temperature supply are expected to play a pivotal role, potentially supplying 50% of sustainable heat by 2050, particularly in urban areas. However, the success of this transition depends on the readiness of existing dwellings to accommodate LTH. Many existing dwellings, originally designed for high supply temperatures, may struggle to maintain acceptable thermal comfort when switched to LTH. Additionally, higher peak demands in these buildings can create bottlenecks, complicating efforts to lower supply temperatures at the district level and to design future networks incorporating sustainable heating sources. As a result, energy renovations are necessary to enable the transition.

Selecting appropriate renovation solutions, however, is complex and fraught with challenges. First, there is a lack of standardised criteria for evaluating the LTH readiness of dwellings, complicating the assessment of renovation needs. Second, the wide range of potential renovation options can lead to decision paralysis, particularly given the heterogeneity of the Dutch housing stock. Further, the decision-making process is complicated by the involvement of multiple stakeholders with diverse preferences and priorities. Decision-makers often face constraints in terms of time and expertise to appraise solutions and gain a comprehensive overview of priorities, leading to information barriers that impede the decision-making process. These challenges underscore the need for a systematic decision-making framework to support the selection of suitable renovation solutions for LTH, contributing to the energy transition of the Dutch housing stock.

To address these challenges and the identified need for a structured decision-making approach, this study is guided by the main research question:

- **How can the selection of renovation solutions that prepare diverse dwellings in the Netherlands to utilise lower temperature heat from district heating systems be systematically supported?**

The main research question was divided into four sub-questions that address specific aspects of the decision-making challenges. Chapters 2 through 5 of this thesis examine these sub-questions in detail. In the current chapter, the conclusions for each sub-research question are presented in Section 1.2, leading toward answering the main research question in Section 1.3. Ultimately, Section 1.4 outlines the limitations of the research and provides recommendations for future studies.

7.2 Addressing sub-research questions

7.2.1 What factors must be considered when selecting renovation solutions to prepare dwellings for adopting lower-temperature heating?

To effectively select renovation solutions for preparing existing Dutch homes for LTH, it is essential to identify the factors influencing the decision-making process. As discussed in Chapter 2, several factors may affect the selection of renovation options at the building level when implementing LTH. These include the diverse characteristics of the heterogeneous dwelling stock, the wide array of available renovation options, and the various performance indicators needed to evaluate the trade-offs among these alternatives. Consequently, a systematic review of existing scientific literature on LTH integration in residential dwellings was conducted. The aim was to identify factors related to the building characteristics, renovation options, and performance indicators that impact the selection of renovation solutions.

Building-level characteristics

The building-level characteristics of a dwelling significantly influence its readiness for LTH. These include dwelling typology, building envelope properties, ventilation, space heating and heat generation systems, and supply temperature levels. Given the heterogeneous nature of the dwelling stock, each dwelling exhibits a unique combination of these features, necessitating tailored renovation solutions. These characteristics were analysed in the literature to identify the essential building-level factors affecting the potential usage of LTH.

The findings revealed that dwelling characteristics such as building envelope insulation properties and airtightness, ventilation systems, the heating capacity of existing space heating systems (such as radiators), and the level of lower temperature supplied could significantly affect the potential of existing dwellings to be heated with LTH and determine the necessity of renovations.

Existing literature addresses various dwelling typologies based on size (e.g., single-family homes, multi-family homes), subtypes (e.g., detached, semi-detached, terraced houses, apartments), and construction year. Most studies utilised archetypes representing the diverse residential stock to investigate LTH integration. These archetypes provide insights into typical thermal insulation and construction limitations, informing renovation needs. However, individual dwellings may deviate from these archetypes due to past renovations or improvements since their original construction. Additionally, no significant relationship was found between dwelling typology and LTH use. Nevertheless, the compactness ratio is suggested as a potential indicator of LTH readiness, as it considers both geometrical and building physics aspects, although it has not been explicitly explored in existing studies.

Furthermore, the studies explored various LTH generation systems, including collective systems such as district heating, individual systems such as heat pumps or high-efficiency boilers, and hybrid systems combining both. The findings indicate that dwelling typology does not significantly influence the choice of heat generation system for LTH supply. Instead, as indicated in the literature, it primarily depends on the availability of infrastructure, business case considerations, or connection costs, which appears to reflect recent developments in the heating sector in the Netherlands.

Renovation options for using LTH

The literature highlights a range of renovation options that have been implemented to facilitate the use of LTH. However, a systematic organisation of these solutions is essential for effectively navigating the available options and selecting the most appropriate solutions for specific dwellings. To achieve this, the study adopted a methodology for generating holistic renovation scenarios, as Figure 2.6 of Chapter 2 illustrates. The methodology includes four key components, namely renovation objectives, scenarios, strategies, and measures, that were used to organise the renovation solutions identified in the literature.

- **Renovation objectives** define the context or purpose of renovations and are broadly categorised into three types: functional (technical and environmental), feasible (financial), and accountable (social). Functional and feasible goals, such as reducing energy use or costs, are quantifiable, while accountability goals are qualitative, focusing on occupant convenience or aesthetics. Current literature primarily focuses on quantitative functional and feasible goals when renovating for LTH, with limited emphasis on qualitative accountability goals. This indicates a gap in incorporating accountability objectives into the decision-making process for selecting LTH renovation solutions.

- **Renovation scenarios** represent different approaches to achieving renovation objectives, defined by the depth or extent of the required interventions: base-case, basic, moderate, and deep. The base-case scenario involves no renovation and serves as a benchmark. Other levels range from minimal modifications to extensive renovations. The choice of intervention level is informed by the dwelling's constructional limitations and can be tailored based on specific performance targets, such as operational and primary energy goals, the extent of envelope upgrades, or other constructional constraints.

- **Renovation strategies** involve building-level approaches categorised into envelope, system, and control strategies.

- **Renovation measures** are specific techniques or products to implement these strategies, each with specific properties such as cost, thermal characteristics, or environmental product declarations. A renovation scenario may involve multiple strategies, each with various measures. Table 2.8 and Figure 3.2 illustrate the identified strategies and measures.

The review revealed that studies often focused on “low-hanging fruit” at the building envelope level, with measures offering the highest energy savings with the lowest investment. These include upgrading thermal insulation, windows and improving airtightness, followed by system-level upgrades, such as ventilation systems improvements. However, different strategies can sometimes conflict, making trade-offs crucial when selecting renovation options. While various renovation measures were studied, the literature highlighted a lack of detailed product-level information. Providing more comprehensive product-level data is essential to enhance the decision-making process. This will allow for a more thorough evaluation of solutions and the selection of the most appropriate options for LTH.

Performance evaluation parameters for LTH

Identifying renovation objectives also provides insights into the specific decision-making criteria and corresponding KPIs used to quantify the performance of renovation solutions and facilitate trade-offs during selection. The review identified various KPIs and assessment methods utilised by the studies to evaluate renovation options for LTH.

Since most studies focused on functionality and feasibility renovation objectives, the criteria and KPIs also reflected this trend. However, the studies highlighted the lack of standardised criteria required to assess the readiness of dwellings for LTH. It was also observed that criteria related to functionality, such as energy efficiency, thermal comfort, and maintaining temperature differentials between supply and return flows, are crucial for evaluating possible renovation solutions. Further, financial criteria are essential for quantifying the feasibility of these possible solutions. This study recommends that these criteria and KPIs be discussed early in the process while developing renovation objectives in collaboration with stakeholders, as outlined in Chapters 5 and 6. This approach ensures that the selected solutions are technically sound, financially viable, and socially acceptable.

7.2.2 How can the readiness of dwellings to utilise lower temperature heat from district heating be defined and assessed to identify the necessary renovations?

Assessing a dwelling's readiness for LTH is crucial for determining the need for renovations and identifying suitable solutions. However, as discussed in Chapter 2, there are no standardised criteria for evaluating LTH readiness. This leads to uncertainty in assessments and hinders effective decision-making when selecting renovation options. To address this gap, the study establishes criteria for evaluating LTH readiness. These criteria are incorporated into a two-step assessment approach designed to evaluate the readiness of the dwelling in question and identify necessary renovation interventions. The two-step assessment approach is illustrated in Chapter 3, Figure 3.1.

LTH readiness criteria

The literature review in Chapter 2 highlighted that, despite the absence of a standardised set of criteria, the performance of a dwelling or the selection of renovation options for LTH has generally been assessed based on energy efficiency and thermal comfort. Building on this, the study proposes a definition of readiness for a dwelling to be heated with LTH: *A dwelling is considered LTH-ready if it can maintain or improve energy efficiency and thermal comfort under lower temperature supply, compared to its existing condition under high-temperature (HT) supply.* This definition is based on the non-compensatory decision-making model in the multi-criteria decision-making (MCDM) approach, where trade-offs between criteria are not allowed. The KPI associated with energy efficiency is the annual space heating demand, while thermal comfort is quantified by calculating occupied underheated hours using the adaptive thermal limit (ATL) model.

Two-step assessment approach

The first step of the assessment involves evaluating a dwelling's suitability for LTH by benchmarking its performance under HT supply. This benchmark is based on the two LTH-ready KPIs: annual space heating demand and occupied underheated hours. These KPIs are then recalculated for the dwelling under lower supply temperatures and compared to the benchmark performance. According to the LTH readiness criteria, if the dwelling's performance under lower temperatures does not meet the benchmark, it is not ready to be heated with the chosen lower temperature supply. In such cases, the next step involves developing a possible renovation solution space.

To create the renovation solution space, this study employs the scenario-based methodology as illustrated in Chapter 3, Figure 3.3, with three levels of intervention: basic, moderate, and deep.

— **Basic interventions** involve no changes to the building envelope but may include upgrades to building systems, such as replacing existing radiators.

— **Moderate interventions** include targeted improvements to the building envelope, with optional changes to systems and controls.

— **Deep interventions** correspond to comprehensive changes to the building envelope, controls, and systems.

Depending on the level of intervention, single or multiple strategies and corresponding measures can be identified based on the specific context of the dwelling. Figure 3.2 in Chapter 3 illustrates the different renovation strategies and measures that can be applied at the building envelope, system, and control levels, as identified from the literature reviewed in Chapter 2.

Findings from case-study application

The proposed assessment approach was applied to a case study of a dwelling built in 1939 to evaluate its readiness for medium temperature (MT: 70/50°C) and low temperature (LT: 55/35°C) supply from DH systems, compared to the HT supply of 90/70°C from the original gas boiler. The findings indicated that the dwelling, in its existing condition, was not ready for LTH, with significant thermal discomfort observed under both MT and LT supply conditions. Moderate interventions, such as upgrading window insulation and radiators, were the minimum required to achieve readiness for MT supply. For LT supply, additional deep renovation interventions, including enhanced airtightness and comprehensive insulation of the building envelope, were necessary. Furthermore, the living room exhibited higher levels of thermal discomfort compared to the bedrooms, suggesting it could serve as a reliable proxy for evaluating the thermal comfort under LTH across the entire dwelling.

Comparison with Standards

The identified renovation measures were compared to the recent standards and target values for home insulation in the Netherlands (*Standaard & Streefwaarden*), which specify space heating demand targets for gas-free heating based on a dwelling's compactness ratio and construction class. The comparison revealed that while some renovation solutions met the space heating demand benchmark set as per the standard, they failed to ensure adequate thermal comfort. This underscores the importance of the LTH readiness criteria defined in this study, which provide a more comprehensive basis for selecting renovation solutions than relying solely on space heating demand standards. Therefore, integrating thermal comfort standards alongside space heating demand benchmarks is essential for a more nuanced evaluation of LTH readiness.

In conclusion, the developed assessment approach proved effective in determining whether a dwelling is LTH-ready and, if not, systematically developing renovation solutions while narrowing down the options by eliminating those that fail to prepare the dwelling for LTH. The implications of this approach are significant, as they address two key decision-making challenges for LTH readiness renovations: establishing clear criteria for LTH readiness and reducing the number of viable solutions. However, since this approach was only applied to a single dwelling type, it is crucial to scale it to other dwelling types, considering their unique characteristics and variations to provide a more comprehensive assessment of LTH readiness.

7.2.3 How can variations in building-level parameters that contribute to diversity within the dwelling stock be incorporated into assessing readiness for lower-temperature heating?

Chapter 3 introduced a two-step assessment approach to evaluate LTH readiness, identify renovation needs, and determine the required intervention level. Initially, this approach was applied to a single case and then qualitatively extended to archetype dwellings to generalise renovation measures for MT and LT supply. While these generalisations can inform policy, they may be limited for individual dwellings. In practice, variations within the housing stock lead to diverse renovation needs, requiring tailored assessments and solutions. Relying solely on archetype-based solutions can result in performance gaps, emphasising the importance of incorporating such variations when assessing LTH readiness.

To address this challenge, the study proposes a sampling-based approach to capture the variability within Dutch dwelling types (terraced-intermediate and apartment types) and assess their LTH readiness. The study had two main objectives: to identify a representative sample size that captures the variation within a dwelling type and to determine the relative influence of building-level parameters that affect LTH readiness for MT and LT supply.

Sample size determination

The first objective was to determine a sample size that reflects the variations within these dwelling types. The study considered building-level parameters influencing LTH readiness (as outlined in Chapter 2) and categorised them into four groups: geometrical, fabric, system, and occupancy and control. Latin Hypercube Sampling (LHS) was used to generate samples based on data from the 2018 National Housing Survey (WOON), which includes four construction year categories. This approach ensures that the samples represent variations across construction years and reflect the current state of the housing stock.

A multi-level sampling approach was employed to generate and simulate samples using a parametric workflow under MT and LT supply conditions for terraced intermediate and apartment dwellings. The output related to LTH readiness, space heating demand and thermal comfort, as described in Chapter 3, was used to determine the appropriate sample size. The simulated output was post-processed to perform a global sensitivity analysis (GSA) using the standardised rank regression coefficient (SRRC) method. This analysis determined that a sample size of 1,300 was sufficient to capture variations due to building-level parameters for both dwelling types. While a larger sample size could improve robustness and reduce uncertainties, it would also increase computational costs.

Relative importance of building-level parameters

Chapter 2 identified the building-level parameters influencing LTH readiness. However, determining their relative importance was essential. To achieve this, a new dataset of 1300 samples was simulated under MT and LT supply conditions, labelled for readiness and analysed using supervised machine learning with the Random Forest algorithm.

The feature importance analysis showed similar trends for terraced dwellings under MT and LT supply, with some variation observed in apartment typologies. The most influential factor was heating setpoints, highlighting the influence of occupant behaviour on LTH readiness. This was followed by factors related to ventilation heat losses, infiltration, and fabric-related characteristics such as the thermal properties of roofs, windows, walls, ground, and doors. While geometric parameters, such as window-to-wall ratio, had minimal influence, the compactness ratio was more significant in apartments due to its impact on positioning. Orientation impacted terraced dwellings to some extent but had minimal influence on apartments. Additionally, radiator oversizing was found to impact the LTH readiness of the studied dwelling types substantially. To accurately assess LTH readiness, the relative importance of the building-level features must be considered, specific to each dwelling type, as outlined in Chapter 4, Table 4.4.

Comparison with archetype-based approach

Chapter 3 recommended renovation measures for terraced-intermediate dwellings to achieve MT and LT readiness based on archetypes categorised by construction year. These recommendations suggested moderate interventions are required for MT and LT supply in dwellings constructed before 1975. For dwellings built after 1975, no renovations are needed for MT supply, and only basic interventions are required for using LT supply. These recommendations indicate a higher level of readiness for this dwelling type, especially the ones constructed after 1975. However, this contrasts with the findings of Chapter 4, which show a lower level of readiness for MT and LT supply in terraced-intermediate dwellings.

This can be explained by the archetypes being based on construction year, representing typical construction and building-level properties for a specific construction period. In practice, dwellings may differ from these archetypes due to maintenance or upgrades already implemented. Therefore, compared to archetype-based analyses, it is essential to incorporate variations into the assessment to provide deeper insights into the LTH readiness of dwellings.

Practical implications

The feature importance analysis in Chapter 4 provides valuable insights for prioritising renovation strategies and developing targeted measures to make dwellings LTH-ready. These insights enable stakeholders to assess the current condition of dwellings within their portfolio and identify the critical parts at the building level where renovations are needed to achieve LTH readiness. By understanding the impact of these parameters, stakeholders can make informed decisions, minimising decision paralysis when selecting renovation solutions. These findings are robust, as they incorporate representative variations within the studied dwelling types, providing a solid foundation for preparing homes for LTH.

7.2.4 How can the multi-criteria decision-making approach be utilised to support the selection of renovation solutions for using lower-temperature heating?

While the previous sections discussed the challenges of selecting suitable renovation solutions, the decision-making process remains complex due to multiple stakeholders with conflicting preferences and priorities. This study has explored LTH readiness criteria, assessment approach, influential parameters and the identification and narrowing of possible solutions. However, actual decision-making requires balancing these competing stakeholder interests and making trade-offs among the solutions. A potential approach to address this complexity is through MCDM methods. Even though various studies have utilised MCDM methods, it remains essential to explore how this approach can further support decision-making in the context of LTH renovations.

To this end, a decision-making framework based on MCDM was developed to assist in selecting suitable renovation options for using LTH. This framework was systematically developed by generalising key steps from existing MCDM literature and adapting them to the specific context of LTH renovations while incorporating insights from previous chapters (Chapters 2-4) at relevant steps. The proposed framework consists of six essential steps, as outlined in Chapter 5, Figure 5.2, and each step is explained below.

- **Step 1: Identification and Diagnosis**
  This initial step focuses on identifying key issues and structuring the renovation process by collecting information on the dwelling's existing conditions. A checklist (Table A.5.1, Chapter 5) is developed to ensure that all relevant data are gathered. Benchmarks are then established to assess LTH readiness and evaluate renovation options. This step also involves identifying stakeholders' interests and setting the project's ambitions and goals, which guide all subsequent decisions. Additionally, supply temperature transition targets are determined at this stage.

- **Step 2: Evaluating LTH Readiness**
  Here, the dwelling's readiness for LTH is assessed using the criteria from Chapter 3, focusing on space heating demand and thermal comfort under lower temperature conditions. This evaluation determines whether renovations are needed to prepare the dwelling for LTH. If the readiness criteria are met, no renovations are required; otherwise, the process continues.

- **Step 3a: Establishing Criteria and Preferences**
  Once the need for renovations is established, decision-making criteria are defined and prioritised based on the goals set in Step 1. A decision tree organises these criteria into sustainability goals—environmental, economic, and social—along with specific objectives. Within this tree are two non-negotiable decision criteria: space heating demand and thermal comfort, used to assess LTH readiness. Table 5.4 in Chapter 5 provides an overview of these criteria, supported by insights from Chapter 2 and the relevant literature. Further, this decision tree is flexible and can be expanded as needed. Stakeholders' subjective preferences are elicited through pairwise comparisons, helping to assign weights to each criterion. This prioritisation is essential for evaluating and comparing the renovation alternatives developed in the following steps.

- **Step 3b: Developing Renovation Alternatives**
  In this stage, renovation solutions are developed based on the dwelling's context, established in Step 1. The goal is to create a range of possible renovation options that can be assessed for LTH readiness (Step 4) and evaluated against multiple decision-making criteria (Step 6) defined in Step 3a. Scenarios are categorised as basic, moderate, or deep interventions, depending on the required renovation level. Each scenario includes strategies for different building aspects, such as the envelope, services, or controls, which are translated into specific measures. Figure 5.3 in Chapter 5 illustrates a sub-framework for organising these solutions, incorporating the relative importance of building-level parameters identified in Chapter 4. This feature importance helps examine the dwelling, pinpoint improvement areas, and develop targeted strategies based on the intervention level needed.

- **Step 4: Filtering LTH Ready Solutions**
  This step filters the renovation solutions by assessing them against the LTH readiness criteria from Step 2. Solutions are simulated under lower temperature conditions and compared to the benchmarks established in Step 1. Those that do not meet LTH readiness criteria are eliminated, ensuring only viable options proceed to the next steps

- **Step 5: Performance Quantification**
  The solutions that pass the LTH readiness filter are then quantified against the decision-making criteria from Step 3a. This involves simulations, expert input, or calculations to evaluate each solution's performance. Solutions failing to meet benchmarks for other criteria may be filtered out, leaving only the most feasible options for final evaluation.

- **Step 6: Ranking Alternatives**
  In the final step, the remaining alternatives are assessed and ranked using the TOPSIS (Technique for Order of Preference by Similarity to Ideal Solutions) method. This approach evaluates each alternative based on its distance from the ideal solution, considering conflicting criteria and stakeholder preferences. The top-ranked alternatives are recommended for implementation, with the option to iterate the process if the rankings do not meet stakeholder expectations.

Findings from case-study application

The framework was applied to a case study involving an MFH complex built in the 1980s. When applied to the pre-renovation condition with equal weights assigned to all decision-making criteria, it identified the same optimal solution initially chosen by the stakeholders, demonstrating its ability to incorporate real-world context and effectively support decision-making. However, this solution was not LTH-ready. Using the framework, an alternative solution that enhanced thermal comfort compared to the initially proposed solution was identified, albeit requiring a higher initial investment and an additional year for payback. Nonetheless, considering the life cycle costs, the additional investment proved beneficial in the long term.

The case study highlighted the framework's holistic decision-making approach, allowing for a comprehensive evaluation of various criteria and trade-offs to support decision-makers in selecting the most suitable solutions. Initially developed for renovations to prepare dwellings for LTH supplied through DH systems, the framework also proved adaptable to LTH supplied via heat pumps. This demonstrates its flexibility in facilitating transitions to diverse LTH-based systems.

Validation of decision support framework

A workshop was conducted with four expert stakeholders to validate the decision support framework, focusing on its usability in real-world contexts and its effectiveness in incorporating stakeholder preferences. Participants confirmed that the framework accurately reflected their decision-making process and appreciated its clear and structured presentation. They acknowledged the thorough analysis of the case study, realistic inputs, and assumptions and generally supported the LTH readiness assessment and solution rankings. However, concerns were raised about the practicality of some solutions, and participants emphasised the importance of addressing social factors, such as occupant inconvenience during renovations. The pairwise comparison method for eliciting preferences was well-received, as it demonstrated the impact of stakeholder input on solution rankings. Nevertheless, inconsistencies in criteria weighting highlighted the need for additional refinement time.

Stakeholders valued the framework's structured, analytical approach, contrasting it with intuition-based processes, and appreciated its ability to integrate both policy-driven and personal preferences for a comprehensive evaluation. They identified potential for its use in evaluating past decisions and policies, demonstrating broader applicability. Suggestions for improvement included incorporating feedback loops to accommodate iterative decision-making, reordering steps for clarity, and filtering non-feasible options based on risk assessments. Overall, the framework showed significant potential in guiding renovation decisions for LTH readiness, with stakeholder insights offering valuable directions for further development and real-world application.

7.3 General Conclusion

The primary goal of this research was to facilitate the transition of existing dwellings in the Netherlands towards LTH systems, contributing to the objective of eliminating natural gas dependency and decarbonising the built environment. This study focused on preparing existing dwellings for DH systems that supply heat at lower temperatures. Energy renovations are essential to ensure that these dwellings can be comfortably heated before transitioning to LTH-based systems. However, selecting appropriate renovation solutions for using LTH poses several decision-making challenges. To address these, the study was structured around the central research question and divided into four core research activities, each explored in detail across different chapters.

In response to the primary research question—*How can the selection of renovation solutions that prepare diverse dwellings in the Netherlands to utilise lower temperature heat from district heating systems be systematically supported?*—this study proposed a decision-making framework, which provides a systematic approach for assessing LTH readiness and renovation needs. It aids in identifying possible solutions, filtering out non-feasible options, and evaluating multiple criteria to select the most suitable solutions for LTH.

As presented in Chapter 5 and illustrated in Figure 5.2, the framework integrates insights from each chapter, forming a structured approach to addressing decision-making challenges as outlined in Section 1.1.3. Figure 7.1 further demonstrates how each chapter, addressing specific research activities, contributes to the sequential steps of the proposed decision-support framework. These challenges were systematically addressed as follows :

Lack of standardised LTH-readiness criteria

The absence of established standards for assessing LTH readiness makes it difficult to determine whether a dwelling requires renovations. To address this, an LTH readiness definition was proposed based on energy efficiency and thermal comfort criteria. The definition follows the non-compensatory model in the MCDM approach, where trade-offs between the criteria are not allowed. Applying this definition to a case-study dwelling through a two-step assessment approach (Chapter 3) provided deeper insights into a dwelling's readiness. This definition forms a foundational step in the decision-making framework, indicating whether a dwelling is ready for using LTH or needs renovations for the same.

Abundance of renovation options

Another challenge is the wide array of available renovation options at the building level, often leading to decision paralysis in selecting a suitable solution. The current study addresses this by proposing two solutions: (1) a systematic approach to identify and organise potential renovation options and (2) a filtering process to narrow down viable options before the decision-making stage. Chapter 3 details the sub-framework for developing and organising potential solutions by defining the extent of intervention (renovation scenario), specific building areas for improvement (strategies), and required products (measures). This approach is integral to the decision-support framework, as it provides a structured process for generating renovation alternatives, facilitating a comprehensive overview of possible options. Ultimately, it streamlines decision-making, reducing both time and effort.

Following solution identification, the next step in the framework is to filter out unfeasible options based on the dwelling's specific context. This begins with filtering solutions against the LTH readiness criteria, eliminating options that do not adequately prepare the dwelling for LTH. Further filtering based on criteria relevant to renovation objectives narrows the solution space. This systematic identification, organisation, and selective filtering offer significant advantages in overcoming decision-making struggles and selecting appropriate renovation solutions.

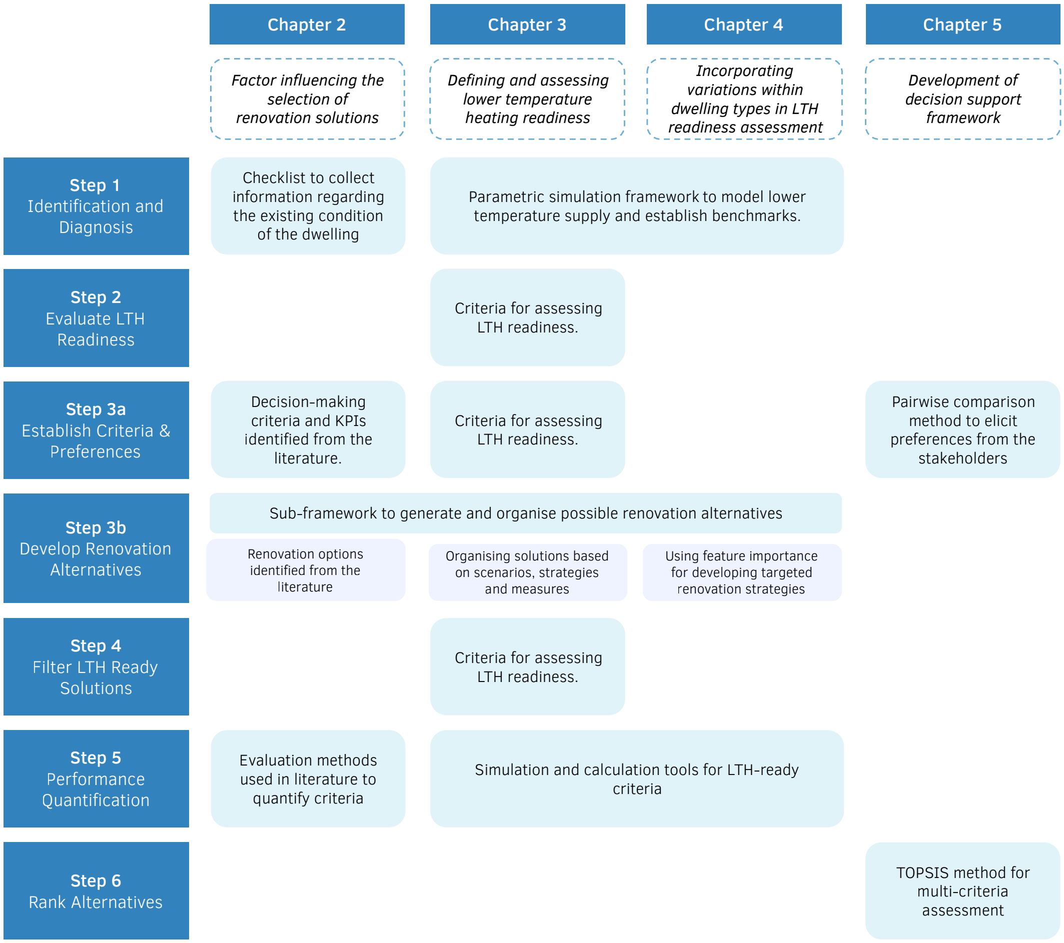

FIG. 7.1 Synthesis of Research Activities into the Decision-Support Framework for Selecting Renovation Solutions for LTH Utilisation.

Heterogenous dwelling stock

The heterogeneity within the housing stock presents additional challenges for renovation decision-making, as the diverse characteristics of dwellings require tailored solutions. In contrast to an archetype-based approach, this study employed a sampling-based approach to analyse a representative sample of 1,300 dwellings, reflecting variations due to building-level features (Chapter 2). This analysis identified the relative importance of these features in predicting LTH readiness for

TOC

dwelling types, particularly for terraced-intermediate and apartment types. These insights support the sub-framework for developing the renovation solution space (Chapter 3) by serving as a tool to evaluate the condition of the dwelling, prioritise renovation strategies, and develop targeted renovation measures. The relative importance of building-level parameters is robust, as they are derived from the actual variation within the housing stock, offering a more nuanced analysis than archetype-based methods.

Lack of decision support insights

The diverse preferences of stakeholders further complicate decision-making in selecting renovation options. Even after filtering and narrowing down the possible and feasible solutions, it is difficult to appraise them comprehensively while balancing priorities, needs and trade-offs to reach a consensus regarding desirable solutions(s). The MCDM approach was applied to address this, using a pairwise comparison to elicit stakeholder preferences on renovation objectives and criteria, and the TOPSIS method for ranking alternatives. These methods were chosen for their ease of implementation and result interpretation. In a validation workshop, participants found these methods to offer quick, analytical insights for decision-making. Additionally, the structured approach of the framework stood out from the typical intuition-based decision-making process.

While the framework was initially developed in the context of LTH supplied through DH systems, it was adaptable to other systems, such as heat pumps (Chapter 5). Further, Chapter 2 concluded that the type of heat generation system does not directly impact LTH readiness. Nevertheless, it is argued that it may influence decisions when selecting renovation options. This aligns with the findings from the validation workshop, where participants considered the heat supply infrastructure an essential external factor in planning renovation projects. Consequently, the framework can be adjusted to account for these factors. For instance, in the diagnosis and identification step (Step 1), the available heat source, infrastructure, and temperature supply level must be determined. In Step 3a, additional criteria related to heating generation systems, such as space required for installation and noise from building services components, can be included. Finally, the performance quantification in Step 5 will account for the additional criteria from Step 3a, as well as criteria such as investment costs, primary energy use, and CO_2 emissions. Therefore, the developed framework is versatile and can be adapted to specific dwellings and local contexts.

7.4 Limitations and Future Recommendations

This research has explored the complexities of preparing Dutch dwellings for transitioning towards LTH systems. While the findings contribute valuable insights, several limitations must be acknowledged, and recommendations for future research are provided to enhance the applicability of the results. The following sections outline the key limitations encountered in this study and suggest directions for future work.

Lower-Temperature Ready Definition:

The definition of LTH readiness in this study was based on non-compensatory criteria, requiring both energy efficiency and thermal comfort to be met simultaneously without any trade-offs. While this approach ensures high standards, it may be rigid in practice. The strict requirement that occupied underheated hours must not exceed those of HT supply could result in the exclusion of otherwise viable renovation solutions that slightly surpass these thresholds but still offer substantial overall benefits. To address this, it is recommended that the criteria for LTH readiness be made more flexible. For instance, allowing a buffer for underheated hours could enable more practical and effective renovation strategies. Additionally, given the rising global temperatures and the associated risk of overheating, it is essential to include overheating analysis within the thermal comfort criteria when evaluating renovation solutions.

Simplified Modelling of Lower Temperature Supply:

The research employed a simplified approach to model lower temperature supplies by calculating and using reduced heating capacities, with the temperature differential between supply and return fixed at 20K. While this approach provided a basis for analysing the effects of lower supply temperatures, it limited the ability to dynamically model return temperatures, which could offer a more detailed understanding of heating capacity and renovation needs. To overcome this limitation, future studies should develop simulation models incorporating more detailed and dynamic modelling of supply and return temperatures. Such enhancements would enable a more accurate analysis of how reduced supply temperatures influence heating capacities and the renovation strategies necessary to achieve LTH readiness.

Analysing the Heterogeneity of the Dwelling Stock:

The analysis of variations within the dwelling stock was limited to terraced-intermediate and apartment dwelling types. While these are prevalent dwelling types in the Netherlands, they do not fully represent the diversity of the housing stock. Additionally, the study primarily focused on the variations due to building-level parameters without accounting for other factors such as local climate, occupancy patterns, or district-level dynamics. This limitation restricts the generalisability of the findings. To address this, future research should expand the analysis to include other dwelling types, such as detached and semi-detached types, thereby capturing the full heterogeneity of the housing stock. Furthermore, incorporating additional variables that influence this heterogeneity would allow for a more comprehensive analysis. Moving beyond individual building assessments to include urban-scale energy models could enable solutions that address district or neighbourhood-level challenges, enhancing the overall effectiveness of LTH readiness assessments.

Effect of Radiator Oversizing:

Radiator oversizing was identified as one of the key factors influencing the dwellings' readiness for LTH. However, the actual extent of oversizing can only be confirmed through on-site inspections, introducing uncertainty into the analysis. This reliance on assumptions about radiator performance limits the accuracy of the readiness assessment. To improve future research, it is recommended that radiator oversizing factors be incorporated into national housing surveys to provide more accurate data. Additionally, future studies should account for the uncertainties associated with radiator oversizing in their analyses, allowing for a more precise evaluation of LTH readiness across the housing stock.

Renovation Solutions for Different LTH Systems:

The research primarily focused on LTH supply from DH systems as a boundary condition. However, it is essential to recognise that LTH can also be supplied through other systems, such as high-efficiency boilers or heat pumps. As noted by the workshop participants, each of these systems brings different considerations to the selection of renovation solutions that extend beyond the readiness of the dwellings for LTH. For instance, the supply temperature from a high-efficiency gas boiler can be lowered to provide LTH with minimal disruption to occupants while also enhancing the boiler's efficiency. However, this approach does not contribute significantly to decarbonisation efforts and fails to reduce primary energy consumption or maintenance and replacement costs, thus challenging the long-term economic feasibility of the strategy.

On the other hand, using a heat pump to supply LTH may require additional space for indoor and outdoor installation, leading to inconvenience for occupants and potentially higher future maintenance and replacement costs. However, this option supports the transition to a natural-gas-free system and can reduce primary energy consumption, depending on the electricity supply's energy mix. Finally, supplying LTH through a DH system depends on the availability of local infrastructure and involves fixed costs that need to be carefully considered.

Future research should utilise the decision-support framework to consider these different heating generation systems and explore whether renovation solutions vary significantly depending on the type of heat supply. This is particularly important for districts or neighbourhoods with varying levels of LTH readiness, as it could guide decision-making to achieve a balanced approach that considers efficiency, cost, and practicality.

Application and Validation of the Decision-Support Framework:

The framework was initially validated within a specific case study and with a limited number of stakeholders. However, the unique characteristics of this case study may not accurately reflect broader contexts, and the small pool of stakeholders may not provide the full range of perspectives needed for a thorough evaluation of the framework's effectiveness. These limitations could hinder the generalisability of the results. To overcome these challenges and enhance the framework's broader applicability, it should be tested in various contexts and case studies. Doing so would help identify any necessary adjustments to ensure its effective implementation across different scenarios and regions. Additionally, future research should involve a more diverse group of stakeholders to capture a wider array of perspectives, thereby improving the comprehensiveness and robustness of the decision-making framework.

Using Machine Learning to Enhance Framework Use:

The proposed decision-support framework currently relies on building simulation models, which can be time-consuming and resource-intensive, especially for stakeholders managing large portfolios of dwellings. Future research should explore integrating machine learning models trained on available or synthetically generated data to address this challenge. These models could predict the performance of dwellings more quickly and efficiently, enabling faster assessments of LTH readiness across large portfolios. By incorporating machine learning into the decision-support framework, stakeholders could gain rapid insights and make more informed decisions about renovation strategies, ultimately streamlining the transition to lower-temperature heating.

7.5 Final Remarks

This research has presented a systematic approach for preparing existing Dutch dwellings for LTH systems, contributing to the broader goal of decarbonising the built environment by transitioning to sustainable heating sources. While the study focuses on the Netherlands, its implications extend beyond this context. For instance, the proposed definition of LTH readiness can be adapted with region-specific benchmarks and integrated into policies to ensure a minimum level of comfort during the transition to sustainable heating systems. Further, the probabilistic sampling-based methods demonstrated in this study can be scaled to diverse global contexts with varying dwelling characteristics, effectively accounting for the heterogeneity of building stock. This provides a robust foundation for developing targeted solutions instead of relying solely on archetype-based analyses.

From a policy and governance perspective in the Netherlands, local municipalities develop heat transition visions for their districts or neighbourhoods. However, individual building owners retain the autonomy to choose their gas-free alternatives, which can lead to discrepancies between municipal plans and actual implementation[5]. For example, some owners may opt for heat pumps over the municipality's preferred plan of connecting to the lower-temperature DH systems. In this context, the proposed decision-support framework offers practical value. Municipalities can use it to provide transparent, relevant and context-sensitive insights to the building owners, fostering alignment with municipal plans and encouraging a collective approach to the energy transition.

Looking forward, the framework and the methods used in the study offer opportunities for developing an application-based decision-support tool. When combined with urban building energy modelling (UBEM), such a tool could provide municipalities and portfolio managers with detailed insights into the LTH readiness of their assets. This could enable targeted renovation planning and policy alignment. Additionally, municipalities could use pairwise comparison features to gather feedback and preferences from individual building owners, creating a consensus-

5 Devenish, A., & Lockwood, M. (2024). Locally-led governance of residential heat transitions: Emerging experience of and lessons from the Dutch approach. Energy Policy, 187. https://doi.org/10.1016/j.enpol.2024.114027

driven approach to decision-making. Heating companies could leverage the tool to strengthen their business cases for network expansion by providing data-driven insights into investment opportunities. Moreover, individual homeowners could use the application as a renovation configurator, accessing tailored insights that integrate stakeholder preferences, policy recommendations, and financial incentives to support sustainable transitions.

Finally, reflecting on the challenges of the energy transition, it is evident that the key issue lies not in the availability of technological solutions but in identifying the solutions that fit within specific contexts. This research addresses this gap to a large extent. However, occupants play a critical role in the energy transition. Their perceptions and responses to LTH systems compared to traditional heating[6] can significantly influence the adoption of these technologies. From an interdisciplinary perspective, exploring intersections of behavioural science, interaction design, and psychology could offer valuable insights into how people perceive energy transitions, adapt to changes in heating systems, and manage their comfort. Understanding occupant behaviour in decision-making processes can enrich efforts to select solutions that are not only technically sound but also socially acceptable and widely adopted.

6 van Beek, E., Boess, S., Bozzon, A., & Giaccardi, E. (2024). Practice reconfigurations around heat pumps in and beyond Dutch households. Environmental Innovation and Societal Transitions, 53. https://doi.org/10.1016/j.eist.2024.100903

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List of publications

Journal Papers

Wahi, P., Koster, V., Tenpierik, M. J., Visscher, H & Konstantinou, T. (2024). Preparing for Lower-Temperature Heating: A Multi-Criteria Decision-Making Framework for Energy Renovations of Existing Dutch Dwellings. Under review Energy Reports

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25#10

Preparing Dutch Homes for Energy Transition

A Decision Support Framework for Renovating Existing Dutch Dwellings for Lower Temperature District Heating

Prateek Wahi

Recent geopolitical events have driven a sharp rise in gas prices, making it increasingly difficult for households to heat their homes affordably and comfortably. Additionally, the environmental consequences of fossil fuel-based heating underscore the urgency of transitioning to more sustainable alternatives. In response, the Dutch government has set an ambitious target to eliminate natural gas heating in 1.5 million homes by 2030, emphasising the need for viable solutions. District heating (DH) systems, particularly those providing lower-temperature heating (LTH), offer a promising alternative—delivering sustainable and cost-effective heating, especially in densely populated areas. However, with their high heating demands, many existing homes require significant renovations before efficiently transitioning to LTH-based systems. The selection of appropriate renovation strategies is complex, often leading to uncertainty and delays.
This research tackles the challenge of preparing Dutch homes for LTH by developing a systematic decision-support framework using a mixed-methods research approach. It is structured around four key research activities. First, it identifies and analyses the critical factors influencing building characteristics, available renovation options and performance indicators. Second, it defines LTH readiness, prioritises thermal comfort and energy efficiency at reduced supply temperatures, and uses a two-step evaluation method to assess a dwelling's readiness and identify necessary interventions. Third, recognising the diversity within the Dutch housing stock, probabilistic sampling and machine learning analyses were employed to quantify the relative significance of building features affecting LTH readiness, accounting for variations across dwelling types. Finally, a structured six-step decision support framework based on multi-criteria decision-making (MCDM) methods was developed and validated through real-world case studies and stakeholder workshops. By providing a clear and actionable decision-support framework, this thesis facilitates energy renovation planning, accelerates the transition to gas-free heating, and contributes to the Netherlands' broader sustainable energy goals.

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