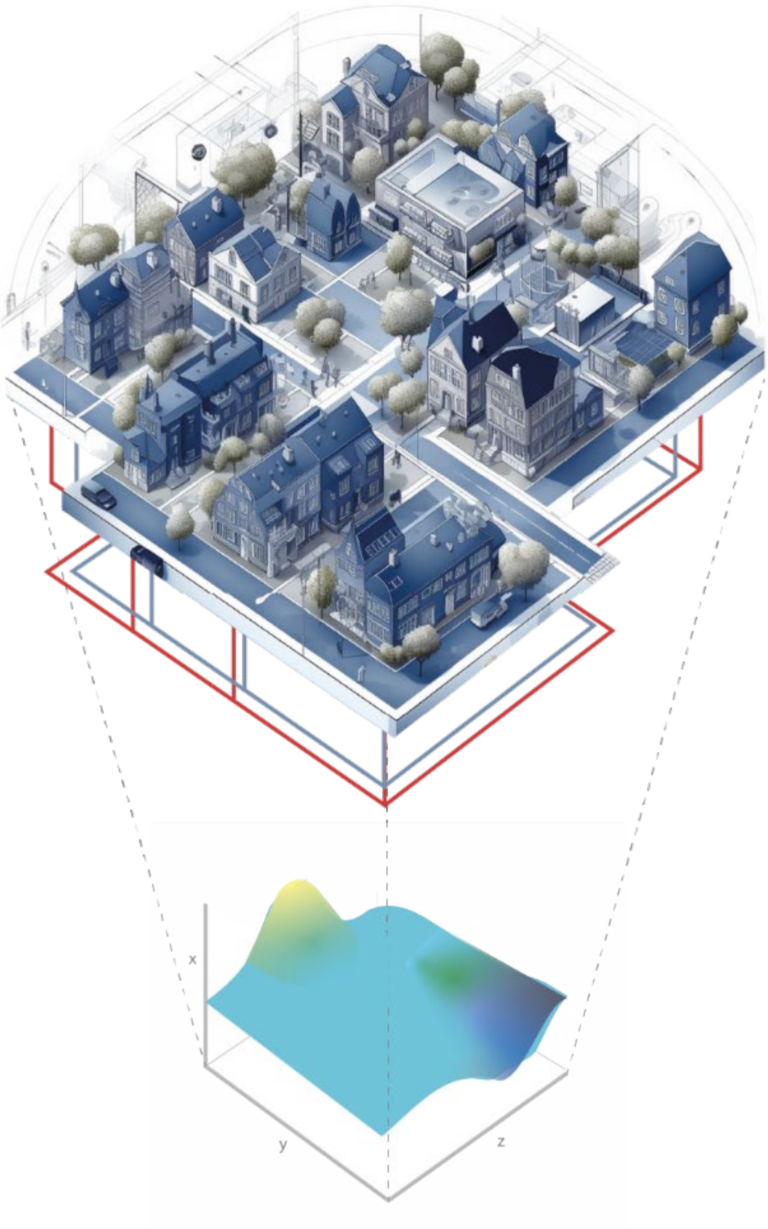

LT-Set: A Surrogate Model-Based Decision Tool for Low-Temperature District Heating Refurbishment

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"Searching and learning is where the miracle process all begins."

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Abstract

The Netherlands aims to reduce greenhouse gas emissions by 49% before 2030, with the built environment contributing 15% of these emissions largely due to the heavy reliance on natural gas to meet space heating demands. To phase out natural gas, alternatives such as heat pumps and district heat networks are being considered. However, adapting existing buildings to lower supply temperature district heating requires effective refurbishment to maintain thermal comfort for occupants. The challenges hindering this process include i) addressing multiple housing typologies at the neighbourhood scale, ii) complexity of evaluating refurbishment measures by decision-makers, iii) uncertainty due to lack of consideration of life cycle costs and occupancy behaviour pre and post-refurbishment leading to performance gaps in energy savings and iv) current computationally demanding and inaccessible tools to assess refurbishment measures. Therefore, this thesis proposes a method to develop a surrogate model-based decision-making tool that can help homeowners efficiently assess optimal, combined refurbishment measures to help homeowners transition to low-temperature district heating. In order to develop this tool, the study examines literature studies that help define the input parameters for the underlying parametric simulation including. This also helped define the key performance indicators including energy savings, hours too cold and global cost. Furthermore, the underlying simulation model with 13 input parameters provides the synthetic training data with 2000 design samples using the uniform Latin hypercube sampling method for each of the three housing archetypes including i) terraced, ii) detached and iii) Portiek apartments. The best-performing model in this instance included artificial neural networks with an R-squared above 0.95. The surrogate model is then integrated into the optimization workflow that forms the framework for an interface decision-making tool that users can use to generate optimal low-temperature ready refurbishment packages. The common low-temperature ready refurbishment packages include maximum airtightness, type C2 CO2 control ventilation system, cavity wall insulation, triple glazing, and internal roof insulation. Furthermore, it can be concluded that its more financially feasible to maintain existing radiators when transitioning to low-temperature heating instead of replacing the radiators with higher capacity. This is because the initial investment in other refurbishment measures not only improves comfort but also delivers significant energy savings that help reduce global costs in the long term.

Keywords: surrogate model, low temperature, district heating, parametric simulation, optimization, Dutch housing typologies, global cost, occupancy behaviour, envelope refurbishment, thermal comfort, radiator capacity, Energy savings

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1. Research Framework

1.1 Background

The Netherlands is one of the 196 participating countries in the 2015 Paris Agreement which commits to limit global warming below 2 °C *(Ministerie van Economische Zaken en Klimaat, 2019)*. Under this agreement, the Dutch government aims to reduce greenhouse gases by 49% before 2030 *(Beckman & Beukel, 2019)*. The built environment contributes to 15% of the national greenhouse gas emissions *(Centraal Bureau voor de Statistiek, 2022b)*. The dependency on natural gas for 90% heating demand for buildings in the Netherlands plays a large role in the national greenhouse gas emissions *(Beckman & Beukel, 2019)*. Therefore the government aims to have 1.5 million homes be phased out of natural gas *(Koster et al., 2022)* and a sustainable renovation target rate of 200,000 homes per year by 2030 *(Ministerie van Economische Zaken en Klimaat, 2019)*.

In order to phase of natural gas and still meet the heating demand there are various kinds of alternatives including all-electric and hybrid heat pumps, biogas also known as 'green gas' and central district heat networks. *(Beckman & Beukel, 2019)*. Furthermore, the current demand for district heating is expected to grow from 6.4% *(Centraal Bureau voor de Statistiek, 2022a)* to 38% by 2030 if the conversion of existing dwellings is achieved in addition to the new dwellings *(Niessink & Rösler, 2015).* Therefore there is a large potential for **low temperature heat networks** to support this growing demand and phase of natural gas with supply temperatures ranging from 50-60 C *(Pomianowski et al., 2020)*. The system i) reduces heat losses in grid pipelines and thus improves efficiency, ii) insures price stability with the integration of renewable or surplus heat energy sources *(Schmidt et al., 2017)* and iii) improves thermal comfort due to reduced temperature gradients *(Eijdems et al., 1999)*.

However, the majority of the existing buildings are designed with space heating in accordance with the current supply temperatures of around 90 C *(Expertise Centrum Warmte, 2020a)*. Therefore, in order to maintain thermal comfort with the lower supply temperature and hence lowered heating capacity, the existing dwellings need to be refurbished *(Brand & Svendsen, 2013)*.

1.2 Problem Statement

To attain the required refurbishment rate to achieve the benefits of low-temperature heat districts, certain challenges need to be addressed :

- The transition to low-temperature district heating needs to be addressed at a neighbourhood scale wherein multiple housing typologies need to be refurbished simultaneously with varying characteristics and limitations.

There are multiple transition paths for HT networks to LT district heating. One suggested transition path could be through introducing LT heating in a separate part of the heat network which would require large-scale area refurbishment with a planned, phased approach *(ECOFYS, 2016)*. Furthermore, the heat networks require to be implemented in clusters or neighbourhood scales to operate profitably *(Expertise Centrum Warmte, 2020b)* and potentially allow contractors to benefit from economies of scale for both the installation of the heating networks and the refurbishment *(Dijkstra, 2018)*. Within each cluster or neighbourhood, there could be multiple housing typologies such as detached, semi-detached, rowhouse, gallery house etc with each construction type built within varying construction periods *(Agentschap NL, 2011; Cornelisse et al., 2021).* The varying housing typologies pose a barrier for the scaled refurbishment of dwellings to implement LT networks effectively.

Previous studies by Smit (2022), addressed this problem by classifying the sensitivity parameters related to building type and construction that impact the LT-ready refurbishment strategy. However, the strategies were not sufficient to meet the requirements for all other typologies excluding the case study and the study assumes unrenovated dwellings as the base case even though it's probable that certain refurbishment interventions have been made especially for older dwellings *(Smit, 2022)*. Additionally, the study by Rutten *(2021)*, Wahi et al. *(2022)*, and Brand and Svendsen *(2013)* consider the refurbishment of one specific dwelling type and advise further investigation into the application of suggested refurbishment strategies on multiple building types. Furthermore, general refurbishment tools like the improvement plan tool by Milieu Centraal have been developed which considers the variation of building typologies and characteristics like wall insulation level, glazing specification etc, however, the tool is a normative tool based on NTA 8800 standard and is largely prescriptive and explorative with many possible interventions for overall energy improvement *(Milieu Centraal)*. The normative calculation methods are static and do not consider thermal zones and occupancy behaviour which can lead to discrepancies in results *(Seddiki et al., 2021)*.

- Currently, owner-occupied dwellings represent the majority of the housing sector and the refurbishment process for the multiple housing typologies is driven by their initiative. Their decision process is hindered by the multiplicity of refurbishment strategies that address multiple building components and the complexity of evaluating these strategies using interdependent criteria.

Refurbishments typically address multiple building components forming many possible strategies which can be challenging for homeowners. Effective refurbishment measures for low-temperature heating include upgrading to a balanced ventilation system with heat recovery replacing windows as they reach the end of their 30-year lifetime or partial external insulation on the façade *(Brand & Svendsen, 2013; Kounaki, 2019; Rutten, 2021)*.

Furthermore, the combination of refurbishment solutions needs to be evaluated by multiple indicators relevant to the homeowner. These include trade-offs between the capital investment and the benefits which could include operational energy reduction, improved comfort, and reduction in CO2 footprint and thus covers economic, environmental and social aspects *(Jafari & Valentin, 2017; Ma et al., 2012)*.

Additionally, these refurbishment measures are undertaken primarily based on the initiative of the homeowners and therefore the complexity and multiplicity pose a significant barrier to the implementation of low-temperature heating *(Wahi et al., 2022)*. Moreover, it is the owner-occupied home sector that accounts for 60% of the building stock and therefore the decision-making process to be designed for this large target user in order to have the most impact *(Ministry of the Interior and Kingdom Relations, 2014)*.

- However, homeowners are faced with uncertainty throughout the refurbishment process with non-comprehensive evaluations of financial feasibility and performance gaps between estimated and actual energy savings.

Barriers to low-temperature refurbishment from a homeowner's perspective are similar to those faced by general refurbishment interventions broadly which would then prevent the effective implementation of low-temperature heat districts for the existing building stock. The barriers are usually associated with capital cost, unbalanced financial plan, unclear processes, uncertainties, and comfort to name a few *(Ebrahimigharehbaghi et al., 2020; Ma et al., 2022)*. Additionally, when homeowners consider refurbishment strategies there is rarely a consideration of cost over the lifetime of the refurbishment measure which contributes to the uncertainty in the decision-making process. For example, a European Commission study considered the life cycle cost to be a better indicator compared to solely initial investment cost as it considers costs over the lifetime of a product including maintenance and operations costs that can be up to 5 times the initial capital cost *(Davis Langdon, 2007)*. Furthermore, homeowners need to be assured that the refurbishment measures undertaken will not require any further improvement in the near future due to inadequacy to match changing performance standards and thus reflects a regret-free procedure.

Moreover, the cost-benefit analysis process is further by the performance gap between the actual energy consumption and savings compared to simulated and estimated results from the proposed refurbishment strategies *(Guerra-Santin et al., 2018)*. These differences increase the uncertainty and risk associated with refurbishment strategies and hence reduce the willingness to invest in refurbishment measures. Studies show that one of the contributing factors to this performance gap and hence uncertainty is the lack of data on the occupancy behaviour of users pre and post-refurbishment procedures *(Guerra-Santin et al., 2018; Majcen, 2016)* as it can result in a variation of final energy use by a factor of two in certain cases *(Steemers & Yun, 2010)*.

- Current tools used to determine the refurbishment strategies and evaluate them based on multiple objectives are computationally expensive and inaccessible to homeowners.

Refurbishments involve multiple components and have mostly been evaluated through the use of the priori approach where a set of refurbishment measures have been pre-defined *(Gero et al., 1983; Jaggs & Palmer, 2000)*. Weights are assigned to each criterion to then form a single weighted sum that is optimised. However, there is no guarantee that the solution reached is the best one and there is no additional information on the sensitivity and interdependency of the criteria. On the other hand, multi-objective optimization is a second, approach to exploring refurbishment options which are implicitly defined by constraints in a design space and allow the further examination of trade-offs between parameters. However, current processes use genetic algorithms that work with underlying building simulations like Energy Plus which result in computationally expensive and time-consuming processing when exploring the design space to reach optimum solutions. Therefore, models are either simplified or a small genetic algorithm population is explored which either reduces accuracy or leads to a non-optimal set of results *(Asadi et al., 2014)*. An LT-ready tool has been developed by Rutten which allows engineers to explore multiple refurbishment options. However, the tool was normative and required validation using dynamic simulation. Moreover, the study by Smit (2022) and Rutten (2021) highlights the computationally expensive process of manually changing individual design parameters on an input-heavy simulation tool like a Design Builder to the refurbishment design space *(Rutten, 2021; Smit, 2022)*. Work by Kounaki utilises a genetic algorithm workflow to evaluate multiple options for façade refurbishments to make a dwelling LT-ready. However, the time limitations in running computationally heavy simulations limited the number of variations explored within the design space *(Kounaki, 2019)*. Therefore current developments in machine learning have led to the use of Response surface approximate models also known as surrogate models that use statistical models that imitate the performance of building simulation whilst maintaining an acceptable level of accuracy and significantly reducing computational time *(Asadi et al., 2014)*. The use of surrogate models in the building design process has been extensively documented by Westermann and Evins which addresses the use of the surrogate model in different stages of building design i)conceptual design stage, ii) Sensitivity analysis, ii) Uncertainty analysis, iv) Optimization process highlighting the ability of surrogate models to accelerate design and assessment of process from multiple perspectives *(Westermann & Evins, 2019)*. Other studies by Balaban (2022) and Asadi (2014) work on developing surrogate models for general refurbishments that consider single zone, simplified models and general energy refurbishment strategies using a limited set of refurbishment interventions *(Asadi et al., 2014; Balaban, 2021)*.

1.3 Objectives

The problem statements above have defined the following research objectives:

1. To develop a decision-making tool that provides homeowners or organisations of homeowners with a **selected set of refurbishment measures** to make their dwellings LT-ready and to initiate the refurbishment process.
2. The tool will need to adapt to variations of **multiple housing typologies** of the homeowners and effectively evaluate the refurbishment strategies with the **relevant KPIs**.
3. The tool must be made **accessible** for homeowners with **minimal computational expense whilst maintaining accuracy**.

1.4 Research Questions

According to the above-mentioned problem statement, the following research question will be answered:

How to develop a **surrogate model**-based decision-making tool to select **combined, no-regret refurbishment measures** using **performance indicators** for **multiple Dutch housing** typologies considering **occupancy behaviour** and **lifecycle cost** to transition to **low-temperature district heating?**

In order to address the research, question the following sub-questions have been devised according to specific phases addressed in the following methodology section:

Phase 1 – Literature study and state of the art

1. What defines the input and output parameters that address the transition to low-temperature district heating?

   - What are the **Dutch housing typologies** and their respective sensitive parameters?
   - What are the Dutch **household behaviour profiles** and their respective sensitive parameters?
   - What are the existing **refurbishment strategies** used to make dwellings low-temperature ready?
   - Which **performance indicators** can be used to evaluate refurbishment measures to define a no-regret refurbishment strategy?
   - What are the methods used to evaluate the **life cycle cost** (LCC) of the refurbishment measures?

2. What are the current methods used to train and evaluate **surrogate models**?

Phase 2 – Using inputs from previous phases to develop a simulation model to collect data to train a surrogate model.

3. How can the simulation model be developed parametrically to generate a representative sample of data to train the surrogate model?
4. What method can be used to generate optimised refurbishment measures considering life cycle cost?

Phase 3 – Validate the use of the surrogate model decision-making tool.

5. How can the decision-making tool prescribes categorised LT – ready refurbishment strategies to facilitate the decision-making process in an accessible manner?

Phase **1** Phase **3** Phase **3**

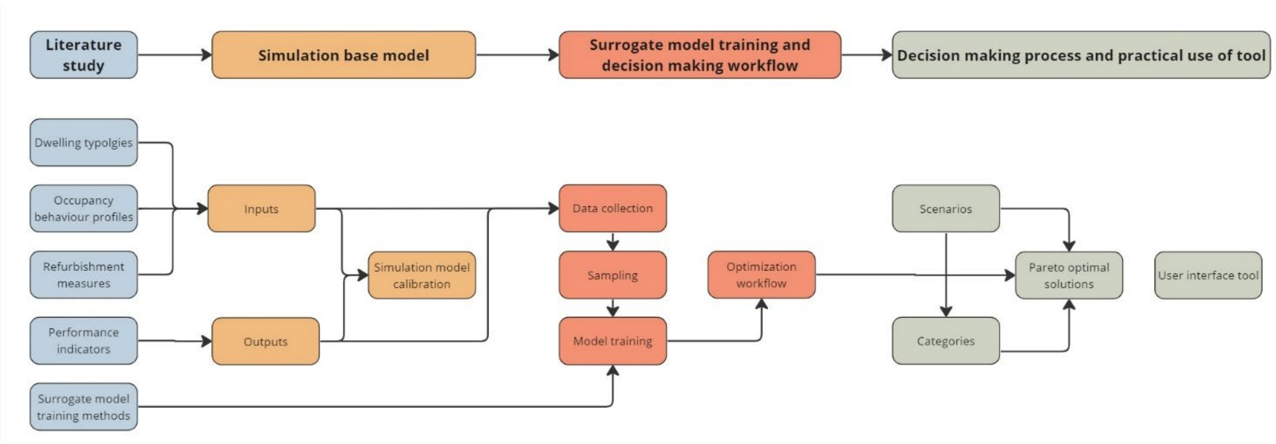


Figure 1 - Research framework

1.5 Research Methodology

Phase 1: Literature study and state of the art

The first stage of the research examines current literature that examines topics like the characteristics of current housing typologies of the Dutch housing stock, low-temperature refurbishment strategies at varying building scales to help achieve the required comfort standards and existing performance indicators required to evaluate the refurbishment strategies. The study of the performance indicators would then help define the selection criteria for the refurbishment measures and eventually lead to a definition for low-temperature ready refurbishment strategies. Moreover, the literature further examines parameters like occupancy behaviour and its sub-parameters to improve the overall decision-making process accuracy and relevance. Finally, the literature study concludes with the study of current computational workflows used to develop surrogate models within the built environment and the methods used to validate the model effectively. Furthermore, each topic within the literature study concludes with a sub-conclusion regarding the findings, definitions or relevant parameters to be used further in the next stages of the study. The sources to find the literature studies include Science Direct, Google Scholar, Scopus and the TU Delft repository.

Phase 2: Simulation setup, training data collection and surrogate model training

During this stage, the grasshopper (honeybee) model will be set up with various input and output parameters. Firstly, a selection of representative house per dwelling type would need to be selected in order to develop the base geometry to run the building simulation. This will further involve the examination of sampling methods to create a representative database, initial validation by running simulation checks and methods to integrate the various platforms and tools. Moreover, the study will need to further examine This stage will conclude with a complete set of simulation data post-processed in order to be used for the next stage of training the surrogate model.

The simulation data comprising of input and output parameters are then processed in modeFRONTIER in which the surrogate model will be developed. This process will involve a stage of familiarizing with the tool to be able to select the optimum algorithm to train and validate the model. Once this response surface is trained and validated, it will then be integrated into an optimization process where different refurbishment strategies will be evaluated in order to arrive at a selected few strategies based on the respective criteria. In order to further filter the strategies and arrive at feasible solutions, a post-processing step of cost evaluation will be conducted. This stage will then end with a set of categorised refurbishment strategies based on various parameters.

Phase 4 – Tool interface and conclusion

The final stage concludes by composing specific scenarios to evaluate the proposed model and workflow in order to gain a deeper understanding of the interpretability and the feasibility of the Pareto optimal solutions and their effectiveness in facilitating the decision-making process Additionally, an interface tool is developed to help users interact with the model and therefore create an accessible decision-making tool. The study will then conclude with a discussion and conclusion on the evaluation of the process of developing the tool, the limitations and then further improvement to develop the tool.

1.6 Final products

The study aims to develop a decision-making tool that allows users to evaluate low-temperature refurbishment strategies according to relevant criteria. Through this process of developing the tool, the study will provide insights into methods to develop representative models for the various housing typologies of Dutch housing stock and therefore provide a method of making neighbourhoods ready for low-temperature heating. Furthermore, the study will demonstrate methods to integrate occupancy behaviour and the lifecycle cost evaluation process within a decision-making framework to provide a basis for further research and development. Finally, the computational workflow used within this study could also indirectly provide a template for the use of surrogate models within other areas of interest in the built environment. Moreover, the user interface will demonstrate an implementation of a computational tool considering the accessibility of the end users in mind.

1.7 Boundary conditions

The current high temperature (HT) supply and return temperature will be specified at 90C/70C as defined by current standards *(Expertise Centrum Warmte, 2020a; Rutten, 2021; Wahi et al., 2022)*. Furthermore, the low temperature (LT) supply and return temperature will be specified at 55/45 C as determined by the TKI Urban Energy Institute, an organisation that stimulates innovations of sustainable energy systems in the built environment in the Netherlands *(TKI Urban Energy, 2020)*.

Refurbishment in the context of this study is defined as the replacement of defective building components and outdated components that no longer meet the acoustic, energy or fire protection performance requirements *(Konstantinou, 2014).*

The refurbishment measures are limited to building envelope and installation scale, and it excludes measures at the specific scale of the room and local comfort variables. This is because the room-scale measures have more of an impact on local thermal comfort standards rather than the global thermal comfort of the dwelling as a whole *(Rutten, 2021)*.- Moreover, other comfort requirements like acoustic, air quality, visual etc are not considered in this study.

The refurbishment measures explored in this study are limited to the dwelling and assume that the dwelling can be connected to district heating. It does not take into account adjustments and measures that need to be made to the heating district.

Phase 1 : Literature study and state of the art

1) What defines the input and output parameters that address the transition to low-temperature district heating?

2) What are the current methods used to train and evaluate **surrogate models**?

2. Literature Exploration

The section includes an extensive literature review to answer the above-mentioned questions. The sources to find the literature studies include Science Direct, Google scholar, Scopus and the TU Delft repository.

2.1 Housing typologies and sensitivity parameters

2.1.1 Housing typologies

The majority of the Dutch housing stock comprises the following: **i) Terraced housing ii) Semi-detached ii) Detached iv) Porch apartments v) gallery apartments** *(Agentschap NL, 2011; Cornelisse et al., 2021).* The different dwelling types vary primarily by their compactness ratio which has a significant effect on the net energy consumption of the dwelling for example terraced houses are considerably more compact on average than detached houses *(Cornelisse et al., 2021)*. Each of the housing typologies includes dwellings built across a range of construction periods. The construction period determines the energy performance of the various building components for each housing typology. This is due to the introduction of various building regulations and practices at that time *(Dijkstra, 2018)*.

Year < 1945

Before the 1900s the Dutch building stock did not have any regulations until the Woningwet was implemented in 1901 *(Rutten, 2021)*. This law introduced the concept of healthy buildings which was not evident during this period. Additionally, as the war ended during this period, large-scale construction took place which minimised the quality of dwellings built. The cavity wall was introduced during this period in the 1930s and within this period cavity walls were infrequently used, and if used were below 40mm and thus unsuitable for post insulation. The construction was characterised by wooden floors, single-glazed windows in wooden or steel frames, natural ventilation and the use of local cost or gas generators *(Cornelisse et al., 2021)*.

The year 1945- 1975

This period was marked by the post-war construction boom, with the introduction of new, standardised construction methods like the use of prefabricated concrete and low-quality façade constructions *(Rutten, 2021)*. In 1965 the first set of energy efficiency regulations was introduced but was insignificant to current standards. Uninsulated cavities and non-insulated concrete floors became more prominent and double glazing was introduced in the 1940s *(Smit, 2022)*. The ventilation and heating system remained unchanged.

The year 1975- 1995

The oil crisis in 1973 resulted in the improvement of energy standards by 1975 *(Smit, 2022)*. The minimal requirements for the façade and roof were set at 1.3 m^2K/W. By 1979 double glazing became the standard whilst walls and floors were still often constructed in prefab concrete *(Cornelisse et al., 2021)*. Furthermore, mechanical ventilation has started to be introduced in nearly half of the single-family houses. The requirements were further improved by the introduction of the Bouwbesluit in 1992 *(Smit, 2022)*.

Year >1995

The Bouwbesluit further improved requirements with closed parts of the façade requiring insulation values of at least 2.5 m^2K/W and double glazing. Ventilation systems applied natural ventilation grills as supply combined with mechanical extraction. The introduction of balanced ventilation with heat recovery during a later period *(Cornelisse et al., 2021)*. The Single-family housing typologies because they account for 68% of the housing stock and terrace housing represents the majority of this accounting for 41% of the dwellings *(Centraal Bureau voor de Statistiek, 2016)*. Moreover, it can be concluded that single-family housing in its current state has higher energy consumption values in its current state compared to apartments as can be seen for example in *Figure 2* therefore refurbishment strategies addressing single-family homes will have a significant impact on district emissions and would require extensive measures *(Cornelisse et al., 2021)*.

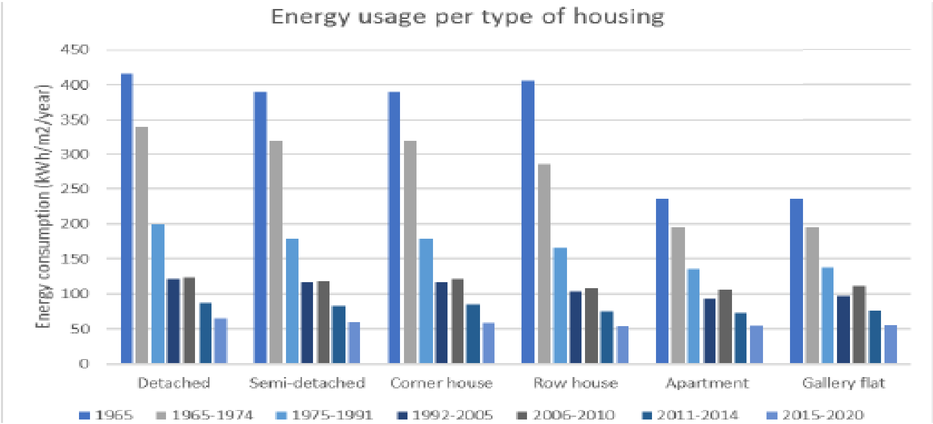


Figure 2- Example dwelling characteristics analysis for Terraced housing (Agentschap NL, 2011; Cornelisse et al., 2021)

The summary of the exploration of the housing typologies pertaining to this study can be found in *Appendix 1. Table 1* gives an example of the data collected for terraced housing. The data used in this study considers properties of the current state of the dwelling (level 0) from the Nieman report *(Cornelisse et al., 2021)* instead of the Agentschap report 2011 *(Agentschap NL, 2011)* The Nieman report is based on a database of 4,506 dwellings based on the recent WoON survey and supplemented by the Agentschap 2011 study. However, it's been acknowledged that an initial comparison between the two databases specifically looking at the current dwelling situation suggests that the performance values are comparably higher than that of the Agentschap 2011 study *(Agentschap NL, 2011; Cornelisse et al., 2021)*. This is because the study estimates the current energy quality to be in line with the average thermal quality from the WoOn 2018 database. The report concludes that the <1945 category would require extensive measures in order to achieve significant energy reduction and that the most significant reduction with a common improvement measure (level 2/3) is in the 1945 – 1975 construction period. This is because in this specific category, there is no difference in the current and original level of construction and thus the dwelling in this category has undergone the least improvement in insulation quality *(Cornelisse et al., 2021)*.

Table 1- Example dwelling characteristics analysis for Terraced housing (Agentschap NL, 2011; Cornelisse et al., 2021)

Parameters	**Terraced housing**			
Construction year	<1945	1945 - 1975	1975 - 1995	> 1995
Average WWR	33.7%			
Average floor area m2	114.0			
Average compactness ratio	1.5			
Ground floor Rc	0.77	0.57	1.16	2.68
Closed façade Rc	0.70	0.84	1.53	2.68
Flat/pitched roof Rc	1.24	1.22	1.50	2.75
Glazing Rc	0.34	0.37	0.35	0.48
Airtightness level 1 (original) dm3/s/m2	3.0	3.0	3.0	1.5
Ventilation system	System A	System A	System C1	System C1
Heating power output level 1 Watts	18,887	12,074	14,241	10,287
Energy Label	G	E-F	D	C

2.1.2 Sensitivity parameters

Sensitivity parameters are defined as the building characteristic that determines or influences the heating demand or thermal comfort and thus the final refurbishment strategy.

Studies have examined the use of certain predictors on energy consumption of dwellings including compactness which is determined by the dwelling type and construction year *(Aksoezen et al., 2015; Kontokosta & Tull, 2017; Mastrucci et al., 2014)*. The dwelling type in combination with the construction year influences the compactness and building envelope properties which influences the heat gains and losses and therefore overall energy use. The parameters can be further subdivided by further specifying the building envelop U values, HVAC system *(Cornelisse et al., 2021; Fonseca & Schlueter, 2015; Smit, 2022)* and airtightness *(Cornelisse et al., 2021; Smit, 2022)*. Additional parameters used include the number of floors, characteristics of being an attached or detached lot *(Kontokosta & Tull, 2017)* and floor area *(Kontokosta & Tull, 2017; Mastrucci et al., 2014)*.

Additionally based on previous literature on LT-ready refurbishment, this study adds the heat output power radiators required for required per dwelling type which will become relevant further when deciding on the refurbishment packages in order to determine the base heat capacity of the dwellings. The study by Nienke attempted to suggest low-temperature ready refurbishment strategies for multiple housing typologies however the strategies were deemed insufficient to meet the standards due to the use of the same heat capacity for all the housing typologies *(Smit, 2022)* and therefore the space heating capacity needs be evaluated.

2.1.3 Sub conclusion

Based on the studies above the building type and construction period can be developed into the following building sensitivity parameters that impact the end energy consumption:

Table 2 (left)– Housing typology sensitivity parameters (Agentschap NL, 2011; Aksoezen et al., 2015; Cornelisse et al., 2021; Fonseca & Schlueter, 2015; Kontokosta & Tull, 2017; Mastrucci et al., 2014)

`	Sensitivity Parameters
Type of housing	Window wall ratio
	Compactness ratio
Construction year (thermal insulation performance)	Insulation closed parts
	Window glazing type
	Airtightness
	Ventilation system
Influenced by both characteristics	Space heating capacity
	Usable area

Housing typologies	Terraced housing	Semi-Detached	Detached	Apartment
Average WWR	33.7%	21.6%	18.7%	43.4%
Average floor area	114.0	124.2	166.4	79.9
Average compactness ratio	1.5	1.9	2.3	1.1

Table 3 - Housing type characteristics (Agentschap NL, 2011; Cornelisse et al., 2021)

Furthermore, the study evaluates the data on the dwelling types and their parameters from the Nieman report (2021) and the Agentschap NL report(2011). The results correspond with previous literature studies mentioned above wherein the construction period correlates with the performance of the dwelling and the housing type correlates with the compactness ratio. Moreover, in relation to the performance of the dwelling, the airtightness (infiltration rate) remained consistent throughout the years except over the last construction period > 1995 with a significant improvement. It must be noted that for airtightness, the parameters were defined based on level 1(original time of construction) due to the lack of data available at the current construction stage (Cornelisse et al., 2021). The rest of the data was derived from level 0 (current performance level). Furthermore, the glazing performance does not improve proportionally to that of the other building components over the years and therefore poses significant energy-saving potential if refurbished *(see Figure 3).*In terms of the type of housing, the compactness ratio varies as expected with apartments being the most compact and detached housing being the least. However, the window-to-wall ratio also varied across the housing typologies ranging from 18% - 44% and it increases as the compactness ratio decreases (*Refer to Table 3*). Moreover, heat output increases as the compactness ratio increases.

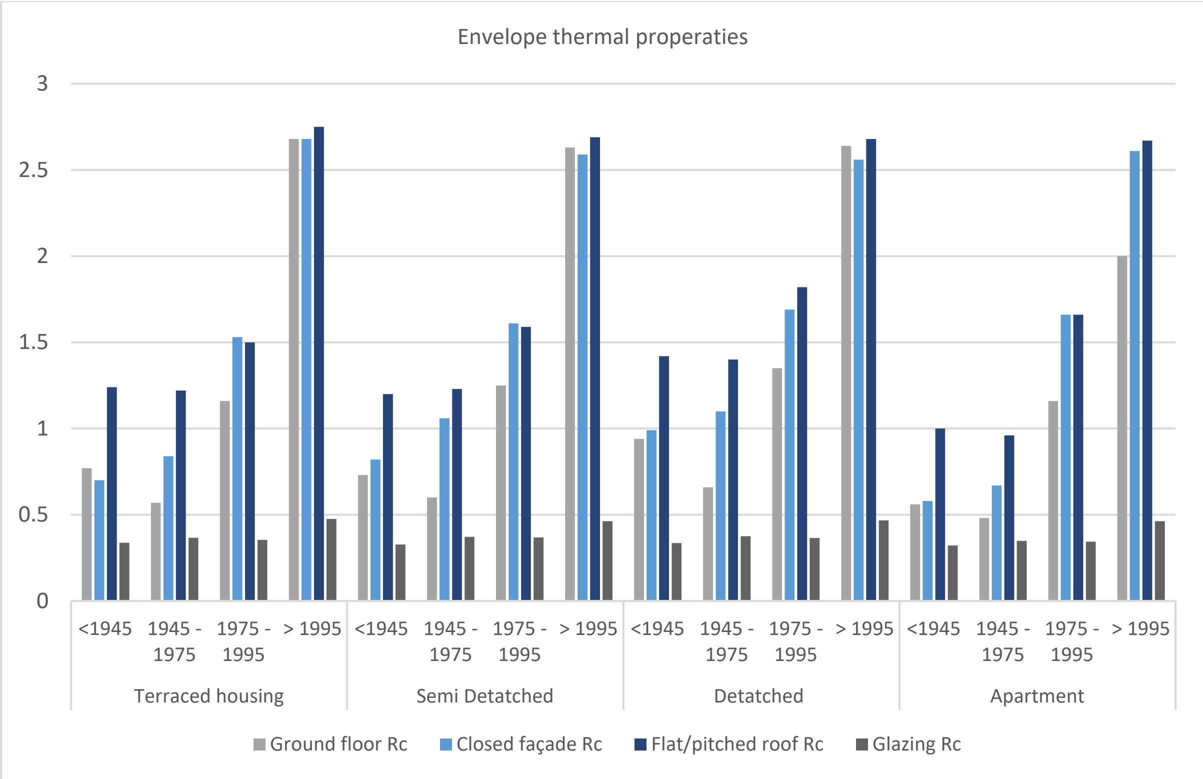


Figure 3- Envelope thermal properties (Agentschap NL, 2011; Cornelisse et al., 2021)

2.1 Occupancy behaviour uncertainty reduction

2.5.1 Household types and profiles based on occupancy behaviour pre-refurbishment.

The lack of consideration and implementation of occupancy behaviour has led to the "prebound effect" in certain cases wherein households consume less energy than is predicted before the refurbishment. Occupancy behaviour can be defined through the operation of buildings through heating, cooling and ventilation systems; and through the occupancy patterns and therefore the corresponding heat gains related to the presence and use of equipment *(Guerra-Santin & Silvester, 2016)*.

Initially, the study evaluates 18 different variables related to presence at home, heating setpoint, use of radiators and ventilation while heating (Refer to *Appendix 2*). Through exploratory factor analysis which is the clustering of variables based on the correlation of that specific variable to a factor. This helps reduce the number of variables and determine related behaviours. The variables were reduced to 6 main factors as shown in *Table 4* including i) Presence at home, ii) Day temperature, ii) Setback temperature, iv)Radiator use in bedrooms, v) Radiator use in service rooms and vi) ventilation while heating. In relation to presence, occupancy data was collected based on the mean number of days, occupants stayed at home and in order to translate that to a weekly schedule, it was assumed that the occupants were more often home at the beginning of the week rather than on weekends that consists of more irregular schedules. Furthermore, spaces for occupancy were categorised into i) living areas, ii) sleeping areas (bedrooms) and iii) short-stay areas (corridors, bathrooms etc). Living areas are occupied during the day hours and sleeping areas at night, whereas short-stay areas are always considered to be empty. Moreover, households with more than two adults considered bedrooms to be occupied during the day and night *(Guerra-Santin & Silvester, 2016)*.

In relation to the thermostat setpoints, these were set according to the mean temperature setpoint for a particular timeslot from the survey and the factor score derived for each household. If a household scores within the middle factor scores of > -0.1 and < 0.1 the thermostat setting was set as the mean temperature range and if it was < -0.1 or <0.1 then the temperature was set at -1 or +1 standards deviations respectively *(Guerra-Santin & Silvester, 2016)*.

Moreover, in relation to setback temperatures which are used during occupant absence and the night time, a distinction is made between high-energy households with setbacks that are the same as the main thermostat setting, therefore assuming the thermostat to always be the same. On the other hand for low-energy households, the setback is set to the mean setback temperature as derived from the survey *(Guerra-Santin & Silvester, 2016)*. Additionally, further research suggests that out of these parameters, the heating temperature has the highest sensitivity with a 1% increase in heating temperature resulting in a 3-5% increase in energy use *(Ben & Steemers, 2014)*. Therefore, the setback and setpoint temperature schedule would have a significant impact on the end energy use.

Using the WoON survey dataset, a set of household types was determined based on size, composition, age and presence of seniors and children as these parameters impacted energy consumption *(Guerra-Santin & Silvester, 2016)*. The household types are shown in *Table 4*.

Table 4 - Occupancy behaviour factors(left), Household types(right) (Guerra-Santin & Silvester, 2016)

Occupancy behaviour	**Household types**
Presence at home	1 senior
Day temperature	2 seniors
Setback temperature	1 adult
Radiator use in bedrooms	2 adults
Radiator use in service rooms	3 adults
Ventilation while heating	Single parent
	Nuclear family

An ANOVA test was then carried out between the household type and the occupancy pattern (factor score) in order to determine the final household profiles*. (Refer to Appendix 3).* These profiles are therefore defined deterministically where all weekdays and weekends are assumed to be the same based on a standard day profile across the year. This makes it easier and more practical to implement into simulation tools and standardised *(Guerra-Santin & Silvester, 2016)*. The results suggest that in terms of presence at home, seniors (single and couple) and nuclear families spend more time at home whereas adults and especially single adults spend less time at home. In relation to the use of thermostats, seniors set thermostats at a higher temperature compared to other households whereas single adults have the lowest temperature setpoint. Furthermore, single seniors, nuclear families, and households with three adults had a higher setback temperature. Moreover, overall households with children tend to heat the bedrooms more frequently than other households *(Guerra-Santin et al., 2018)*. These are summarised in *Table 5*.

Table 5 - Summary of household profiles and their occupancy behaviour intensities. (Guerra-Santin & Silvester, 2016)

	Presence	**Temperature**	**Setback**	**Radiators in bedroom**	**Ventilation while heating**	**Radiators, others**
1 senior	More	Warm	Wasteful	Semi-open	Higher rate	Semi-open
2 seniors	More	Warm	Setback	Semi-open	Average rate	Open
1 adult	Less	Cool	Setback	Semi-open	Higher rate	Closed
2 adults	Less	Average	Setback	Semi-open	Average rate	Semi-open
3 adults	Average	Average	Wasteful	Closed	Average rate	Open
Single parent	Average	Average	Setback	Open	Lower rate	Closed
Nuclear family	More	Average	Wasteful	Open	Higher rate	Semi-open

2.5.2 Post-refurbishment occupancy behaviour

Furthermore, the study examined the impact of occupancy behaviour change on retrofit measures and suggest that a behavioural change from a high energy level energy user to that of a low energy could potentially save 62%-86% of energy depending on the retrofit level. The definition of energy users and their characteristics is summarised in *Table 6*. As the retrofit level increases the impact of behavioural change decreases. On the other hand, if users from low/med increase their energy use, the change in consumption could offset physical improvements at any retrofit level *(Ben & Steemers, 2014)*. Additionally, single adults, in particular, are shown to underheat spaces pre-refurbishment and therefore a considerably rebound effect is expected in order to achieve more comfort for this household type thus it can be suggested that a rebound effect can be specifically driven by an increase in temperature setpoint. On the other hand, reduced energy consumption can be expected from household types like single seniors which are associated with better use of the thermostat setback and only heating the spaces occupied *(Guerra-Santin et al., 2018)*.

Table 6 - Post occupancy user behaviour types. (Ben & Steemers, 2014)

	Low energy user	**Medium energy user**	**High energy user**
Heating set point and setback (outside heating schedule)	Setpoint: 18 C Setback : none	Setpoint: 21 C Setback : 15 C	Setpoint: 24 C Setback : same as setpoint
Heating schedule	Weekdays – 7am – 9am 4pm - 11pm Weekends : 7am – 11pm	Weekdays – 7am – 9am 4pm - 11pm Weekends : 7am – 11pm	Weekdays – 24h Weekends : 24h
Window opening	none	7am – 9am	24h

2.5.3 Sub – conclusion

The study demonstrates that the occupancy behaviour of users has a significant impact on the energy consumption estimates both before refurbishment measures and post-refurbishment. Therefore, firstly the occupancy behaviours will be defined according to the respective household types. Single adults and single-parent households show the least intensive energy consumption behaviour overall whereas households with seniors and nuclear families are considered more energy-intensive users.

Table 7 - Heating profiles (°C) for thermostat and radiators. (Guerra-Santin & Silvester, 2016)

		23:00–06:00		06:00–09:00		09:00–12:00		12:00–15:00		15:00–18:00		18:00–23:00	
1 senior		T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3
	Mon–Wed	20	20	22	22	23	22	23	22	23	22	24	22
	Thu	20	20	22	22	23	22	21	21	23	22	24	22
	Fri	20	20	22	22	21	21	21	21	21	21	24	22
	Sat–Sun	20	20	21	21	21	21	21	21	21	21	21	21
1 adult		T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
	Mon–Tues	10	10	12	12	14	14	14	14	14	14	17	14
	Wed	10	10	12	12	10	10	10	10	14	14	17	14
	Thu	10	10	12	12	10	10	10	10	10	10	17	14
	Fri–Sun	10	10	10	10	10	10	10	10	10	10	10	10
	*T3–10℃												
2 adults		T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3	T1	T2/T3
	Mon–Wed	15	15	17	17	18	18	18	18	19	18	20	18
	Thu–Fri	15	15	17	17	16	16	16	16	16	16	20	18
	Sat–Sun	15	15	16	16	16	16	16	16	16	16	16	16
2 seniors		T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2
	Mon–Thu	19	19	21	21	22	21	22	21	22	21	23	21
	Fri	19	19	21	21	20	20	20	20	20	20	23	21
	Sat	19	19	21	21	20	20	20	20	20	20	20	20
	Sun	19	19	20	20	20	20	20	20	20	20	20	20
3 adults		T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2	T1/T3	T2
	Mon–Wed	17	16	17	16	18	16	18	16	19	16	20	16
	Thu	17	16	17	16	16	16	16	16	19	16	20	16
	Fri	17	16	17	16	16	16	16	16	16	16	20	16
	Sat–Sun	17	16	16	16	16	16	16	16	16	16	16	16
Single parent		T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3
	Mon–Tues	15	15	17	15	19	15	19	15	19	15	20	15
	Wed	15	15	17	15	19	15	16	15	19	15	20	15
	Thu	15	15	17	15	16	15	16	15	19	15	20	15
	Fri	15	15	17	15	16	15	16	15	16	15	20	15
	Sat–Sun	15	15	16	15	16	15	16	15	16	15	16	15
Nuclear		T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3	T1/T2	T3
	Mon–Wed	18	18	18	18	19	18	19	18	19	18	20	18
	Thu	18	18	18	18	16	16	16	16	19	18	20	18
	Fri	18	18	18	18	16	16	16	16	16	16	20	18
	Sat	18	18	16	16	16	16	16	16	16	16	20	18
	Sun	18	18	16	16	16	16	16	16	16	16	16	16

Notes: T1 = thermostat 1 (main thermostat, usually in the living room); T2 = thermostat 2 (radiators temperature in bedrooms); T3 = thermostat 3 (radiators temperature in office, bathroom and kitchen).
Black background = night setback temperature;
grey background = day setback temperature.

Furthermore, the heating setpoint and setback temperature are expected to have the most impact on the end energy consumption and the parameters can easily be defined within a simulation tool. Furthermore, the literature study above suggests these parameters are more sensitive both before and after refurbishment measures due to household type. Moreover, it is the occupancy within the dwelling which determines the respective setpoint and setback temperatures and thus it is interdependent. The table below summarises the temperature heating profiles that would be used pre-refurbishment. Furthermore, the suggested heating setpoint and setback measures of the low and high-energy users as shown in *Table 7* will be used to suggest post-refurbishment occupancy behaviour changes or make aware of potential rebound effects depending on the household type and the base scenario.

2.2 LT ready refurbishment strategies

2.2.1 Refurbishment scenarios

Before the development of refurbishment strategies, a formal exploration of the various refurbishment scenarios needs to be considered. The base scenario or the no refurbishment stage is considered to be the current condition of a dwelling which is used as a benchmark to compare the improvement in performance indicators for different refurbishment strategies. Moreover, scenarios could involve the exploration of refurbishment measures as individual refurbishment strategies *(Wang, Laurenti, et al., 2015; Wang, Ploskić, et al., 2015)* or a scenario in which refurbishment strategies are combined. The combined strategies follow variations of minimum, moderate and deep refurbishment strategies *(Brand & Svendsen, 2013; Rutten, 2021; Wahi et al., 2022).*

The minimum refurbishment strategies create minor inconvenience, alteration to building components and cost less. Therefore they could include a change in the radiator system or certain instances radiators have been over-dimensioned and due to lack of poor hydraulic control, certain systems are unnecessarily heated at high temperatures and therefore require minor adjustments *(Østergaard & Skaarup, 2018; Rutten, 2021; Wahi et al., 2022)*. Light to moderate refurbishment strategies involves a limited set of improvements to the building envelope like change in windows and external insulation *(Brand & Svendsen, 2013; Wahi et al., 2022)*. Deep refurbishment strategies incur higher costs and inconvenience with a change in ventilation systems, airtightness and increased levels of envelope insulation performance *(Wahi et al., 2022)*. Moreover, scenarios can also be formulated based on certain building constraints based on the housing type and construction period including lack of space for larger mechanical ventilation units, lack of sufficient space in cavity walls for post insulation or a reluctancy to change the external appearance of the existing façade as is the case in heritage dwellings for example *(Rutten, 2021)*.

2.2.1 Refurbishment Strategies and Measures

Refurbishment strategies can be classified into i)building envelope, ii)building installation and ii)room level. *(Rutten, 2021; Wahi et al., 2023)*. The room level of refurbishment strategies is not considered in this section as the solutions impact local comfort more specifically and are not necessarily widely used in refurbishments. *(Rutten, 2021)*. At the building envelope level, the main aim of the refurbishment is to minimise transmission losses by reducing the U value of the envelope *(Rutten, 2021; Wahi et al., 2022)*.

Table 8 - Building envelope refurbishment strategies (Konstantinou, 2014; Milieu Centraal)

Building envelope strategy	Description	Limitation
Wall		
Cavity insulation	Existing cavity filled with loose cellular insulating material. Easiest and cheapest method.	Houses built after the 1920s usually have a cavity and it needs to be between 4-6 cm. Not sufficient on its own to meet standards.
Exterior façade insulation	Rigid insulation on top of existing façade sheathing solves existing thermal bridge issues and is then plastered.	Requires permit in certain instances due to change in external appearance. Moisture risk due to improper vapour barrier prevents drying. Low impact resistance.
Interior façade insulation	Use of metal studs or timber battens on the inside with rigid or soft mineral insulation with a membrane layer in internal plasterboards.	Does not solve thermal bridge issues. Uses up internal space used by homeowners. Internal condensation risk due to lower external wall temperature.

Floor		
Above-ground-floor insulation	Rigid insulation with a new floor deck.	It eliminates the construction of existing thermal mass and minimises the internal height of space. It needs to be compression resistant.
Below ground-floor insulation	Insulation was added between joists.	Depending on the accessibility of the space below and in the case of timber, it is limited by the height of the joists.
Roof		
pitched roof insulation inside/outside	Loose or rigid insulation between rafters on the inside. For external insulation rigid insulation is placed on top with the roof tiles replaced with vapour membrane on the warm side.	Outside insulation on the roof could raise the height of the finished roof. Internal insulation is limited by an internal rafter and would require an additional insulation layer and use up storage space.
Flat roof insulation outside/inside	The preferred method is to place insulation on the outside to form warm roof construction with a waterproofing membrane and ballast layer to stabilise.	Insulation on the inside reduces ceiling height and increases the risk of condensation. External insulation would mostly need to be pressure-resistant.
Attic insulation	Loose or rigid insulation on the attic floor slab in the case where the attic space is not heated.	The attic space needs to be ventilated to prevent the risk of condensation.
Window		
Only window upgrade	In most instances, a single-glazing pane is replaced with double-glazing with an additional attachment at minimal expense.	Limited thermal performance improvement due to limitation of glazing width based on existing frame and no improvement of airtightness.
HR++ and triple glazing upgrade with window frame replacement	The window frame and glazing are replaced with HR++ or triple-glazing units along with the window frame.	Air tightness and enhanced performance need to be guaranteed by proper sealing of gaps around the frame.

The building installation level interventions primarily involve the improvement of active systems like the ventilation system and the heat delivery system *(Rutten, 2021; Wahi et al., 2023)*.

Table 9 - Building installation refurbishment strategies (Milieu Centraal; Rutten, 2021; Vabi)

Building installation strategy	Description	Limitation
Ventilation		
Type A1	Fresh air flows through seams, cracks, and grilles and the air is exhausted through vertical channels in the kitchen and bathroom. Air flow is driven by cross ventilation, stack effect or single-sided ventilation.	At least 1.5 cm of space is required under each interior door. Cold drafts can occur due to fresh air supplied by the ventilation grills. (Rutten, 2021)
Type C1 – Natural supply and mechanical exhaust	Often common in houses built after 1975 where fresh air enters through ventilation grills within the façade and air is mechanically exhausted at valves in the kitchen and bathroom.	Cold drafts can occur due to fresh air supplied by the ventilation grills.
Type C4 – Natural supply and mechanical exhaust with C02 sensors (demand driven)	It has a similar system as that of type C1 with the benefit that the amount of fresh air is regulated based on the occupant demand and thus saves energy through ventilation loses.	
Type D1 – Balanced ventilation	Both supply and exhaust are controlled by a mechanical system and are therefore balanced.	Requires significant refurbishment intervention in order to install the exhaust and supply ducts and also therefore more expensive. Requires maintenance to clean filters.
Type D2 – Balanced ventilation with heat recovery (WTW)	Heat recovery systems in combination with balanced ventilation systems preheat incoming air with that of the exhaust air which saves energy.	
Type D4b - Balanced ventilation with heat recovery (WTW) with CO2 control	The above system combined with CO2 sensors to control supply in accordance with demand.	
Type D5b – Decentralised ventilation with heat recovery and C02 control	This is a balanced ventilation system designed to ventilate one room with the unit located in the outside wall. Heat is recovered locally and thus prevents draughts.	These are more expensive to maintain due to the number of systems and have lower air exchange rates. *(Wolf)*
Heating system		
Conventional heating systems	Conventional radiators are primarily hydraulic with types varying based on the number of plates and convectors. For example, Type 22 has 2 plates and 2 convectors.	In certain instances, radiators are over-dimensioned or not used efficiently due to dimensioning based on extreme conditions. Therefore even with conventional radiators, 60% of the year can be supplied at low temperatures at an operative room temperature of 22C. *(Brand & Svendsen, 2013; Østergaard & Skaarup, 2018)*

LT radiator	In order to maintain the same heat output at low temperatures, low-temperature radiators include an increased number of plates and convectors. Additionally, radiators are covered by cases or supplemented by add-on fans that increase the convection rate and therefore improve the heat capacity.	Restricted by the existing two dimension limits of the existing radiator panels due to space restriction. *(Wahi et al., 2022)*
Large surface emitters	Large surface emitters like floor heating systems can be supplied with temperatures as low as 35 C with an improvement in overall comfort due to uniformity.	Inability to effectively counteract down drafts caused by cold window surfaces and involves an intensive installation process for existing dwellings that can be expensive.

2.2.2 Impact of measures

The cheapest method refurbishment strategy is to upgrade to LT radiators. However, it has minimal improvement on comfort and energy demand but not necessarily enough to be LT ready depending on the particular case. Instead, resources should be spent on refurbishing the building envelope and reducing heating demand *(Rutten, 2021; Wahi et al., 2022)*. Effective measures, including the replacement of windows to HR++ that significantly improve thermal comfort and minimised air infiltration, help reduce heat loss. Furthermore, windows are a relatively smaller investment and require replacement at the end of their 30-year lifetime *(Brand & Svendsen, 2013; Rutten, 2021)*. Overall, in relation to thermal, energy and investment budget, the balance ventilation system combined with HR++ leads to the best-performing results *(Rutten, 2021; Wang, Ploskić, et al., 2015)*.

2.2.2 Sub conclusion

This study concludes that refurbishment measures need to consider refurbishment measures at building envelope and building system level in combination in order to achieve optimal results including envelope measures like replacing the window and upgrading the ventilation system to balanced ventilation systems. Moreover, the implementation of each refurbishment measure is highly dependent on the existing condition and characteristics of the building envelope, use of space by occupants, budget restrictions and external aesthetical limitations. In relation to the classification of the intervention level (minimum, moderate, deep) in this study the refurbishment measures will be defined individually and then a decision-making tool will be used to explore the design space in order to form the refurbishment measure combinations which will then be classified as a post-processing step contrary to traditional refurbishment workflows. Furthermore, Table 10 & Table *11* summarises the refurbishment measures and their respective cost and characteristics. The data is an average from industry partners and the cost includes i) equipment, ii) material and iii) labour *(Rijksdienst voor Ondernemend Nederland)*. These strategies cover a broad range of widely available measures used for refurbishing residential dwellings in accordance with industry databases like the Rijksdienst voor Ondernemend Nederland and the bouwkosten online platform *(Bouwkosten Online; Bouwkosten.nl; Rijksdienst voor Ondernemend Nederland).* Additionally, the measures are in line with previous studies conducted in previous low-temperature refurbishment studies. *(Brand & Svendsen, 2013; Rutten, 2021; Wahi et al., 2022; Wang, Ploskić, et al., 2015)*

Table 10 - Selected refurbishment measures and their respective costs: building envelope strategies (Bouwkosten Online; Bouwkosten.nl; Cornelisse et al., 2021; Rijksdienst voor Ondernemend Nederland).

Building envelop strategy	**Measure**	**Material**	**Rc m²K/W additional)**	**cost (incl labour and storage) € /m2**
Cavity				
		EPS foam beads	1.6	22.8
		EPS foam beads	2.1	26.1
Wall				
	Exterior	EPS insulation (with mineral stone slips)	3.4	122.51
	Exterior	EPS insulation (with mineral stone slips)	4.7	126.19
	Exterior	EPS insulation (with mineral stone slips)	5.1	127.3
	Interior timber stud wall	Mineral wool	1.5	67.7
	Interior timber stud wall	Mineral wool	2.5	74.74
	Interior timber stud wall	Mineral wool	4	80.42
Roof				
	pitched roof external (incl. roof tiles)	PIR	3.7	144.7
	pitched roof external (incl. roof tiles)	PIR	6.3	167.49
	Pitched roof internal	PIR	3.7	58.89
	Pitched roof internal	PIR	4.2	75.06
	Pitched roof internal	PIR	5.2	80.4
Floor				
	Floor insulation- underside wooden ground floor	Mineral wool	2.1	40.3
	Floor insulation- underside wooden ground floor	PIR	3.7	52.66
	Floor insulation- underside wooden ground floor	Resol	4.2	67.82
	Floor insulation- top wooden ground floor	Resol	3.1	70.16
Window			**U value W/m²K**	
	HR++ (Instead of standard double)	-	1.2	124.25
	Triple glazing (instead of standard double)	-	0.8	162.27
Airtightness			**qv;10 dm³/s m²**	
	Medium (level 3 avg)	-	0.7	747.16
	High level (level 4 avg)	-	0.4	1379.56

Table 11 - Selected refurbishment measures and their respective costs: building installation strategies (BOUWKOSTEN; Radiator Kopen; RADSON; Rijksdienst voor Ondernemend Nederland)

Building installation strategy	Measure	Specification		
Ventilation				**cost (incl labour and storage) € /m2**
	Original			
	C1	Exhaust ventilation		2384.5
	C4	Exhaust ventilation C02 sensor (demand-driven)		3494.37
	D2	Balanced ventilation with heat recovery		4233.55
Heating system			**55/45 C Watts**	**Total cost (incl. installation cost)**
	Original - type 22	1440*600*100mm	1200	390
	Original - type 22	800*600*100mm	685	320
	LT radiator U low E2 comfort mode - type 22	1440*600*141 mm	1562	1064
	LT radiator U low E2 comfort mode - type 22	800*600*141 mm	893	814

2.3 Refurbishment measures performance indicators and sensitivity parameters

2.3.1 Literature KPI

A literature review by Prateek Wahi examines the various KPIs used to evaluate the refurbishment strategies. According to the review, the most widely used indicators evaluate Energy efficiency, indoor comfort, and financial feasibility *(see Figure 4)*. This is supported by the study done by *(Centraal Bureau voor de Statistiek, 2012; SCP, 2021; Straaten & Kanne, 2021)* where costs are considered one of the major barriers for Dutch homeowners to refurbish their dwellings. However, financial benefits are closely followed by the requirement for the improvement of thermal comfort and indoor climate and in most instances, the financial consideration from the homeowner's perspective is exaggerated. Although there are a comparable number of studies evaluating the overall environmental impact of the refurbishment measures, it can be argued that from a homeowner's perspective, the environmental impact is not considered as often *(Easterbrook & Sabet, 2016)*, and is influenced by an individual's beliefs and understandings of energy-environment issues *(Wilson et al., 2015)*. Therefore, it can be concluded that Energy efficiency, indoor comfort and financial feasibility are the following KPIs to be utilised in this study to evaluate the refurbishment strategies.

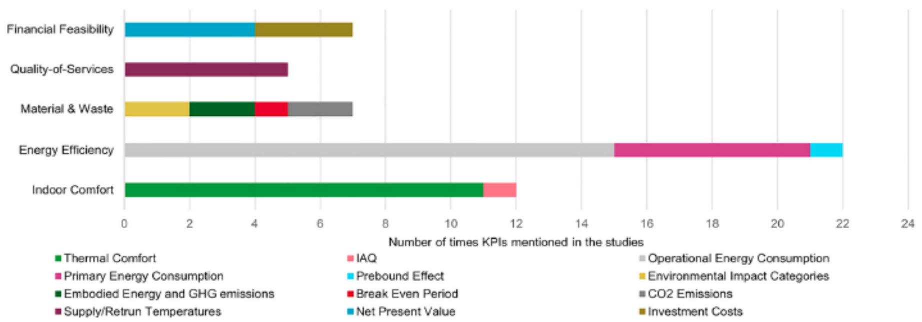


Figure 4 - Literature overview of refurbishment performance indicators.(Wahi et al., 2023)

2.3.2 Energy efficiency

The literature review by Wahi concludes that in relation to energy efficiency, most studies evaluate the operational energy consumption in terms of heating demand or the net energy demand in terms of space heating, hot water and electricity. Additionally, the criteria of selection are based on the highest energy savings compared to the base case *(Wahi et al., 2022)*.

Furthermore, the Nieman report proposes a standard target for heat demand for the refurbishment of dwellings. Two options were considered in the report i) utilising one fixed standard value per housing type based on the lower, median or upper bounds and ii) the use of a base trend line correlating the heat demand with the compactness ratio of the dwelling with a base level 3 refurbishment package. The second option was chosen proposed standard in the report as it can be used for multiple housing typologies without having to define ranges for each housing type. The disadvantage of this proposed method is the compactness ratio is not easy to determine for homeowners *(Cornelisse et al., 2021)*. Since this study will consider a representative house for each housing typology and the compactness ratio will not be actively input by the user, the proposed standard value could still be used as a benchmark value to asses a target value to achieve after a refurbishment measure *Table 15.*

Furthermore, in the current dwelling stock of the owner-occupied sector, C is the most common energy label *(Ebrahimigharehbaghi et al., 2019)* which corresponds to a total theoretical primary energy consumption of 175 kWh/m2 *(Filippidou et al., 2016)*. Therefore, if an existing dwelling has an energy label below C, it must at a minimum be raised to label C and if it is currently at label C it must aim to achieve label B or higher.

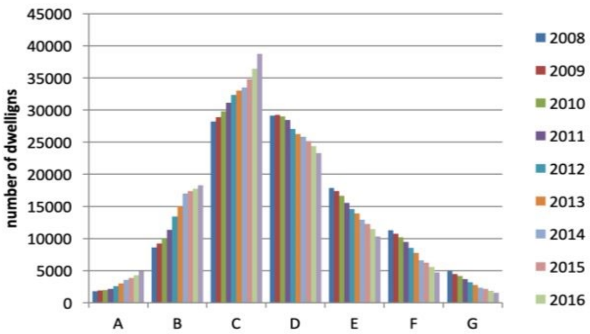


Figure 5 - Energy label distribution over the years. (Ebrahimigharehbaghi et al., 2019)

Energy performance label	Energy index	Total primary theoretical energy consumption (KWh/m2/year
A	≤ 1.20	138.48
B	1.21 - 1.40	162.08
C	1.41 - 1.80	174.27
D	1.81 - 2.10	195.60
E	2.11 - 2.40	211.55
F	2.41 – 2.70	223.83
G	> 2.70	232.10

Table 12 - Energy label and consumption. (Filippidou et al., 2016)

2.3.3 Thermal comfort

In order to evaluate thermal comfort, the two most common evaluation methods used are the predicted mean vote and % Hours too cold below-set point temperature as discomfort hours due to underheating *(Wahi et al., 2023)*.

The PMV or predicted mean vote is based on Fanger's model, which is a mathematical model that predicts the level of comfort of a theoretical group. The model takes into account different environmental variables like mean radiant temperature, air temperature, air velocity, relative humidity, metabolic rate, and clothing level *(Rutten, 2021).* The ISO 7730 standard formalises this for the Netherlands, by creating various categories that combine the PMV with other local comfort criteria like PPD and temperature asymmetry *(ISO 7730)*.

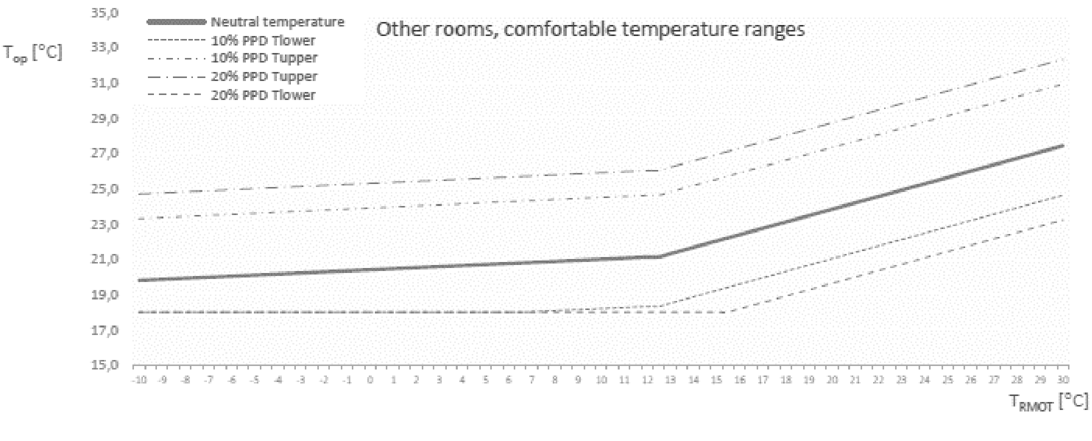
Table 13 - Categories according to ISO 7730. (Rutten, 2021)

Category	Thermal state of the body as a whole		Local discomfort			
	Predicted percentage of dissatisfied (%)	Predicted mean vote range	Percentage of dissatisfied (PD) due to draught (%)	PD due to vertical air temperature difference (%)	PD due to cool of warm floor (%)	PD due to radiant temperature asymmetry (%)
A	<6	−0.20 to 0.20	<10	<3	<10	<5
B	<10	−0.50 to 0.50	<20	<5	<10	<5
C	<15	−0.70 to 0.70	<30	<10	<15	<10

However, the drawback of such standards is that they have been developed based on the office environment. Thus, these standards do not lend themselves well to the residential setting wherein there are specific possibilities to adapt to a user's level of comfort *(Rutten, 2021)*. These adaptation possibilities include *(Peeters et al., 2009)*:

i) Psychological – adaptation is based on the experience of the environment, time exposure, naturalness, and perceived control *(Nikolopoulou & Steemers, 2003).*
ii) Physiological – through acclimatization over a short period.
iii) Behavioural thermoregulation – by adjusting their environment through the opening or closing of windows and heating systems or a change in clothing, posture, and activity.

Therefore this study considers the adaptive thermal comfort model developed by Peters et al that considers the above-mentioned possibilities of thermal comfort adaptation in dwellings *(Peeters et al., 2009)*. The model makes a distinction between different rooms in the dwelling including bathrooms, bedrooms, and other rooms. Additionally, the model takes into account the running mean average of days before and thus its impact on the perception of indoor thermal comfort *(Rutten, 2021)*. Furthermore, it defines the neutral temperature line and then a comfort band for 90% (10% PPD) and 80% acceptance (20% PPD)*(Wahi et al., 2022)*. Therefore, the least number of "hours too cold", that exceed the comfort band of 80% acceptance can be used as a criterion to evaluate the thermal comfort as a minimum after the transition to low-temperature heating post-refurbishment. The hours too cold has been evaluated specifically in the living room as it is the room in which occupants spend the majority of the time and have a higher acceptance range in other rooms. Furthermore, in most housing typologies the living room spans the width of the dwelling and thus aligns with the main orientation of the dwelling and therefore provides an indicative performance for the entire dwelling. *(Rutten, 2021; Wahi et al., 2023)*.



$$T_n = 0.06 \times T_{RMOT} + 20.4\ °C \quad \text{for} \quad T_{RMOT} < 12.5\ °C \quad \text{in [°C]} \quad (3.15)$$
$$T_n = 0.36 \times T_{RMOT} + 16.63\ °C \quad \text{for} \quad T_{RMOT} \geq 12.5\ °C \quad \text{in [°C]} \quad (3.16)$$

Figure 6 - Comfortable temperature range in other rooms like kitchen and living room according to ATC method. (Rutten, 2021)

2.3.4 Financial feasibility

Financial feasibility is evaluated by multiple studies through two main methods i) the consideration of investment cost at the initial stage, ii) taking into account the life-cycle of the refurbishment method through the LCC and more specifically the Net Present Value (NPV) *(Wahi et al., 2023)*. The second method takes into account operation cost, maintenance cost and investment cost throughout the building which is 30 years *(The European Commission, 2012)*. A study by Berry & Davidson, 2015 the assessment a step further by including the societal economic benefits like health and productivity. Therefore in that study, NPV was defined as the difference between benefits and costs over the discount period and thus the end objective is to maximise the NPV value over the duration *(Berry & Davidson, 2015)*.

$$NPV(i) = \sum_{t=0}^{N} \frac{(\text{benefits} - \text{costs})_t}{(1+i)^t}$$

Equation 1 - NPV(Berry & Davidson, 2015)

$$Global\ cost\ (GC) = \sum_{i=1}^{j} IC_{a,j} + \sum_{i=1}^{j} RC_j + OC + MC$$

Equation 2 - Global cost method (Kotireddy, 2018)

N = effective life of the action t = time of the cashflow i = discount rate	IC = Additional investment cost RC = replacement cost OC = operating cost MC = Maintenance cost i = refurbishment measure within a package j = total number of refurbishment measures in the package

Another, method of defining the life-cycle cost is through the global cost *(NEN-EN 15459, 2007)*. This method considers solely the global cost for a financial calculation. This includes the sum of the initial investment cost, the sum of the replacement cost and the disposal cost if applicable. If a macroeconomic perspective is considered, then the cost of greenhouse gas emission is added which helps consider the larger societal perspective. In this study, the global cost model excluding the greenhouse gas emission cost is considered as it takes into account the life cycle perspective and clearly defines all components from a cost perspective and it is the prescribed directive from the European Commission *(The European Commission, 2012)*.

$$OC = El_{imp} \cdot P_{El} + E_{NG} \cdot P_{NG}$$

Equation 3 - Operating costs (Kotireddy, 2018)

$$OC_{ds} = f_{pv} \cdot OC$$

Equation 4 - Operating cost discounted. (Kotireddy, 2018)

$$f_{pv} = \frac{1-(1+R_R/100)^{-n}}{1+R_R/100}$$

Equation 5 – Present value factor (NEN-EN 15459, 2007)

$$R_R = \frac{R - R_i}{1 + R_i/100}$$

Equation 6 - real interest rate. (NEN-EN 15459, 2007)

OC = Operating cost $\boldsymbol{El_{imp}}$= imported electricity **kWh** $\boldsymbol{P_{El}}$ = Price of electricity €/kWh $\boldsymbol{E_{NG}}$ = imported natural gas m3 $\boldsymbol{P_{NG}}$ = Price of natural gas €/m3	f_{pv}= discount factor OC = operating cost	R_R = real interest rate n = calculation period e = escalation rate	R_R = Market interest rate R_i = inflation rate

Table 14 - Energy prices. (Centraal Bureau voor de Statistiek, 2023)

	Fixed Transport rate €/ year	**Fixed delivery rate €/ year**	**Net fixed rate €/ year**	**Variable delivery rate €/m3**
Natural gas (euro/m3)	172.4	65.5	237.8	1.82
Electricity (euro/kWh)	240.6	65.4	306.0	0.53

Operating costs are the sum of the annual energy costs of gas and electricity multiplied by their respective unit prices (Kotireddy, 2018). In this instance, a single tariff rate is utilised due to the ease of use and therefore an up-to-date tariff rate is required. Based on the latest CBS data for 2022 November are shown in *Table 14*.

Furthermore, to calculate the net present value of the operational cost, the operational cost needs to be multiplied by a discount factor, that considers the real interest rate along with the escalation rate of energy prices. The discount rate should be between 0% and 4% *(ISO,2008)* and the long-term real interest rate in the Netherlands is 2.43% *(CEIC)*. Additionally, previous studies have used discount rates of 3% and 4% *(Dijkstra, 2013; Gopalan, 2018; Kotireddy, 2018)* and therefore it can be estimated that the discount rate in this study will lie between 2- 4 % depending on the commodity escalation rate.

Maintenance of building components includes staff inspection and annual cleaning contracts of building components. (NEN) Currently, there is a limited set of data on the maintenance cost of building components for the Dutch building stock. Therefore, current studies have left out the maintenance cost due to the lack of this data *(Dijkstra, 2013; Gopalan, 2018; Kotireddy, 2018)*. The NEN 15459 includes standards on the lifespan and maintenance cost as a percentage of the initial investment, however, the data is limited to the technical installation of a dwelling and thus is limited *(NEN-EN 15459, 2007)*. In order to supplement the LCC analysis and compare different alternatives the net savings can be calculated at the end in order to compare the base case to the alternative refurbishment measures *(Kneifel & Webb, 2020)*.

2.3.5 Sub-conclusions

The performance indicators, the methodology used to evaluate them, and the selection criteria examined above to derive the definition of a no-regret LT-ready refurbishment strategy. The no-regret refurbishment strategy is defined as when the owner no longer needs to incur further modifications to the same building components within the technical lifespan in anticipation of the transition to district heating *(Cornelisse et al., 2021)*.

Studies have evaluated the effectiveness of refurbishment measures in order to transition to low-temperature dwellings by evaluating the increase in operative air temperature and the highest energy savings,*(Wahi et al., 2022; Wang, Ploskić, et al., 2015)* and reduction in head space heating demand and a reduction in the number of hours for which the supply temperature remains above a certain threshold to maintain the specified operative temperature *(Brand & Svendsen, 2013)*. Furthermore, it has also been defined in terms of maintaining existing levels of comfort by comparing the number of hours cold according to the ATC method *(Rutten, 2021; Wahi et al., 2022)*. A static method of LT readiness has also been defined, comparing the heat capacity of radiators to that of the maximum heating demand throughout the year and therefore has no acceptance of demand exceedance which leads to over-dimensioned requirements *(Rutten, 2021)*.

Based on the indicators explored above, in order to be no regret LT ready the following set of criteria devised would need to be met first as shown in *Table 15*.

Table 15 - Selected performance indicators and their selection criteria.

Performance indicator	Selection criteria		
Energy efficiency :	Housing type	Compactness ratio	Net head demand (kWh/m2)
Net heat demand	Single-family home < 1945	< 1.00 ≥ 1.0	≤ 60 ≤ 60 + 105 * (A_{ls}/A_g-1.0)
	Single-family homes > 1945	< 1.00 ≥ 1.0	≤ 43 ≤ 43 + 40 * (A_{ls}/A_g-1.0)
AND	Multi-family home < 1945	< 1.00 ≥ 1.0	≤ 95 ≤ 95 +70 * (A_{ls}/A_g-1.0)
	Multi-family homes > 1945	< 1.00 ≥ 1.0	≤ 45 ≤ 45 + 45 * (A_{ls}/A_g-1.0)
Total energy performance	If the energy label below C	Minimum : < 175 kWh/m2	
	If energy label C or higher	Highest energy savings from base	
AND Thermal comfort	A minimum number of "hours too cold" with respect to the 80% acceptance comfort band using the ATC method, compared to the base situation.		

Once the initial set of criteria is met to meet the basic requirements for a no-regret LT-ready scenario, the narrowed set of results can be further evaluated based on their financial feasibility as defined below:

Table 16 - Financial feasibility performance indicator

Performance indicator	Selection criteria
Financial Feasibility	Minimum global cost based on *Equation 2* with a discount rate between 2- 4%. Therefore the maximum net saving.

2.2 Surrogate model workflow

2.6.1 Conceptual workflow

Existing literature comprises two variations of conceptual surrogate model frameworks. The first is top down-models that predict energy consumption and performance of existing homes through the correlation of aggregated data like the gross domestic product, income, and unemployment combined with econometric or technological indicators of dwelling. These models are primarily used to predict overall energy consumption trends within the national building stock and thus cannot be used to analyse individual buildings on a large scale and predict energy performance in a detailed manner *(Kavgic et al., 2010)*.

On the other bottom-up models can evaluate the energy performance of dwellings at a micro or meso level by taking into account specific characteristics of the building stock *(Dijkstra, 2018)*. The disaggregated data could include construction period, surface area and building type. Two variations of the bottom model include i) the engineering model, and ii) the statistical model. The statistical model is based on correlating the energy performance of individual buildings based on a set of parameters including, surface area, use, age, building or household characteristics like income or occupancy behaviour type etc *(Dijkstra, 2018)*.On the other-hand engineering, models use specific data that is physically measurable of building characteristics like the thermal properties of the envelope, the efficiency of space heating systems, internal temperatures etc *(Kavgic et al., 2010)*. The advantage of the engineering model is that it can deliver information regarding the impact of refurbishment measures which is relevant to this study. On the other hand, they require high-level data with specific data that forms a complex model compared to statistical models *(Mastrucci et al., 2014)*.

The overall approach to training the surrogate model is based on key steps. i) to build a detailed and representative simulation model, ii) generation of representative data of the design space, iii) use statistical models to fit the data and iv) test model performance *(Aijazi & Glicksman, 2019; Asadi et al., 2014; Yang et al., 2016)*. In order to arrive at the optimised set of results the trained response surface then needs to be within a genetic algorithm *(Asadi et al., 2014)*.

There are two potential workflows when developing the non-dominated Pareto front through an optimization process i) a linear development of the RSM optimization and ii) an iterative RSM optimization development process. In the Linear development of the RSM and the optimization process, the simulation data is used once to train the model. The iterative RSM optimization process uses the simulation data in two stages, first to reach a narrowed-down set of results which is then used to redefine the initial design variables and develop the RSM further. In this study, this workflow can be utilised after assessing the performance of the response surface after the first iteration *(Westermann & Evins, 2019; Yang et al., 2016)*.

Furthermore, one of the platforms used to train surrogate models is modeFRONTIER by ESTECO. The tool is used as a multi-disciplinary engineering design tool, to automate and optimize design processes whilst providing quantitative data analysis and visualization tools. The platform also provides the means to communicate with other third-party software like Grasshopper using the myNODE tool or customised interface *(Yang et al., 2020; Yang et al., 2016)*.

2.6.2 Developing training data and sampling methods

To generate the data for a bottom-up engineering-based surrogate model, studies use simulation engines like TRNSYS *(Asadi et al., 2014)* and Energy Plus which are combined with other tools and interfaces like Grasshopper(Rhino) *(Aijazi & Glicksman, 2019; Yang et al., 2016)* to model and parametrise the base input geometry *(Westermann & Evins, 2019)*. The input variables need to be defined by constraints and can either be defined as continuous parameters within a set range *(Aijazi & Glicksman, 2019; Yang et al., 2016)* or in discrete steps defined by products standards *(Asadi et al., 2014; Kounaki, 2019)*. For example in the work done by Asadi, each retrofitting decision variable is assigned a specific type number *(Asadi et al., 2014)*.

In order to shorten the size of the training database whilst maintaining adequate levels of representation, a uniform sample of the design space is required *(Aijazi & Glicksman, 2019)*. The most commonly used static sampling method is the Latin hypercube sampling method *(Asadi et al., 2014; Kavgic et al., 2010; Westermann & Evins, 2019)* and a sample of more than twice the number of parameters is an adequate sample size to maintain accuracy *(Asadi et al., 2014)*. The Latin hypercube sampling method divides the range of the respective variables into strata of equal probability wherein one value is randomly selected from each stratum. *(Aijazi & Glicksman, 2019)*. The LHS algorithm can be implemented using the modeFrontier DOE node or the GHpython tool in Grasshopper *(Tseranidis, 2015; Yang et al., 2020)*.

2.6.3 Training algorithms

Surrogate models have been trained using multiple algorithms and are the most widely used in the building context. The most common include regression models including multiple linear, polynomial and stepwise regression as they are relatively easy to develop *(Dijkstra, 2018; Westermann & Evins, 2019)*. These are examples of parametric models wherein an assumption is made on the function that describes the relationship between input and outputs and only the parameters need to be calibrated *(Westermann & Evins, 2019)*. In multiple linear regression, wherein multiple independent variables are multiplied by coefficients to form a linear equation to best predict the dependent variable by fitting a straight line or surface *(IBM)*. The stepwise linear regression optimises this process by iteratively evaluating the significance of each independent variable and therefore its influence on the dependent variable *(Adam Hayes, 2022)*.

Artificial neural networks (ANN) are another extensively used non-parametric model to train response surfaces. The ANN is based on the human neural system comprising parallel layers of units called neurons. Signal and data are passed through a series of weighted links that connects the neurons *(see Figure 7).* The neurons layers can be devised into three types i) the input layer which receives input information from outside, also known as the independent variable, ii) the output layer which delivers the results known as the dependent variable and iii) the hidden layers between the input and output layers where the inputs are weighted, summed and then used in an activation function that decides whether a neuron should be at fired activated and adds non-linearity to the output of the neuron in order to learn complex patterns *(Asadi et al., 2014; Westermann & Evins, 2019)*.

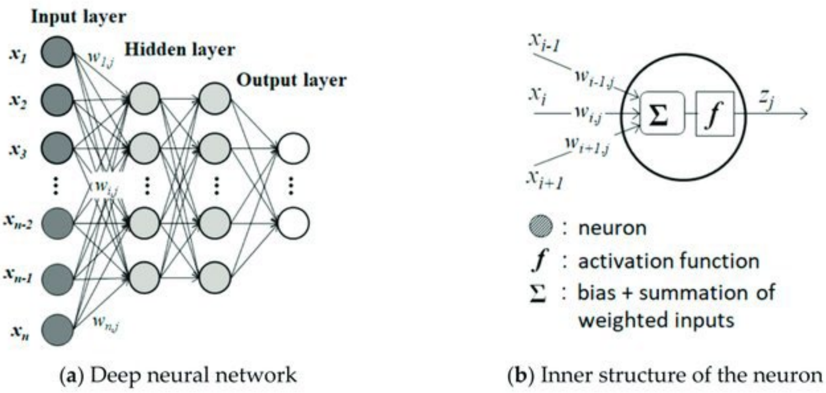


Figure 7 - Artificial neural network conceptual framework.(Kimura et al., 2019)

2.6.3 Methods to Test the Accuracy of Models.

In order to validate the surrogate model, the dataset is split into the training data set and a dedicated test dataset; empirical data suggest a data plot of 80-70% and 20-30% for training and testing data respectively *(Gholamy et al., 2018)*. The accuracy is tested using the dedicated test data set using two methods i) R^2, ii) (CV)RSME *(Aijazi & Glicksman, 2019; Asadi et al., 2014; Westermann & Evins, 2019)*.

The R^2 metric is used to evaluate the fit of regression models. It defines the proportion of variance explained by my line of best fit or predicted values compared to the variation of the actual values from the mean value of the dependent variables. The RMSE or root mean squared error represents the absolute, average variation between the predicted value and the actual data points. The coefficient of variation of root means squared error CVRSME normalises the RSME metric by the average dependent variable value in order to be able to use the metric to compare surrogate models *(Sharma, 2019; Zach, 2021)*. Overall, it can be concluded that model CVRMSE error is higher for Pareto optimal designs as these optimal designs are mostly located at the extremes of the independent variable input range *(Aijazi & Glicksman, 2019)*.

2.6.4 Sub conclusion

The surrogate model will be trained using a bottom-up engineering model-based approach wherein a detailed building simulation model will be developed on Grasshopper based on building characteristic details. Once the model is parametrically defined, a representative sample of the input variables will be simulated and the corresponding output variables will be extracted through the EnergyPlus tool, using the Latin hypercube sampling method. The input and output parameters of the representative sample will then be stored in modeFRONTIER and then split into the training and test dataset. The training data set will be used to fit various models using artificial neural networks, linear regression etc through modeFRONTIER and then evaluated using the R^2 and root mean squared error method. Throughout the process, the modeFRONTIER platform and grasshopper platforms will be integrated in order to benefit from the integration of sampling methods and evaluation of multiple models using quantitative analysis and visualization tools within modeFRONTIER and the parametric definition capabilities of Grasshopper *(Yang et al., 2020)*. The overall workflow is summarised in *Figure 8.*

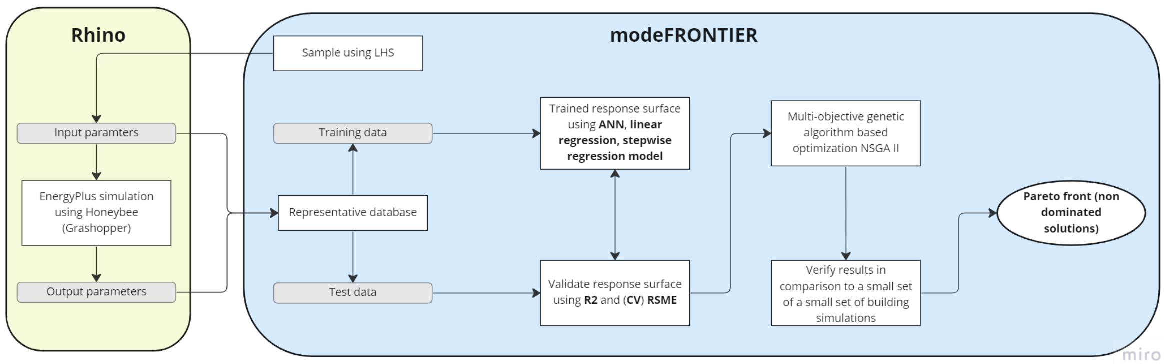


Figure 8 - Surrogate model computational workflow. (Source: Own)

Phase 2 : Development simulation model and surrogate model

3) How can the simulation model be developed parametrically to generate a representative sample of data to train the surrogate model?

4) What method can be used to generate optimised refurbishment measures considering life cycle cost?

3. Development of simulation model

The literature review discussed above formalised the global data required to classify and represent the Dutch housing stock, the current state of the art in terms of refurbishment measures and performance indicators used to evaluate the strategies at an integrated level and the overall computational workflow to develop a surrogate model underlying the decision-making tool. The next stage involves defining the underlying building simulation model based on the inputs gathered to form the training data that will be used to train the surrogate model.

3.1 Data collection

3.1.1 Terraced house Base Geometry

The first housing type to be addressed is the Terraced housing and a representative house was selected to base the geometric properties of the energy model on. This was done by selecting a terraced house correlating with the average living area defined by the literature review, a typical façade appearance and floorplan layout.

Figure 9 - Terraced house front facade. (funda)

Figure 10 - Terraced house back façade (funda)

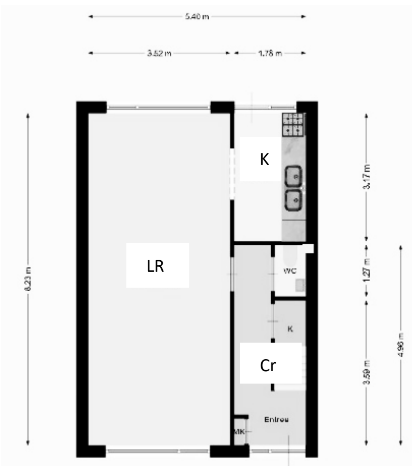


Figure 11 - Terraced house ground floor plan (funda)

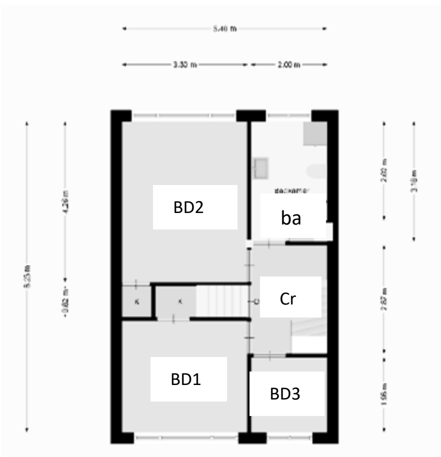


Figure 12 - Terraced house first floor plan (funda)

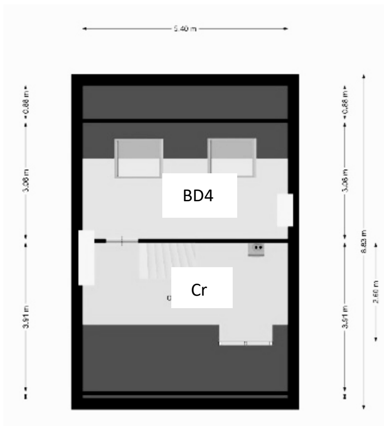


Figure 13 - Terraced house attic floorplan (funda)

The terraced house is in Bodegraven, with a living room, toilet and kitchen located on the ground floor. The second floor comprises of 2 main bedrooms, smaller office space and bathroom and finally the third floor comprises of an attic service room and the third bedroom. The total gross area of the dwelling is 113 m2 and the window to WWR is assigned to the dwelling based on the literature study previously at 35%. Furthermore, the operable window-to-wall ratio has been estimated based on the images of the envelope.

Table 17 - Overview of Terraced dwelling zone based input parameters

	Living room	Kitchen	Corridor	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bathroom
Area	28.96	5.48	36.3	14.08	13.12	3.88	21.60	6.14
Height [m]	2.70							
Conditioned	yes	yes	no	yes	yes	yes	yes	yes
People [ppl/m2]	3		-	3				1
	0.087		-	0.056				0.16
Ventilation rate	0.7 [dm3/s/m2]	21 [dm3/s]	-	0.7 [dm3/s/m2]				14 [dm3/s]
Window operable ratio %	30%	-	-	50%	50%	50%	-	80%

Table 18 - Terraced house envelope and geometry properties

Envelope property	
Opaque wall area m2	39.1
Window area m2	18.4
WWR %	35%
Roof area m2	50.1
Footprint floor area m2	43.2
Compactness ratio	1.4

Table 19 - Detached house envelope and geometry properties

Envelope property	
Opaque wall area m2	169.6
Window area m2	31.3
WWR %	16%
Roof area m2	93.2
Footprint floor area m2	43.2
Compactness ratio	2.2

Table 20 – Portiek apartment envelope and geometry properties

Envelope property	
Opaque wall area m2	23.3
Window area m2	17.1
WWR %	42%
Roof area m2	-
Footprint floor area m2	83
Compactness ratio	0.5

3.1.2 Detached house base geometry

The second housing type to be addressed is the Detached housing and a representative house was selected to base the geometric properties of the energy model on. This was done by selecting a terraced house correlating with the average living area defined by the literature review, a typical façade appearance and floorplan layout.

The detached house is located in Riel with a living room, toiler and kitchen located on the ground floor. The second floor comprises of 2 main bedrooms and 1 smaller bedroom and a bathroom. Finally, the third floor comprises of service room and 2 additional bedrooms. The total gross area of the dwelling is 168 m2 and the window-to-wall ratio is 16% which is in line with the previous literature study.

Figure 14- Detached dwelling front façade (funda)

Figure 15- Detached dwelling back façade (funda)

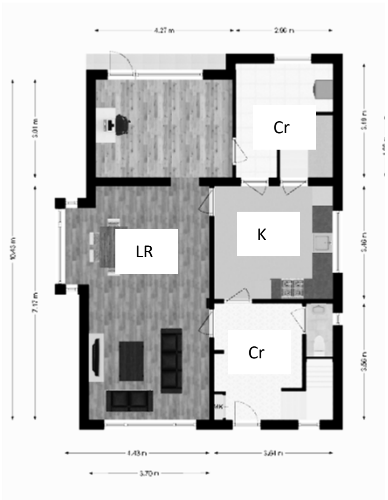


Figure 16 - Detached dwelling ground floor plan (funda)

Figure 17 - Detatched dwelling first floor plan (funda)

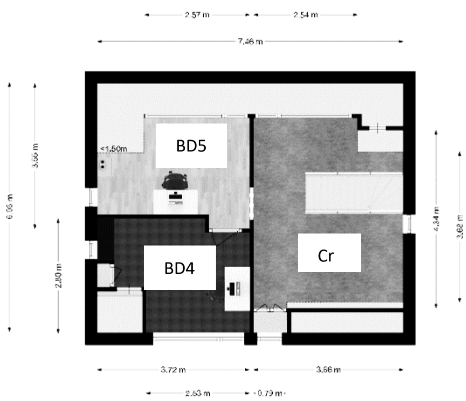


Figure 18 - Detatched dwelling attic floor(funda)

Table 20 - Overview of detached dwelling zone based input parameters

	Living room	Kitchen	Corridor	Bedroom 1	Bedroom 2	Bedroom 3	Bedroom 4	Bedroom 5	Bathroom
Area	28.3	12.5	36.3	14.2	13.9	9.68	14.16	14.16	9.68
Height [m]	2.70								
Conditioned	yes	yes	no	yes	yes	yes	yes	yes	yes
People	3		-	3					1
[ppl/m2]	0.052		-	0.044					0.16
Ventilation rate	0.7 [dm3/s/m2]	21 [dm3/s]	-	0.7 [dm3/s/m2]					14 [dm3/s]
Window operable ratio %	30%	-	-	50%	50%	50%	-	30%	80%

3.1.3 Portiek apartment

The third housing archetype that is studied includes the portiek apartment type. The housing typology accounts for nearly 12% of the Dutch building stock. The chosen portiek apartment is located in Layenburg, Den Haag and is selected based on typical floorplan layouts that correlate with the average gross floor area as determined by the literature review. For this specific case a middle apartment is selected at the first level, although other variations like ground, top floor or corner apartments can exist. It consists of 3 main bedrooms, a toilet and a living room. The total gross area of the dwelling is 83 m2 and the window-to-wall ratio is 42%.

Figure 19 - Portiek apartment front façade (funda)

Figure 20 - Portiek floorplan (funda)

Table 21 - Overview of portiek dwelling zone-based input parameters

	Living room	Kitchen	Corridor	Bedroom 1	Bedroom 2	Bedroom 3	Bathroom
Area	25.9	5.8	13.2	15.8	13.8	13.8	5.0
Height [m]	2.70						
Conditioned	yes	yes	no	yes	yes	yes	yes
People [ppl/m2]	3		-	3			1
	0.09		-	0.07			0.2
Ventilation rate	0.7 [dm3/s/m2]	21 [dm3/s]	-	0.7 [dm3/s/m2]			14 [dm3/s]
Window operable ratio %	30%	-	-	50%	50%	50%	-

3.2 Input parameter setup

3.2.1 Envelope parameters

The parameters shown above in Table 18, and Table 20 & Table 21 remain constant across construction years. The next step defines the input parameter ranges and the respective steps to represent the envelope properties across the defined construction years and the improved values of the refurbishment strategies as defined in the literature review. Additionally, the table below summarises the physical approximation of the construction layers of the facade to gain a better understanding of how the thermal performance values mentioned in Neiman's report translate to the construction layers.

Table 22 - Physical potential construction of Nieman dwelling characteristics.

Construction year	U value	Rc value	Description
<1945	1.44		100mm brick 40 mm air cavity 100 mm brick
1945 - 1975	1.19		10mm Asbestos cement board 40mm mineral wool insulation 12mm Gypsum board
1975 - 1995	0.65		100mm brick 30mm mineral wool 100mm concrete hollow block units
>1995	0.37		10mm Asbestos cement board 80mm EPS 20mm Fibreglass batt

To define the envelope property parameters 3 main objectives were identified. The first objective was to be able to accurately represent the thermal performance of the various construction years and the refurbishment strategies using the same parameter in order to be able to efficiently represent the pre-refurbishment and post-refurbishment situation using one model. The second objective was to limit the number of custom-defined wall typologies whilst maintaining flexibility for users to adjust default envelope properties when using the decision-making tool. Thirdly, the parameter must be able to consider certain limitations that could be incurred when undergoing refurbishment which have been defined in Table 24.

Table 23 - Base construction build-up

Base component		Rc m2·K/W	U value W/m2·K
Cavity wall	100mm brick 50mm air cavity 100mm inner concrete block leaf	0.74	1.35
Uninsulated timber rafter roof	Roof shingles Timber joists Gypsum boarding	0.5	2
Uninsulated timber joist floor	Gypsum boarding Timber joists Deck boarding	0.4	2.5

To meet the above-mentioned objectives, a base opaque construction without insulation has been established as described in Table 23 and Table 24 as this doesn't have a significant contribution to the overall insulation of the construction and is widely applicable across construction years *(Cornelisse et al., 2021).* The parameters defined can then be adjusted for the individual insulation layers within each of the envelope components in order to match the construction year thermal performance whilst also addressing the refurbishment strategies. Furthermore, by defining the envelope parameters in relation to the layers of the construction, certain limitations can be considered by constraining the depth of the individual layers.

Furthermore, a step size of 0.2/0.5 has been chosen so that the design space covers both the current construction year properties as well as the refurbishment strategies whilst reducing the number of variables in terms of computational cost. Additionally, this method of defining the input parameters assumes that existing insulation layers are completely replaced by new insulation rather than adding additional layers on top of the existing insulation due to potential moisture damage. *(Konstantinou, 2014)*

Table 24 - Envelope input parameter definition

Envelope parameter		Range	Steps (Discrete)	Thermal conductivity W/(m·K)	Refurbishment constraints
Façade Rc m2·K/W	External insulation	0 - 6.5	0.5	EPS : 0.038	Limited external depth or change in appearance.
	Cavity	0 - 2	0.5	EPS: 0.038	Construction built before 1920 with insignificant cavity depth
	Internal insulation	0 - 5	0.5	Mineral wool: 0.035	Space restriction
Pitched Roof Rc m2·K/W	External	0 - 6.5	0.5	PIR : 0.021	Limited external depth or change in appearance.
	Internal	0 - 4	0.5	PIR: 0.021	Space restriction
Floor Rc m2·K/W	Underside	0 - 4.5	0.5	Mineral wool: 0.035 If Rc = 3.5: PIR: 0.021 If Rc = 4.0 Resol: 0.020	Limited access to crawl space
	Top	0 - 3	0.5	Resol: 0.020	Space restriction
Window U value W/m2·K	-	0.8 - 3	0.2	-	<2.0 requires frame replacement
Airtightness dm3/s.m2	-	0.2 - 1.6	0.2	-	-

Minera wool - (Knauf Insulation, 2022)
EPS - (IsoBouw)
PIR - (Kingspan)
PU foam - (Kimpur)
Resol - (Unilin insulation)

During this stage, the parameters are defined whilst considering the user experience when the tool is finally implemented. In relation to the envelope parameters, the values are set by default based on the construction year and therefore certain assumptions are required. If the construction year is <1920, current insulation layers are assumed to be added to the internal wall because the cavity depths are too narrow to be considered for post-insulation. Furthermore, insulation on the interior wall is a cheaper option compared to outer wall insulation and thus users are assumed to have considered the cheaper option by default *(Milieu Centraal)*. For other construction years, if the Rc ≥ 2.0, the maximum insulation value of Rc 2 is first achieved within the cavity and the remaining thermal capacity is assumed to be added to the internal wall. Additionally for the roof, the current insulation is assumed to be added between the roof rafters forming a cold construction. Similarly, the existing insulation layer is added under the floor between the wooden floor joist by default.

In the original report by Nieman *(Cornelisse et al., 2021)* the airtightness is defined in dm3/m2 at a pressure difference of 10 pascals in accordance with the NTA 8800 standards. However, the component defined within the ladybug/grasshopper environment requires the infiltration value to be defined under conditions of 4-pascal pressure difference. Thus the power law equation as shown in Equation 7 and the exponent n in this instance is 0.67 as used most commonly in literature when defining the type of flow *(Thamban, 2020)*. This resulted in the adjusted infiltration input parameter range mentioned in Table 24.

$$Q_{10} = Q_4 * (10/4)\hat{}n$$

Equation 7 - Infiltration power law equation (Gowri et al., 2009)

3.2.2 Ventilation System and Radiator capacity definition

The ventilation systems can be broadly categorised as natural ventilation driven by the window opening percentage with their respective opening schedule and the mechanical ventilation system with their respective set points. Each of these two respective installation systems is formalised as discrete categorical variables.

The natural ventilation system is governed by the window opening percentage as shown in Table 17, Table 20 & Table 21, which is determined based on the subdivision of the mullions on the façade based on elevation images for all the rooms. Furthermore, for each room, the window opening is governed by the minimum outdoor temperature setpoint of 10 C, which is the average annual temperature in the Netherlands *(Centraal Bureau voor de Statistiek, 2023).* In addition to the minimum outdoor temperature a setpoint of 20 C for the minimum indoor temperature is set for the bedroom. This was done to make sure the window opening in the bedroom only occurs during the day and primarily during the summer periods when temperatures are higher as the bedrooms are not occupied as often as the living room. Furthermore, the occupancy profiles are then attached to the ventilation components to define the window opening schedule as prescribed later in this report. Moreover, the mechanical ventilation setpoints are set to 0 when the natural ventilation system is in use in order to prevent both systems from working simultaneously. These settings result in a definition of a suboptimal ventilation profile with the window opening coinciding with heating as would be expected in a natural ventilation system with uncontrolled amounts of ventilation governed by window openings percentage rather than the Bouwbesluit *(Bouwbesluit, 2012)*.

The definition of the various mechanical ventilation systems considered is summarised in Table 25. Each of the ventilation systems is defined using the simple ideal air loads HVAC component and distinguished using the schedule and operational settings like heat recovery. In this instance, the ventilation capacity is defined in accordance with the Bouwbesluit requirements as defined in the table *(Bouwbesluit, 2012)*

Table 25 - Ventilation system definitions

Ventilation type	Discrete category	Ventilation rate	Schedule	Setpoint
Natural ventilation	0	Window opening ratio	occupancy	Min outdoor 10 ℃ (for all zones) **and** Min indoor temperature 20℃ (for bedrooms)
C1 – only mechanical exhaust	1	acc. Bouwbesluit	24 x 7	-
C2 - mechanical exhaust with CO2 sensory (DDV)	2	acc. Bouwbesluit	occupancy	DDV
D2 - balanced ventilation with heat recovery	3	acc. Bouwbesluit	24 x 7	Heat recovery on

Furthermore, the radiator plays an important role in defining if a dwelling is low-temperature ready as its capacity is impacted by the supply temperature and it in turn affects the thermal comfort within a zone. Since the radiator capacity is directly related to the thermal performance of the overall construction and can vary over different construction periods, the ISSO 51 has been used to determine the heat capacity of the radiators based on a heat loss calculation. This is used to define the maximum heating capacity for the ideal air loads HVAC component replicating the sizing limitations of a typical radiator *(ISSO, 2017)*.

Furthermore, the temperature supply changes from a high-temperature supply (90/70 ℃) to a low-temperature supply (55/45 ℃) when the transition to a low-temperature heating district. Therefore, the radiator capacity of the original radiator with the lowered supply temperature can be determined using the following equation:

$$Q_{heat\ emitter} = \left(\frac{\Delta\Theta\ lower\ supply}{\Delta\Theta\ original\ supply}\right)^{n} * \varphi_0$$

Equation 8 - Radiator capacity (Østergaard & Skaarup, 2018)

Moreover, in addition to building constructional refurbishment strategies, the current radiator systems can also be upgraded to a low-temperature efficient radiator that includes dynamically controlled fans and casing that introduces a chimney effect and improves heat transfer through convection. The U low E2 comfort mode- Type 22 radiator by RADSON is used as a reference product and by sampling (Refer to *Appendix 4*) certain radiator sizes and comparing it to a traditional Type 22 radiator by PURMO of similar sizes, an average increase in capacity with a factor of **1.3** was determined. Therefore, the radiator systems can be classified as i) High temperature (base condition), ii) Low-temperature supply and ii) Low-temperature comfort (higher heating capacity) radiator systems.

3.2.3 Occupancy Profile and program setpoints

The occupancy schedule and programmatic setpoints are determined in accordance with the household profiles defined by Guerra-Santin & Silvester (2016). The adult couple, senior couple, nuclear family and single-parent household profiles are selected as the representative profiles most likely to live in single-family dwellings and cover a range of low and highly intensive behaviour profiles.

As mentioned earlier, the behaviour profiles of the different profiles are primarily defined by the temperature setpoints and the use of setback temperatures coinciding with the occupancy schedule for each of the rooms. To efficiently define both the temperature setpoint/setback profile and occupancy profile, a base schedule as shown in Table 26 is defined for each household profile. The numbers from 6 – 18 represent the clusters of hours in a day which can be replaced by the respective temperature setpoints during the day whilst also signalling hours of presence. (Refer to Table 26 - Table 28) Furthermore, 0 (highlighted in light grey) represent hours of absence with the application of the setback temperature in certain instances whilst -1 (highlighted in dark grey) represents the night hours signalling hours of presence for bedrooms and hours of absence for the living room. Refer to Appendix 5 - Appendix 8 for the base schedules and setpoint values for all the household profiles including the nuclear family base schedule in Table 26.

Furthermore, the nuclear family behaviour profile is classified as high intensive behaviour and thus there is no use for setbacks throughout the week *(Guerra-Santin & Silvester, 2016)*. Therefore, unlike the schedules defined Guerra-Santin & Silvester (2016), the nuclear family schedule defined in this study specifically addresses the lack of use of setback temperature by using the same heating schedule on Monday across all the days of the week.

Table 26 - Base schedule nuclear family

Hours	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	-1	-1	-1	-1	-1	-1	-1
1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	-1	-1
3	-1	-1	-1	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	6	6	6	6	6	0	0
7	6	6	6	6	6	0	0
8	6	6	6	6	6	0	0
9	9	9	9	0	0	0	0
10	9	9	9	0	0	0	0
11	9	9	9	0	0	0	0
12	12	12	12	0	0	0	0
13	12	12	12	0	0	0	0
14	12	12	12	0	0	0	0
15	15	15	15	15	0	0	0
16	15	15	15	15	0	0	0
17	15	15	15	15	0	0	0
18	18	18	18	18	18	18	0
19	18	18	18	18	18	18	0
20	18	18	18	18	18	18	0
21	18	18	18	18	18	18	0
22	18	18	18	18	18	18	0
23	-1	-1	-1	-1	-1	-1	-1

Table 27- Nuclear family Heating setpoint values in living room and bedrooms (open)

Hours	Heating setpoint
-1	18
0	none
6	18
9	19
12	19
15	19
18	20

Table 28 - Nuclear family Heating setpoint values in kitchen and bathroom (semi-open)

Hours	Heating setpoint
-1	18
0	none
6	18
9	18
12	18
15	18
18	18

Table 29 - Occupancy setpoints

Room	Value condition	State
bedroom	= -1	Presence
Living room/kitchen	≤ 0	Absence

Additionally, the profiles also need to consider a change of behaviour post refurbishment and can be either classified as a high energy consumption behaviour profile or a low energy consumption profile. The setpoints for the high and low energy consumption behaviour post refurbishment were defined by examining the highest and second lowest setpoints for each hour from the profiles determined by Guerra-Santin & Silvester (2016) which resulted in the profiles in Table 30 & Table 31. The second lowest values are used for the low energy consumption behaviour profile so that the setpoints are still comparable to the suggested setpoint temperatures in EN 15251. These values only impact the setpoints whilst maintaining the same occupancy schedule for each of the household profiles.

Table 30 - High energy consumption profile post refurbishment.

Hours	Heating setpoint living room
-1	20
0	none
6	22
9	23
12	23
15	23
18	24
Other rooms	**Setpoint**
Bedroom radiator use	Open: setpoint same as living room
Kitchen and bathroom	Open : setpoint same as living room with max 22 °C

Table 31 – Low energy consumption profile post refurbishment.

Hours	Heating setpoint living room
-1	15
0	16
6	17
9	18
12	18
15	19
18	20
Other rooms	**Setpoint**
Bedroom radiator use	Closed: Second lowest setpoint 16 °C
Kitchen and bathroom	Closed: Lowest setpoint 15 °C

3.3 Output parameter setup

3.3.1 Hours too cold

As defined in the literature the ATG method for residential dwellings is used to evaluate the thermal comfort within a space. Since there is no native component within the grasshopper environment to assess this specific indicator, a custom component will be developed to calculate this (Peeters et al., 2009). In order to calculate the hours exceeding the 20% PPD three specific inputs are derived from the calculation tool. This includes the i) average daily outdoor temperature which is used to calculate the four-day running mean average over the year, ii) the indoor mean operative temperature assessed within the living room and iii) the occupancy schedule in order to evaluate the number of hours too cold only during hours of occupancy. Using the equation defined by Peeters et al. (2009) the neutral temperature line and 20% PPD upper and lower limits are defined to check for exceedance hours.

3.3.2 Final Input and primary energy

The energy output from the script can be classified into two outputs i) Space heating demand, ii) Final energy input and iii) Primary energy demand. The space heating demand is directly correlated with the refurbishment measures output from the simulation model without any requirement for post-processing. On the other hand, the final energy input and primary energy demand require further inputs to be evaluated accurately.

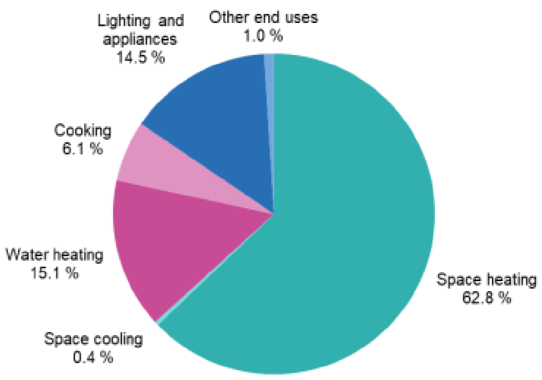


Figure 21 - Household energy consumption distribution (Eurostat, 2022)

The final input energy consumption is defined as the energy that is consumed by the end-user that reflects on their energy bill (Eurostat, 2021). This will impact the operational energy use within the lifecycle cost assessment. As shown in Figure 21 space heating demand, lighting, and water heating account for nearly 77% of the final energy consumption of households. Therefore, in order to determine a representative value for the final input energy consumption whilst simplifying the post-processing step, these three subcategories of energy consumption are considered to represent the majority of the consumption. It must be noted that the lighting and water heating consumption in this study has been set to the default inputs from the simulation model that are based on the default honeybee library that is set in accordance with the ASHRAE norms (Ghobad, 2018).

In order to determine the final input energy from the energy demand, the energy demand is divided by the respective coefficient of performance (COP) for the building services systems which is a simplification of the method defined by the NTA8800 (Stichting Koninklijk Nederlands Normalisatie Instituut, 2022). This however provides a viable indication of the final input energy. Natural gas boilers account for nearly 89% of Dutch heating systems (Ende, 2017). Additionally, heat pump systems are on the rise accounting for 2.3% of heating systems in 2017. The COP values for the different systems are illustrated in Table 32. Furthermore, the COP used in district heating systems is determined based on the heat exchangers used to distribute the heat from the network to the individual dwellings. Additionally, COP values for heat pumps can vary considerably but, in this study, the average COP determined by NTA8800 was considered.

Table 32 - Building services COPs

Heating system	COP	
Gas boiler	0.85	1
Heat pumps	2.8	2
District heating (heat exchangers)	0.9	3
1) *(Ünlü, 2019)* 2) *(Stichting Koninklijk Nederlands Normalisatie Instituut, 2022)* 3) *(Ipieca, 2022)*		

Table 33 – Primary energy factors

Energy carrier	Primary energy factor
Natural gas	1.0
Electricity	1.45
District heating	0.9

Additionally, the primary energy demand covers the energy demand includes the final energy consumption of the users and also includes the energy consumed by the grid through transformation and distribution losses (Eurostat, 2021). The primary energy demand is used to evaluate the energy label of a dwelling in accordance with ISSO 51 standard which is another indicator that will be addressed within this study. To be able to derive the primary energy demand from the final input energy, it needs to be multiplied by the primary energy factor in accordance with the NTA8800 shown in Table 33 and this is a simplification of the method defined by the NTA8800 *(Stichting Koninklijk Nederlands Normalisatie Instituut, 2022)*.

3.4 Simulation workflow and validation

The input and output parameter setup in the previous chapter was then translated into the parametric simulation model. This model was validated by running a sensitivity check to understand if the change in parameters correspondents to a reasonable variation in the output values. Additionally, the local sensitivity check helps evaluate the significance of certain parameters to reduce the total number of parameters required to train the surrogate model. This model will then be used to generate the underlying data to train the surrogate model that will be incorporated into the decision-making tool.

3.4.1 Grasshopper script workflow

The computational workflow chosen for this specific study involves the use of a grasshopper. This has been chosen specifically to develop a parametric workflow that can be varied in order to be able to evaluate multiple existing dwelling states and generate multiple refurbishment measures for each as shown in Figure 22. The parametric workflow enabled the quick adjustment of the various components of the envelope using a slider which made it easy to assess multiple dwelling setups with minimum effort. Additionally, the simulation requires a dynamic, pre-calculation of the radiator capacity based on the construction thermal performance and hence construction year of the dwelling to determine the impact on thermal comfort before running the energy model. Thus, the grasshopper workflow helped formulate a custom gh python component to dynamically calculate the capacity based on the ISSO 51 standard within the energy simulation. Additionally, the evaluation of thermal comfort assessment requires the ATC method developed by Peters et al *(2009)* and thus the gh python was used to incorporate this evaluation method into the parametric workflow in order to determine the number of hours too cold accurately for each iteration. Therefore, the grasshopper parametric workflow enabled the flexible adjustment of input parameters with the ability to customise both the input and output parameters to match the required workflow.

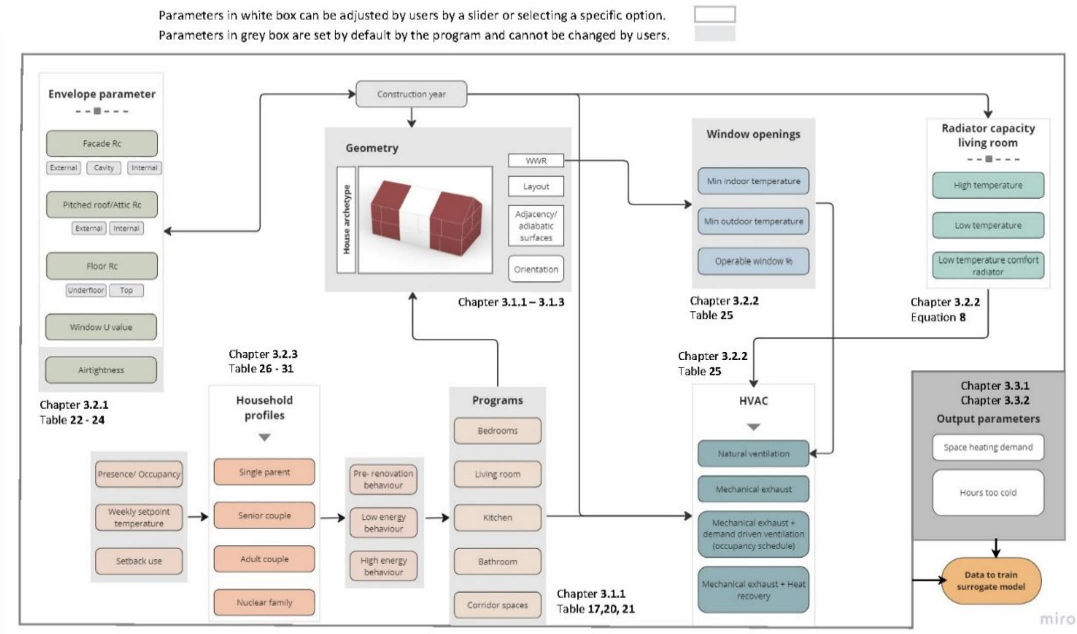


Figure 22 - Parametric building simulation model workflow

Furthermore, as shown in the script workflow Figure 22 the input parameters highlighted in white can be by the user whilst the parameters highlighted in grey are set by default in the script and cannot be adjusted directly by the user. Moreover, since the housing typologies vary by both construction year and housing type, the simulation model would need to be replicated for other housing typologies like semi-detached, detached etc. The parametric grasshopper setup facilitates by simply recreating the base geometry of the various housing typologies and referencing the closed brep zones to the respective honey 'room from solid components for each of the distinctive programs within a dwelling. Once this is done, the corresponding input parameters in relation to ventilation, radiator capacity, occupancy profiles (setpoints) etc. are assigned automatically. Refer to see a pseudo script of the grasshopper simulation in

3.4.2 Simulation validation

In order to validate the outputs of the results, the space heating energy demand was compared to space heat demands determined by Nieman *(Cornelisse et al., 2021)*. This helps to evaluate if the assumptions and step sizes chosen can still accurately evaluate the various dwelling variations. The report acknowledges that the results can vary due to variations in indoor setpoints, behaviour differences and ventilation systems. Therefore, the occupancy schedule and thermal setpoints are set in accordance with the NEN 16798. As shown in Figure 23 the results from the simulation model are comparable with a normalised root mean squared error of 20%.

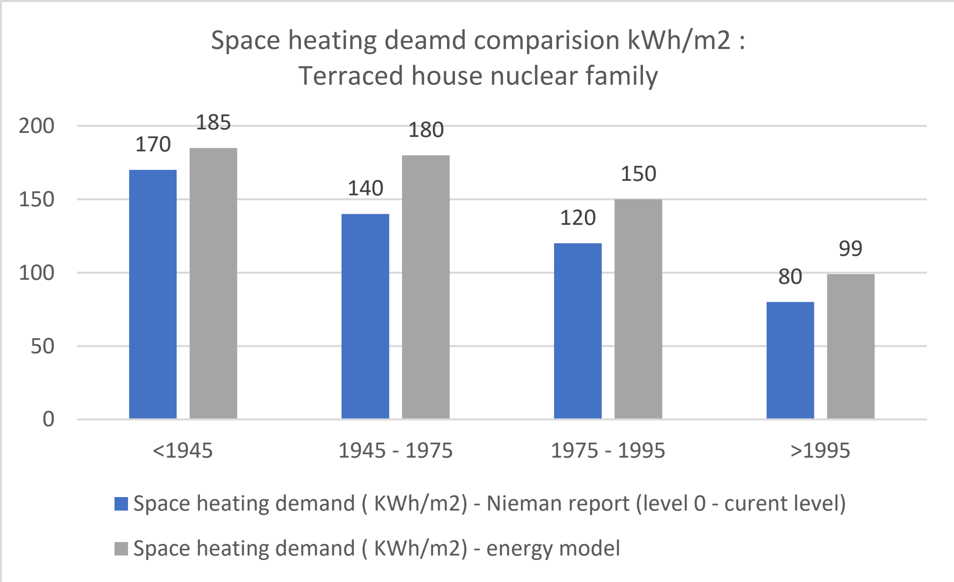


Figure 23 - Terraced house space heating demand comparison

3.4.3 Simulation model sensitivity analysis

The next step of the validation process involved conducting a local sensitivity analysis to understand if the behaviour of the simulation model is in line with what would be expected compared to previous literature. Additionally, the sensitivity analysis would give a better understanding of the effectiveness of the individual parameters and the ones that can be removed from the model training data.

The terraced house built before 1945 and occupied by a nuclear family was chosen as the base case to conduct the sensitivity analysis as shown in Table 34. The space heating demand derived was 195.2 kWh and the number of hours too cold was 2477. To conduct the sensitivity analysis, the parameters are varied by twice the step size for the individual parameters in both the positive and negative direction where applicable. The results are shown in Figure 24.

Table 34 - Sensitivity analysis base case

Orientation	Household profile	Façade Rc value	Roof Rc value	Floor Rc value	Glazing U value	Ventilation system	Airtightness dm3/s/m2	Radiator type
0	Nuclear family	0.74	1.2	0.6	3	Natural Ventilation	3	HT (original)

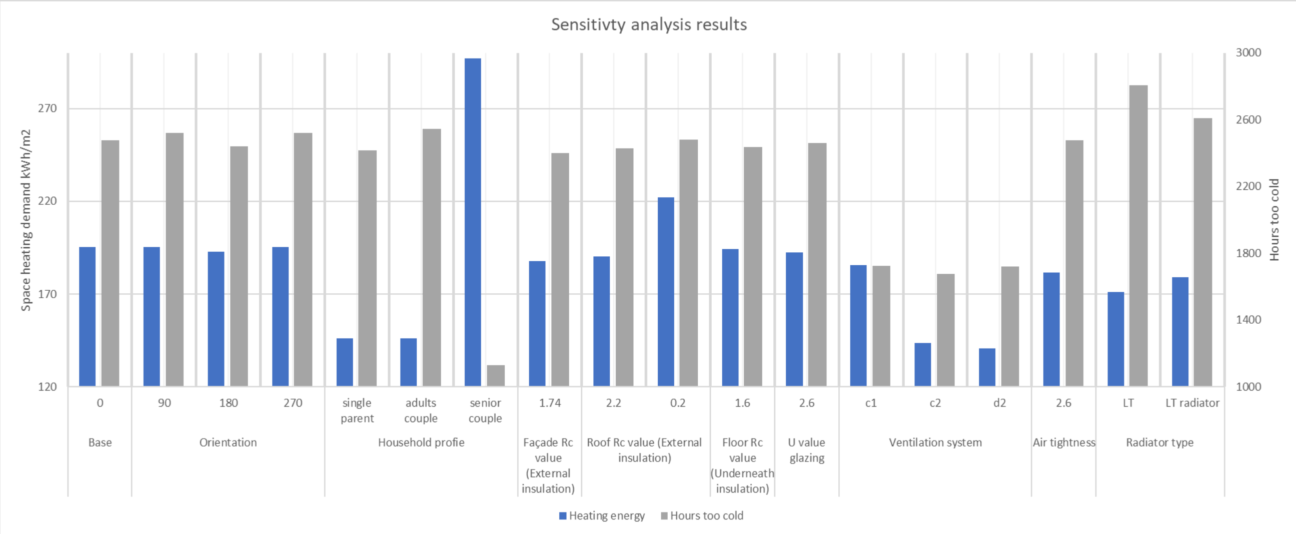


Figure 24 - Sensitivity analysis results of input parameters

To gain a better understanding of the sensitivity of the input parameters, at first glance the parameters are divided into parameters with larger sensitivity and those with lower sensitivity. As shown in Figure 25 the parameters with lower relative variation are the envelope parameters and orientation of the dwelling. The reduction of the roof Rc value has the most drastic impact on energy demand with minimal variation in hours too cold. Furthermore, the façade Rc value and glazing U value have a larger impact on overall comfort which can be attributed to the fact that vertical adjacent surface temperatures to the living room impact the operative temperature and hence the overall thermal comfort within the space. Additionally, the southern orientation seems to have a higher impact on heating demand reduction as more of the dwelling program benefit from the southern daylight exposure. On the other hand, there is no difference in both comfort and heating demand between the east, and west orientations as would be expected and thus one of the two orientations can be removed. from the simulation model.

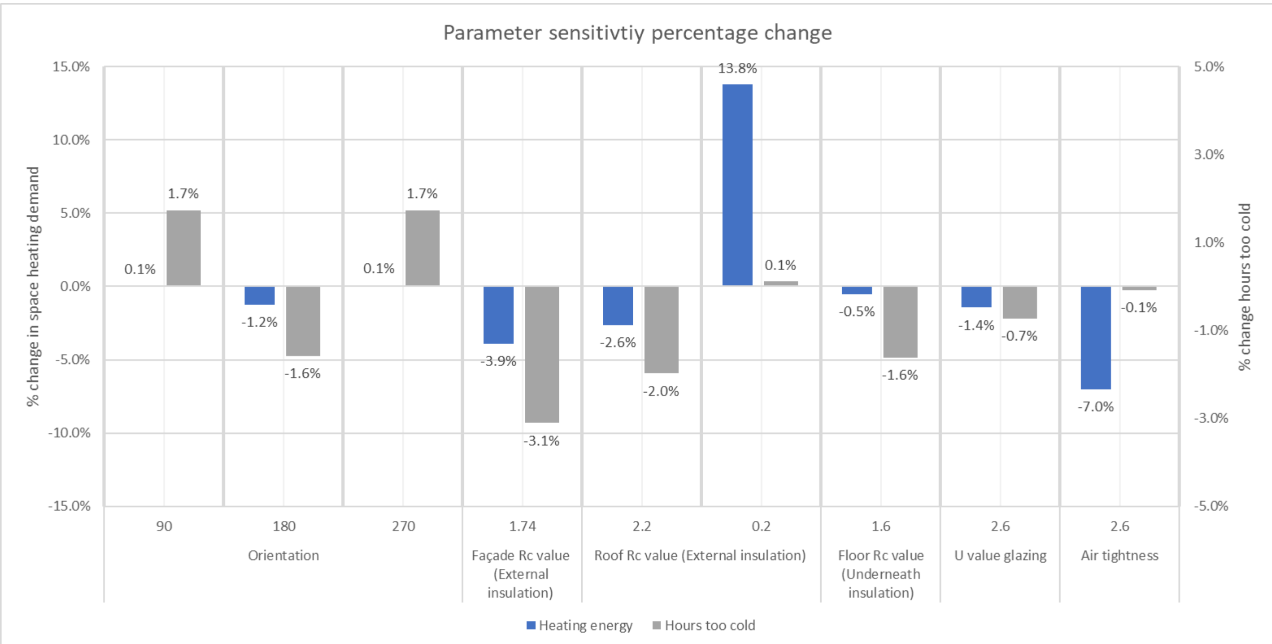


Figure 25 - Low sensitivity parameters percentage change

The next set of input parameters grouped are the household profiles and installations interventions within a dwelling and these parameters have a comparably higher sensitivity as shown in Figure 26. This is because the setpoints within the household profile and the installations are expected to have a larger impact on both the energy performance and thermal comfort within a space as they involve drastic changes that directly influence the heating demand and heat loss of space. As suggested by Guerra et al *(2018)* the single-parent and adult couple household profiles have a considerable reduction in energy consumption whilst increasing the number of hours too cold due to the reduced setpoint temperatures. However, both profiles seem to behave relatively similarly and thus one of the households can be removed from the simulation model. On the other hand, the senior household couple drastically increases its energy consumption due to the increased setpoint temperatures in the room with an increased presence at home. Furthermore, the transition to the mechanical ventilation system also considerably reduces the heating demand and improves thermal comfort as would be anticipated due to minimised heat loss to the outside air entering the space. The CO2 demand-controlled ventilation system and heat recovery system are comparable in performance. Additionally, the change to a low-temperature supply (LT) radiator results in a reduction in energy consumption whilst increasing the number of hours too cold which correlates with the reduced heating capacity of the radiator. Overall, the input parameters behave as expected with reasonable sensitivity and thus it can be concluded that the simulation model is valid.

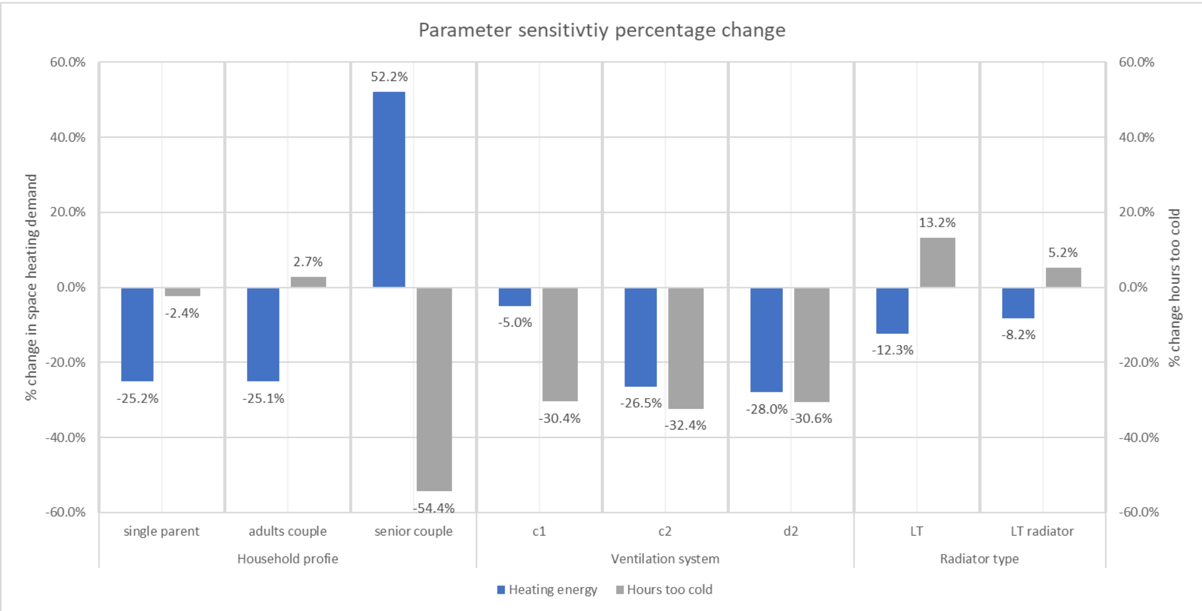


Figure 26- High sensitivity parameters percentage change

Furthermore, a sensitivity analysis of the post-refurbishment occupancy behaviour for each of the household profiles is conducted including high and low energy consumption behaviour. This was done to understand if the post-refurbishment, high and low energy consumption behaviour varies significantly between the various household profiles to reduce the number of input parameters. As shown in Figure 27 the high and low energy consumption behaviours for each household profile are comparable to each other and therefore the occupancy schedule does not have as much of an impact as the setpoint does on the space heating demand and the number of hours too cold. The results in Table 35 suggest that the nuclear family's high and low behaviour profile is the closest to the average profile of both high and low behaviour profiles across the household profiles. Therefore, it can be used as a representative profile to assess the impact of occupancy behaviour changes post-refurbishment whilst significantly reducing the total number of occupancy profiles to be evaluated in the simulation model.

Table 35 - Average high and low energy consumption behaviour profiles compared to that of nuclear family

Performance indicators	Average high energy consumption behaviour	Average low energy consumption behaviour	Nuclear family high energy consumption behaviour	Nuclear family low energy consumption behaviour
Space heating demand kWh/m2	359	136	360	139
Hours too cold	957	2736	972	2705

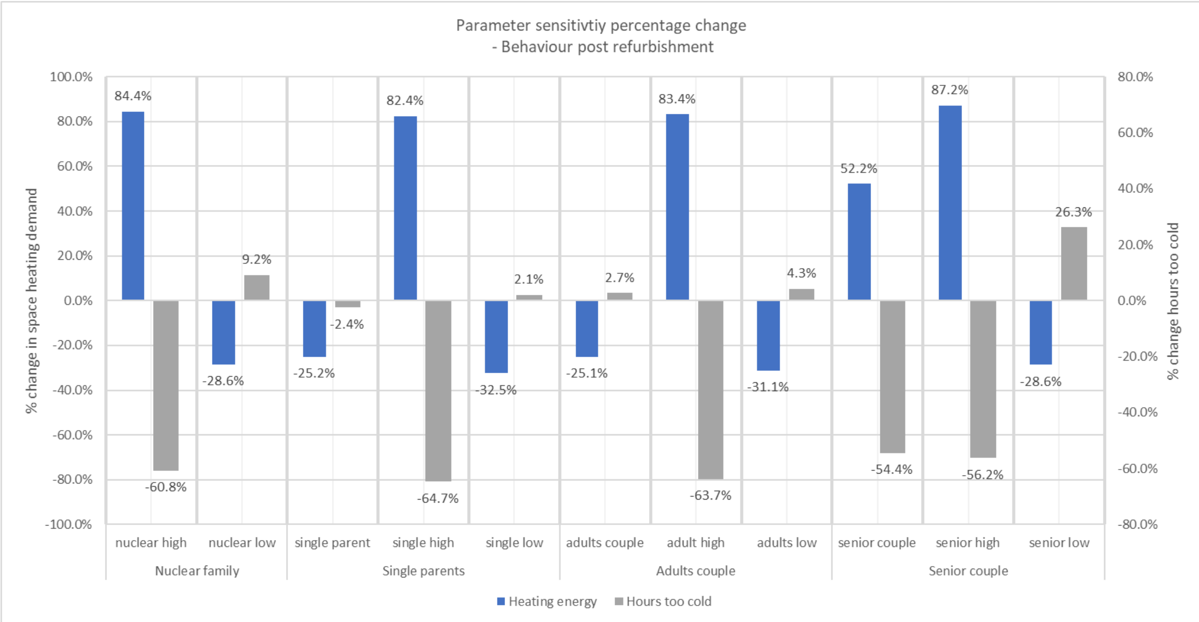


Figure 27 - High and low energy consumption behaviour sensitivity percentage change

4. Development of surrogate model and integration with LCC analysis

The next stage in this study involves the use of the validated simulation model to collect data in order to train a surrogate model. This model was specifically used to approximate the performance of the building energy model and generate the two dynamic outputs including space heating demand and the number of hours too cold. Once the model was trained for three housing typologies including terraced dwellings, detached dwellings and Portiek apartments the model was integrated into a multi-objective optimization workflow. Along with the surrogate model, the workflow includes a database of the refurbishment measures established previously in the literature study and a mathematical function to calculate the global life cycle cost of the combination of measures. This will result in a complete multi-objective optimization workflow that can be used to determine a Pareto front set of combined refurbishment measures.

4.1 Surrogate model

4.1.1 ModeFRONTIER platform setup and data sampling

The grasshopper simulation model was connected to Modefrontier using the "grasshopper node" as shown in Figure 29. A set of 13 input parameters were introspected within the platform and the bounds and steps of the input's parameters are set in accordance with the conditions with definitions defined in Table 24 of the previous section.

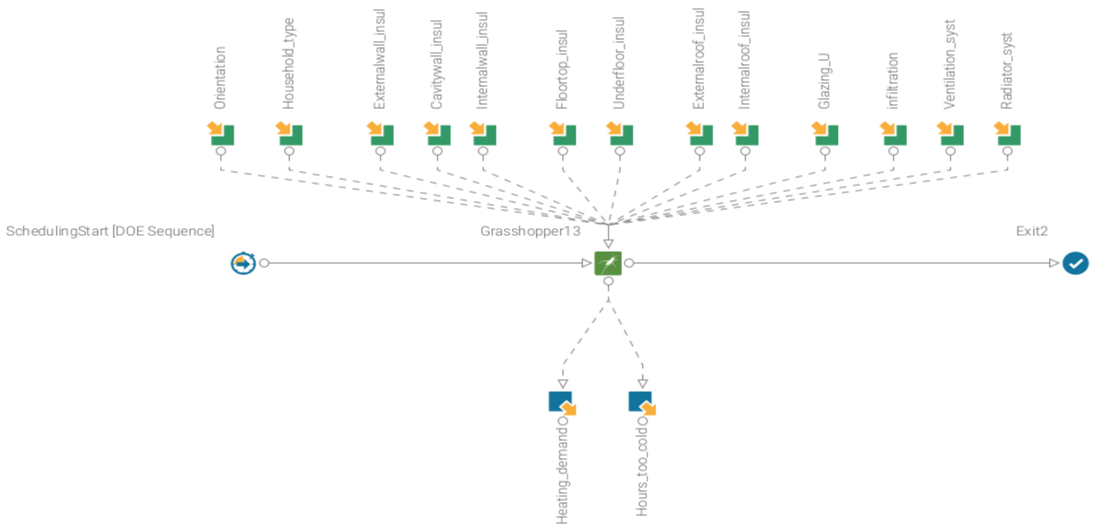


Figure 29 - modefrontier workflow and input-output parameter overview

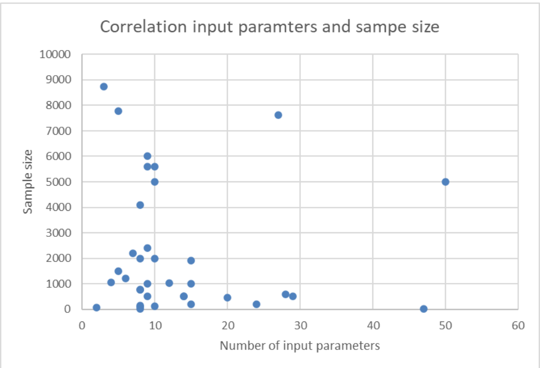


Figure 28 - correlation inputs to sample size

The SchedulingStart node helps define the design of experiments using the uniform Latin hypercube sampling method. The uniform Latin hypercube sampling method is a specific application of the Latin hypercube sampling method wherein solutions are uniformly distributed amongst the design space. Additionally, the sampling method reduces the correlations between input variables and is not limited to continuous input variables as is the case with classic Latin hypercube sampling methods (ESTECO).

To determine the number of adequate samples, the review of the use of surrogate models of building performance analysis by Westermann *(Westermann & Evins, 2019)* is used to plot the correlation between the number of input parameters and the sample size used in the various study as shown in Figure 28. Considering 13 input parameters are used within this study, a sample size of 2000 was determined. Once the samples are generated, the outputs are generated by running the simulations on a parallel network of computer nodes that distribute the simulations by facilitating concurrent simulations, thereby reducing overall run time to roughly 20 hours per housing archetype.

In order to facilitate the training of the surrogate model including the categorical variables like household type, ventilation system and radiator system type, the data collected was one hot encoded. During this process, each unique categorical variable is assigned a separate column and therefore represented as binary vectors. To avoid the problem of multi-collinearity where independent variables can be predicted by other independent variables, one of the 'dummy variables' were removed randomly from the dataset *(Luna, 2021)*

4.1.2. Model training and evaluation

Once the data was pre-processed, the data was split by using 5% of the data for validation and the rest to train the data (100 samples). Based on the literature study, four algorithms were selected based primarily selecting nonparametric algorithms in order to effectively model (refer to the behaviour of non-linear building performance without needing to define parameters prior based on assumptions *(Westermann & Evins, 2019)*

Table 36 – Terraced house Model training algorithm validation results heating demand.

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	2.93	0.951
Kriging	2.14	0.976
Gaussian Process	1.15	0.991
Neural network	1.10	0.991

Table 37 – Terraced house Model training algorithm validation results hours too cold

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	4.32	0.957
Kriging	3.65	0.970
Gaussian Process	2.01	0.986
Neural network	2.02	0.991

Table 38 – Detached house Model training algorithm validation results heating demand.

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	2.97	0.973
Kriging	1.74	0.992
Gaussian Process	1.53	0.993
Neural network	1.56	0.994

Table 39 – Detached house Model training algorithm validation results hours too cold

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	5.34	0.953
Kriging	3.84	0.972
Gaussian Process	3.43	0.977
Neural network	3.12	0.978

Table 40 - Portiek apartment Model training algorithm validation results heating demand.

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	2.80	0.928
Kriging	0.53	0.998
Gaussian Process	0.25	0.999
Neural network	0.25	0.999

Table 41 - Portiek apartment Model training algorithm validation results hours too cold.

Training algorithm	Normalised mean squared error %	R^2
Stepwise regression	3.62	0.977
Kriging	1.27	0.007
Gaussian Process	0.82	0.999
Neural network	0.62	0.999

The validation results shown in Table 36 - Table 41 suggest that the neural network model with 46 hidden neuron layers for the terraced house model and 52 hidden neuron layers for the detached house, approximates the behaviour of the real data to a high degree based on the R^2 value for both output variables and therefore this was selected as the surrogate models to use in the optimization workflow further.

4.2 Generating Pareto set solutions.

4.2.1 Elaboration of the LCC Analysis

Before determining the Pareto set of measures, the life cycle cost for the combination of refurbishment measures, the replacement cost and maintenance costs need to be further defined. In addition to Equations 2- 6 in the literature review, Equations 7 – 9 define the additional life cycle costs. The replacement cost depends on the life expectancy for the refurbishment measures. For this study, the existing construction, and envelope insulation measures have a life expectancy that is comparable to that of the building lifespan and therefore exceeds the calculation period of 30 years used in this study. Therefore, the lifespan of the components relevant includes the glazing, ventilation system, radiator system and combi boiler as shown in Table 40. Although the combi boiler is not explicitly a refurbishment measure in this study, it is considered a base condition that is required to heat domestic hot water in order to mitigate the risk of legionella *(Toffanin et al., 2021)* whilst also delivering space heating originally. In order to calculate the replacement cost for the combi boiler system, the CW4 boiler is considered a representative unit with a cost of € 1,500 *(Homedeal, 2023)*. Additionally, the maintenance rate is 2.75% and is a percentage of the investment cost specifically for the generation and distribution systems which include the radiators, ventilation system and boiler *(NEN-EN 15459, 2007)*. Furthermore, in order to establish a comparative base condition to compare the global cost of the refurbished condition, the study assumes the operating cost as a proxy for the global cost.

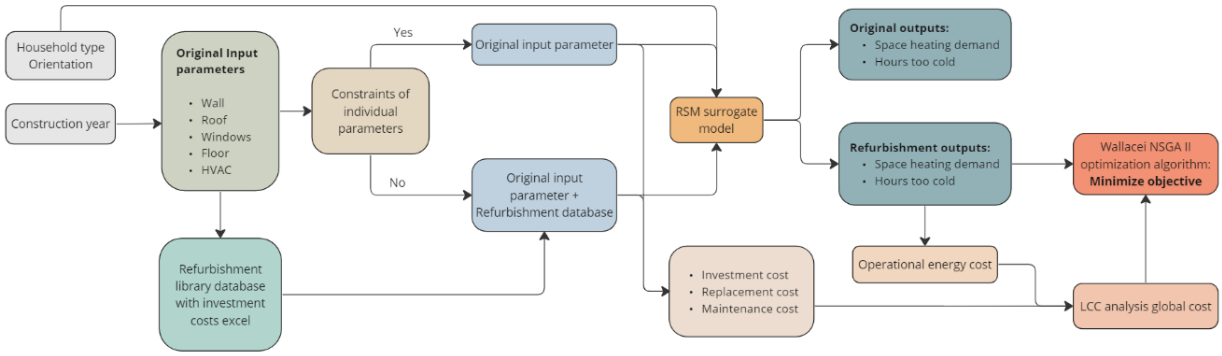
$\boldsymbol{MC = IC \cdot R_{MC}}$	$\boldsymbol{RC_j = IC \cdot R_d}$	$\boldsymbol{R_d(p) = \left(\frac{1}{1 + R_R/100}\right)^p}$
Equation 9 – Maintenance cost	*Equation 10 – Replacement cost*	*Equation 11 – Discount rate*
$\boldsymbol{R_{MC}}$ = Maintenance rate IC = investment cost	R_d= Discount rate	R_R= real interest rate

Table 42 - Building component lifespans

Building component	Life expectancy
Glazing	30
Ventilation system	20
Radiator system	15
Combi boiler	15

4.2.2 Optimization workflow

Once the surrogate model and life cycle assessment framework was established, the components are formalised into an optimization workflow so that the surrogate model and lifecycle assessment can be utilised in a flexible manner and parametrically.



Firstly, the construction year establishes a pre-set definition of the input parameters including the building envelope and installation setup. These parameters can be customised and are then appended to the refurbishment database to establish a base configuration that can be part of possible refurbishment solutions at no additional cost. Furthermore, if certain parameters are constrained due to restricted access or space for example, then the refurbishment measure for that parameter is limited to the original value. Then the refurbishment measures are combined with base conditions inputs like the selected orientation and occupancy behaviour profile to determine the building's physical performance output parameters. Additionally, the formalised refurbishment measures are then used to calculate the investment, replacement and maintenance costs and then combined with the operational energy cost to determine the global cost. Finally, the input parameters are combined with output parameters at the Wallacei X NSGA II multi-objective optimizer to generate the pareto front solutions.

Phase 3: Use of tool and validation of results

5) How can the decision-making tool prescribe categorised LT – ready refurbishment strategies to facilitate the decision-making process in an accessible manner?

5. Practical use of the tool

The next phase involves the use of the surrogate model in the optimization workflow to generate Pareto front solutions for different scenarios and then the filtering of the Pareto optimal solutions into specific categories that can facilitate the decision-making process. This process will help understand the strengths of the practical use of surrogate models whilst highlighting potential limitations in this context. The section first establishes the respective scenarios that will be evaluated and their base input and output parameters. Then the solution space is examined by clustering the solutions by category to outline general trends for each category. This is subsequently followed by comparing the solutions by scenario. Additionally, the impact of varying occupancy behaviour on the performance indicators is determined by a selected set of refurbishment measures. The section concludes with a proposal of a user interface tool that can be translated into a web-based application further to demonstrate the potential of integrating the surrogate model-based decision-making tool in a user-friendly manner, that can improve accessibility for the decision-makers.

5.1 Refurbishment solutions

5.1.1 Base Cases, categories, and Scenarios

The practical application of the workflow was examined across specific scenarios summarised in Figure 31. These scenarios include a combination of housing archetypes, construction years and building limitations. The study acknowledges that these do not cover the entire breadth of possible scenarios, however, these selected scenarios can provide an initial understanding of the performance of the surrogate model. Furthermore, based on the literature conducted earlier, the scenarios also examined constraints on the refurbishment measures that can potentially be foreseen.

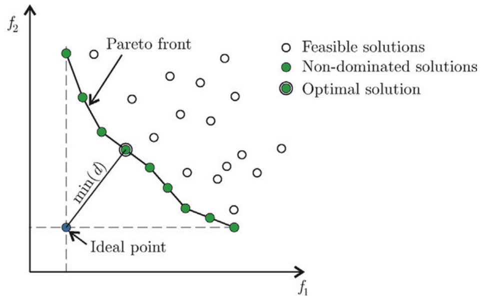


Figure 30 - Schema of Pareto front (Bre & Fachinotti, 2017)

Once the Pareto optimal solutions are determined for each of the scenarios, 4 categories are used to further narrow the solutions. The categories are defined based on the three main performance indicators and optimization objectives including space heating demand, hours too cold and global cost. In addition to these indicators, the lowest investment cost is a component of the global cost indicator, and this sub-data is used as a criterion for decision-making. Additionally, the best-performing solution considers the best possible combination of refurbishment measures based on the evaluation of all three performance indicators equally. To determine the best-performing solution, the distance between the origin point is compared to each of the Pareto optimal solutions and the minimum distance solution is selected as shown in Figure 30.

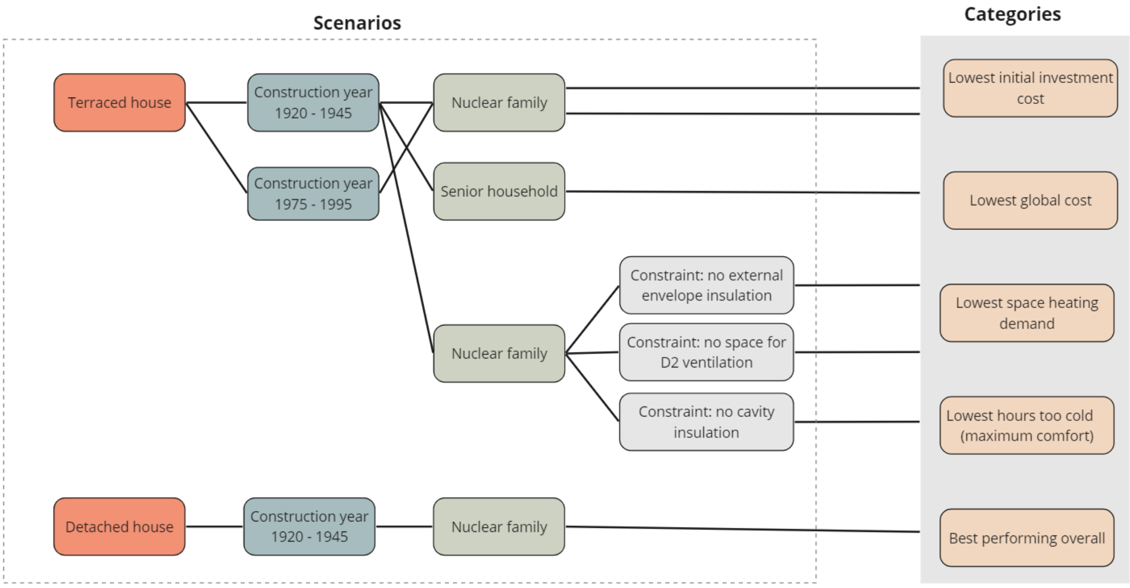


Figure 31 - Evaluation scenarios and categories

Table 43 - Base case of scenarios

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & Comfort		Global cost
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	GC
Terraced house - 1920 – 1945 Nuclear family	0	0	0	1	0	0.5	0	3	0.0016	0	0	187	2447	149202
Terraced house: 1975-1995 Nuclear family	0	1	0	1.5	0	1	0	2.8	0.0016	1	0	175	1301	143334
Terraced house: 1920 – 1945 Senior couple	0	0	0	1	0	0.5	0	3	0.0016	0	0	297	1300	206532
Detached house. 1920-1945 Nuclear family	0	0	0	1	0	0.5	0	3	0.0016	0	0	299	2474	295427
Portiek apartment 1920 – 1945 Nuclear family	0	0	0	-	-	-	-	3	0.0010	0	0	165	1937	120041

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

Table 44 – No regret space heating targets (Cornelisse et al., 2021)

	Compactness ratio	Nieman target space heating kWh/m2
Terraced house - 1920 – 1945 Nuclear family	1.4	≤ 102
Terraced house: 1975-1995 Nuclear family	1.4	≤ 59
Detached house. 1920-1945 Nuclear family	2.2	≤ 186
Portiek apartment 1920 – 1945 Nuclear family	0.5	≤ 45

As shown in Figure 42, the base conditions of the base scenarios are established including the space heating demand and hours too cold as determined by the trained model. Additionally, the table also includes the global cost that is calculated primarily based on the final input energy consumption of the base condition. These values form the base conditions from which the refurbishment measures will be compared. Furthermore, as defined earlier in the literature, the refurbishment measures need to result in energy demands that are lower than those defined for each of the respective scenarios as shown in Table 42 and the number of hours too cold would need to be lower than the base scenario in order to be classified as no regret low-temperature ready refurbishment measures when the dwelling transitions to low-temperature district heating.

5.1.2 Evaluation of Pareto front solutions by Category

The first stage of evaluating the Pareto front solutions is clustered by the four categories to establish general trends that occur within the optimised Pareto front solutions.

Lowest investment cost

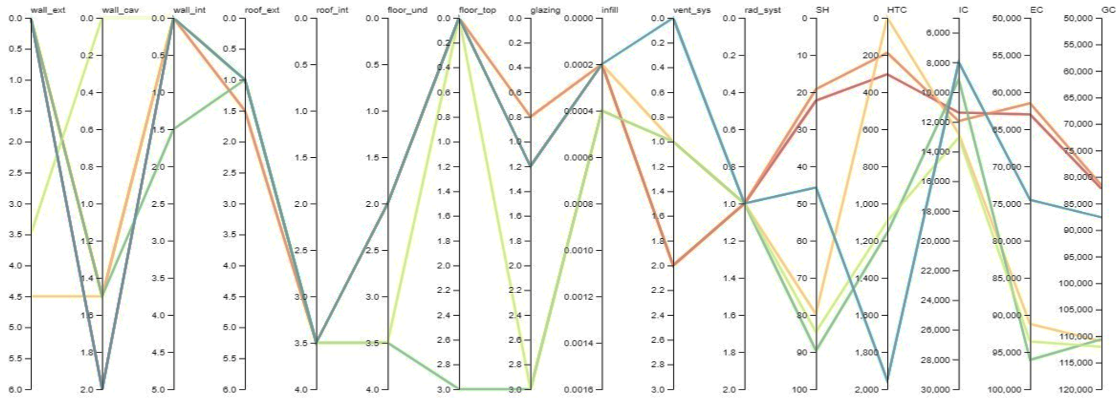


Figure 32 - Parallel cordinates plot - lowest investment cost

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
1920 - 1945	0	2	0	1	3.5	2	0	1.2	0.0002	2	1	22.3	304	11376	63022	82219
1975-1995	0	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	19.2	188	11945	61508	81571
Senior	4.5	1.5	0	1	3.5	2	0	1.2	0.0002	1	1	79.8	0	12796	91225	110974
no cavity insulation	3.5	0	0	1	3.5	3.5	0	3	0.0004	1	1	84.6	1094	13046	93579	112017
no external façade and roof insulation	0	1.5	1.5	1	3.5	3.5	3	3	0.0004	1	1	89.6	1156	9147	96055	110595
no space for D2 Ventilation	0	2	0	1	3.5	2	0	1.2	0.0002	0	1	45.7	1953	7991	74514	87606

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

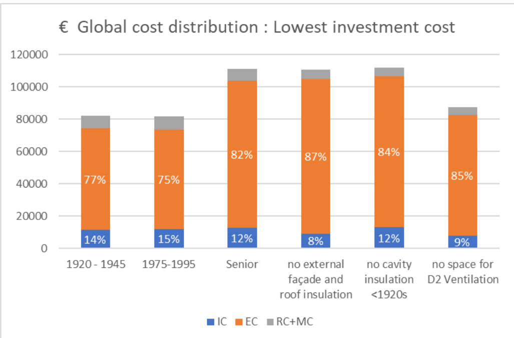


Figure 33 - percentage share % investment cost and energy cost fow lowest investment cost measures

The result of Figure 32 shows that external wall insulation is used in limited instances which is due to the higher per-unit cost of installing external wall insulation. Furthermore, cavity wall insulation is the primary measure of insulating the façade envelope due to its cost-effectiveness and there is no additional requirement for internal wall insulation. Furthermore, the roof includes a high degree of insulation of Rc 3.5 and underfloor insulation is mostly upgraded to 2 RC. Glazing can either be left at the original level or upgraded one step further to HR++ glazing. Additionally, maintaining the existing natural ventilation system or upgrading to a C1 ventilation system is a common measure. Similarly, the original radiator is kept when switching to low-temperature heating. Additionally, infiltration is reduced to the minimum level as it can be seen as a cost-effective and highly impactful measure as seen in the previous sensitivity analysis. These measures result in 20 – 90 kWh/m2 in energy space heating demand, which contributes to a relatively higher global cost of € 85,000 to € 115,000. Furthermore, the hours too cold range can exceed 1000 hours but is still lower than the base condition and therefore can still be considered low temperature ready. The investment cost is within the range of € 8,000 to € 14,000. As shown in Figure 33, the initial investment cost and energy costs account for an average of 12% and 82 % of global cost respectively.

Lowest global cost

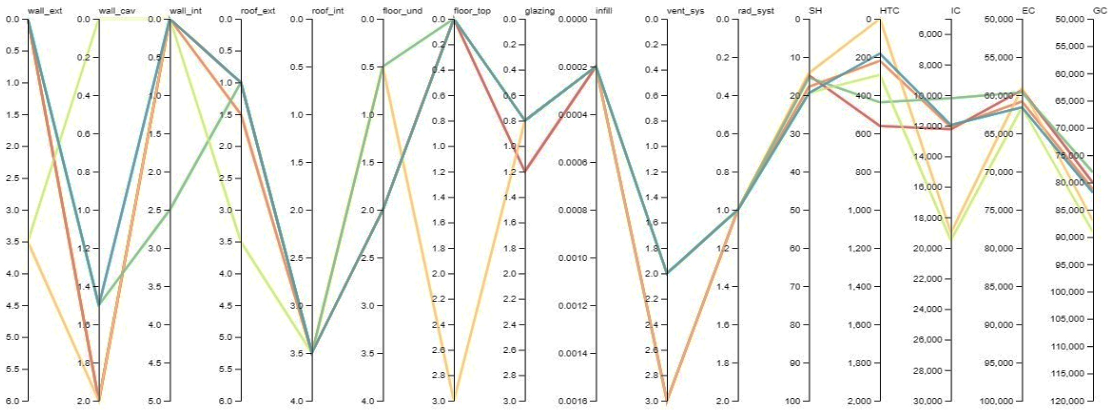


Figure 34 - Parallel cordinates plot - lowest global cost

	Wall Rc m²·K/W			**Roof Rc** m²·K/W		**Floor Rc** m²·K/W		**W/ m²K**	**m3/s-m2**	**Installations**		**Energy & comfort**		**Investment, energy, global cost €**		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
1920 - 1945	0	2	0	1	3.5	2	0	1.2	0.0002	3	1	14.8	561	12225	59341	80069
1975-1995	0	2	0	1.5	3.5	2	0	0.8	0.0002	2	1	17.8	220	12074	60838	81210
Senior	3.5	2	0	1	3.5	0.5	3	0.8	0.0002	3	1	14.2	0	19003	59056	87039
no cavity insulation	3.5	0	0	3.5	3.5	2	0	0.8	0.0002	2	1	19.4	293	19494	61596	89089
no external façade and roof insulation	0	1.5	2.5	1	3.5	0.5	0	0.8	0.0002	2	1	15.4	438	10204	59633	78135
no space for D2 Ventilation	0	1.5	0	1	3.5	2	0	0.8	0.0002	2	1	19.4	182	11945	61594	81837

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

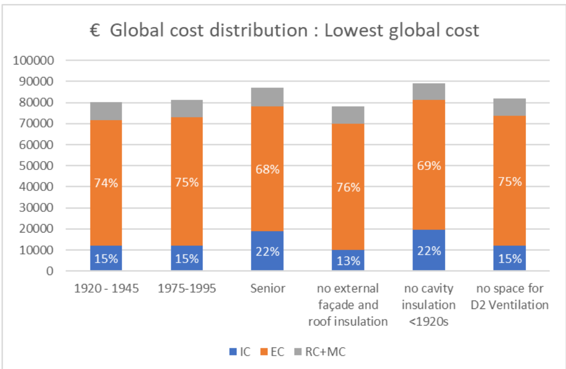
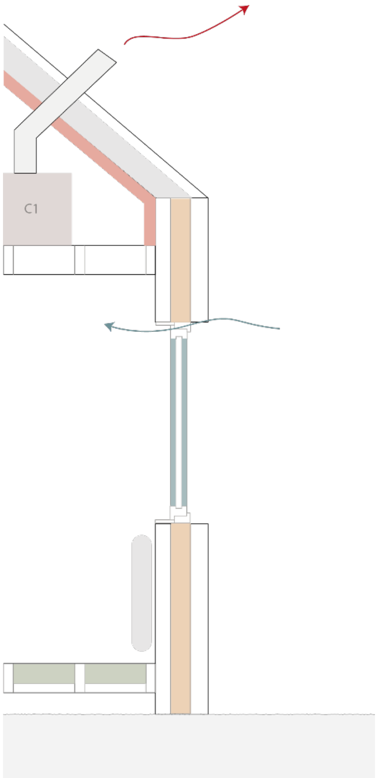


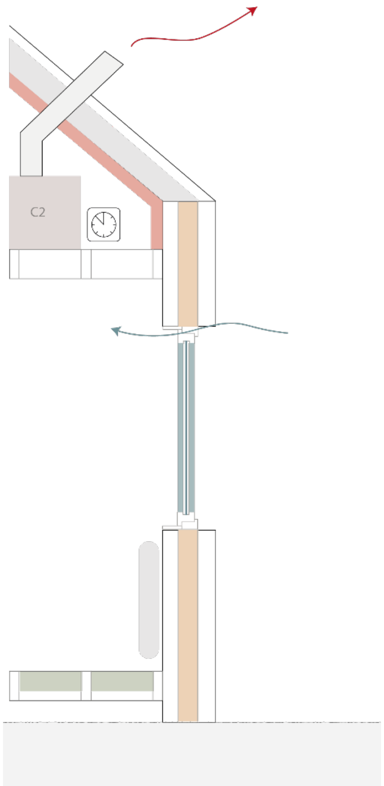
Figure 35 - percentage share % investment cost and energy cost for lowest global cost measure

Compared to the lowest investment cost measures, the individual wall insulation layers are comparable. Additionally, there is a clear requirement for the most thermally efficient triple glazing with a U value of 0.8. Moreover, infiltration levels are maintained at the lowest level. Furthermore, the ventilation system is preferably upgraded to type C2 with mechanical exhaust ventilation in combination with CO2-controlled ventilation or D2 balanced ventilation system for better energy performance. The overall space heating demand of the measures falls within 15 – 20 kWh/m2 and the hours to cold remain below 600 hours. The lower energy demand results in an overall lower global cost range between € 75,000 to € 85,000 compared to that of the lowest investment cost solutions and as shown in Figure 35 the investment cost and energy cost accounts for roughly 18% and 72% respectively of global cost.



Lowest investment cost

- Foam beads cavity wall insulation 50mm
- Internal roof 74mm PIR insulation : Rc 3.5
- Underfloor joist 70mm Mineral wool insulation: Rc 2
- HR ++ glazing U value 1.2
- Airtightness 0.2 dm³/s m², Apply chink seals to window openings and closed façade parts
- Type C1 ventilation
- Original Radiator at low temperature supply.



Lowest global cost

- Foam beads cavity wall insulation 50mm
- Internal roof 74mm PIR insulation : Rc 3.5
- Underfloor joist 70mm Mineral wool insulation: Rc 2
- Tripple glazing U value 0.8
- Airtightness 0.2 dm³/s m², Apply chink seals to window openings and closed façade parts
- Type C2 ventilation
- Original Radiator at low temperature supply.

Figure 36 - Representative refurbishment measures for lowest investment cost and lowest global cost categories.

The figures shown above demonstrate a possible materialization of refurbishment measures as possible best practices to achieve each of the respective categorical objectives based on the analysis of the parallel coordinate chart.

Lowest space heating demand

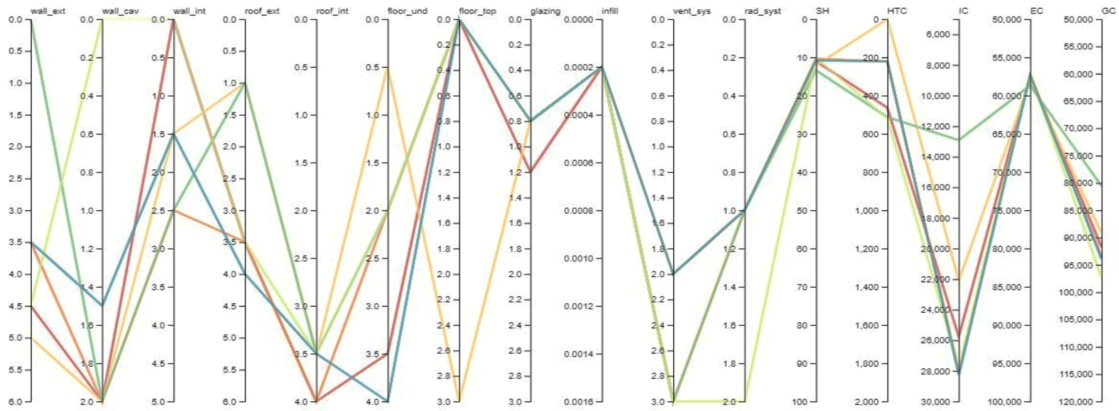


Figure 37 - Parallel cordinates plot - lowest space heating demand

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
1920 - 1945	4.5	2	0	3.5	4	3.5	0	1.2	0.0002	3	1	11.0	464	25752	57482	91738
1975-1995	3.5	2	2.5	3.5	4	2	0	0.8	0.0002	2	1	10.4	223	28068	57182	93548
Senior	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179
no cavity insulation	4.5	0	0	3.5	3.5	2	0	0.8	0.0002	3	2	10.2	519	27766	57289	97333
no external façade and roof insulation	0	2	2.5	1	3.5	2	0	0.8	0.0002	3	1	13.4	513	12923	58686	80589
no space for D2 Ventilation	3.5	1.5	1.5	4	3.5	4	0	0.8	0.0002	2	1	10.8	222	28251	57369	93918

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

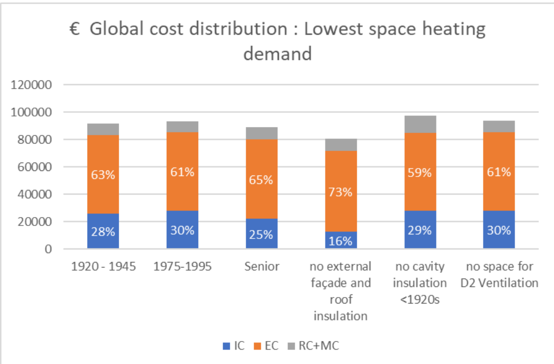


Figure 38 - percentage share % investment cost and energy cost for lowest space heating demand

The lowest space heating demand solutions introduce more extensive measures including the introduction of external wall insulation with Rc 4 – 5 in addition to cavity wall and internal wall insulation of 2 Rc. Similarly, roof insulation is improved with the addition of external roof insulation of 3.5 Rc. Furthermore, the underfloor is comparable to previous measures at around Rc 2 – 3 with no insulation on top of the floor. Less emphasis on the floor layers can be attributed to a lower sensitivity of this layer when considering heat loss. Additionally, the most efficient glazing and lowest infiltration level are selected. Furthermore, the type D2 ventilation system is the most effective ventilation system to reduce energy demand. The measures result in a space heating demand ranging from 10 -12 kWh/m2 which. The savings in energy cost is negated by the high initial investment cost required to achieve the more expensive measures that are at the end boundary conditions and it ranges from € 20,000 to €30,000. This directly impacts the global cost which lies between € 80,000 to € 95,000. As seen in Figure 38, there is an increase in the share of the initial investment costs accounting for 25% of the global cost on average and energy costs account for 65% of the global cost on average.

Lowest number of hours too cold

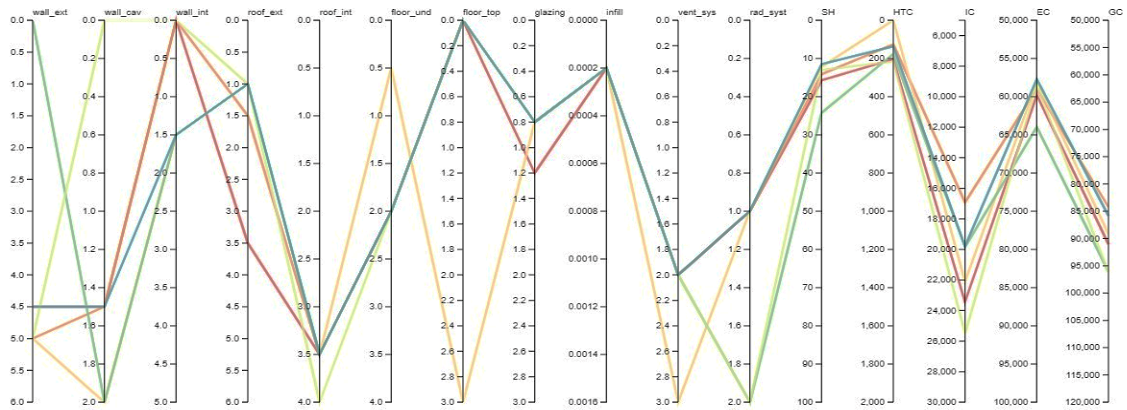


Figure 39- Parallel cordinates plot - lowest hours too cold

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
1920 - 1945	4.5	1.5	0	3.5	3.5	2	0	1.2	0.0002	2	1	15.7	204	23430	59806	91058
1975-1995	5	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	14.1	126	16922	58993	84213
Senior	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179
no cavity insulation	5	0	0	1	4	2	0	0.8	0.0002	2	2	13	216	25494	58478	96250
no external façade and roof insulation	0	2	1.5	1	3.5	2	0	0.8	0.0002	2	2	24.2	177	19836	63962	96076
no space for D2 Ventilation	4.5	1.5	1.5	1	3.5	2	0	0.8	0.0002	2	1	11.5	137	19801	57723	85823

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

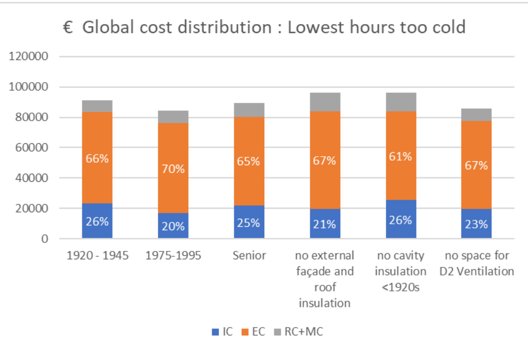


Figure 40 - percentage share % investment cost and energy cost for lowest hours too cold

The external roof Rc value for the majority of the scenarios is slightly reduced compared to that of the lowest space heating demand solution with Rc 1 – 2. This aligned with the previous sensitivity analysis where the increase in external roof insulation had a larger impact on space heating demand than comfort. This correlates with the comfort assessment method conducted in the living room which is located on the ground floor. Furthermore, the façade requires high-level external insulation in addition to cavity insulation, internal wall insulation and triple-glazing windows. This helps reduce transmission heat loss in the overall operative temperature of the room which significantly reduces the number of hours too cold between 120 – 200 hours. Additionally, the ventilation system used frequently includes type C2 ventilation systems in combination with the occurrence of low-temperature comfort radiators. These measures result in 12 – 25 kWh/m2 of energy demand. Furthermore, the reduced external roof insulation and instead maintaining it at the original level helps reduce the initial investment cost between €16,000 to €26,000. As shown in Figure 40 the initial investment cost and energy cost account for on average 23% and 66% of the global cost.

Best performing overall

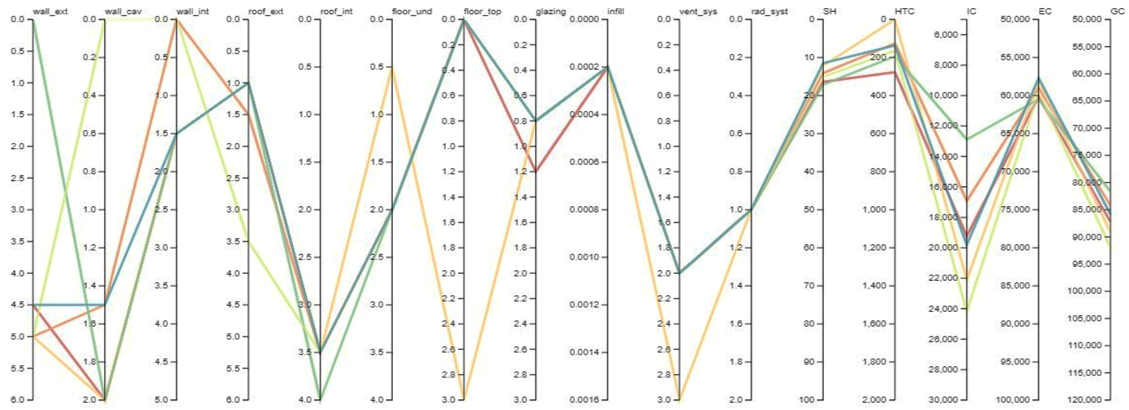


Figure 41 - Parallel cordinates plot – best performing overall

	Wall Rc m²·K/W			**Roof Rc** m²·K/W		**Floor Rc** m²·K/W		**W/ m²K**	**m3/s-m2**	**Installations**		**Energy & comfort**		**Investment, energy, global cost €**		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
1920 - 1945	4.5	2	1.5	1	3.5	2	0	1.2	0.0002	2	1	16.4	277	19232	60142	87196
1975-1995	5	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	14.1	126	16922	58993	84213
Senior	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179
no cavity insulation	5	0	0	3.5	3.5	2	0	0.8	0.0002	2	1	15.1	164	24172	59480	91950
no external façade and roof insulation	0	2	1.5	1	4	2	0	0.8	0.0002	2	1	17.1	194	12884	60481	81664
no space for D2 Ventilation	4.5	1.5	1.5	1	3.5	2	0	0.8	0.0002	2	1	11.5	137	19801	57723	85823

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

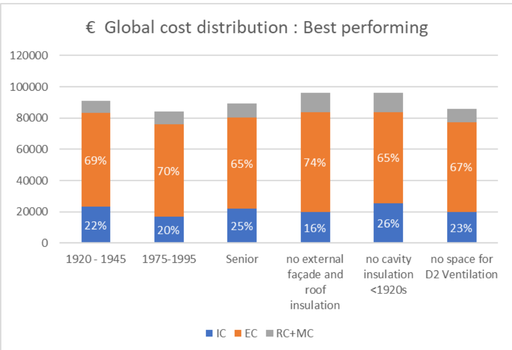
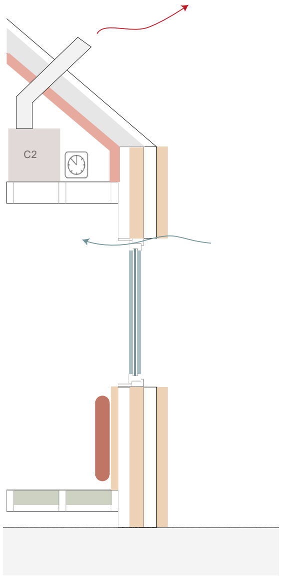


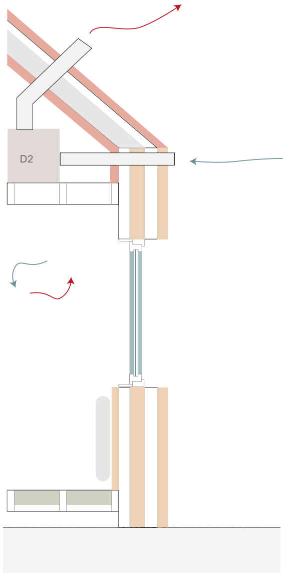
Figure 42 - percentage share % investment cost and energy cost for best performing overall

To arrive at measures that perform the best overall in terms of comfort, cost and energy consumption, a high Rc 4.5 value for the external façade and cavity wall insulation of 2 Rc. Additionally, the roof prioritises a high internal roof insulation value rather than additional external roof insulation as it can be prohibitively expensive with minimal additional energy savings. Furthermore, the lowest infiltration rate and triple glazing are required. Additionally, the type C2 ventilation system and maintaining the original radiator system are sufficient to deliver both energy savings and comfort overall. The hours too cold range from 120 – 300 hours with space heating demand between 10 – 18 kWh/m2. Additionally, the investment cost lies between €16,000 to €24,000 and it accounts for 22% of global cost. Furthermore, energy cost accounts for 68% of global cost and global cost ranges from €80,000 to €90,000.



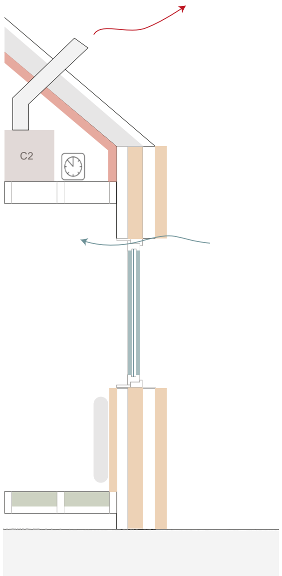
Lowest hours too cold

- External wall 158mm EPS insulation: Rc 4.5
- Foam beads cavity wall insulation 50mm
- Internal wall 54mm Mineral wool insulation: Rc 1.5
- Internal roof 74mm PIR insulation : Rc 3.5
- Underfloor joist 70mm Mineral wool insulation: Rc 2
- Tripple glazing U value 0.8
- Airtightness 0.2 $dm^3/s\ m^2$, Apply chink seals to window openings and closed façade parts
- Type C2 ventilation
- LT comfort radiator at low temperature supply.



Lowest space heating demand

- External wall 158mm EPS insulation: Rc 4.5
- Foam beads cavity wall insulation 50mm
- Internal wall 54mm Mineral wool insulation: Rc 1.5
- External roof 74mm PIR insulation: Rc 3.5
- Internal roof 74mm PIR insulation: Rc 3.5
- Underfloor joist 70mm Mineral wool insulation: Rc 2
- Tripple glazing U value 0.8
- Airtightness 0.2 $dm^3/s\ m^2$, Apply chink seals to window openings and closed façade parts
- Type D2 ventilation
- Original Radiator at low temperature supply.



Best performing overall

- External wall 158mm EPS insulation: Rc 4.5
- Foam beads cavity wall insulation 50mm
- Internal wall 54mm Mineral wool insulation: Rc 1.5
- Internal roof 74mm PIR insulation: Rc 3.5
- Underfloor joist 70mm Mineral wool insulation: Rc 2
- Tripple glazing U value 0.8
- Airtightness 0.2 $dm^3/s\ m^2$, Apply chink seals to window openings and closed façade parts
- Type C2 ventilation
- Original Radiator at low temperature supply.

Figure 43 - Representative refurbishment measures for lowest hours too cold, lowest space heating demand and best performing overall categories.

5.1.3 Evaluation of Pareto front solutions by Scenarios

The next stage involved evaluating the results by examining the categorised refurbishment measures for each of the individual scenarios to understand how the range of suggested refurbishment measures is driven by the tool.

Terraced house - <u>1920 – 1945</u> - Nuclear family:

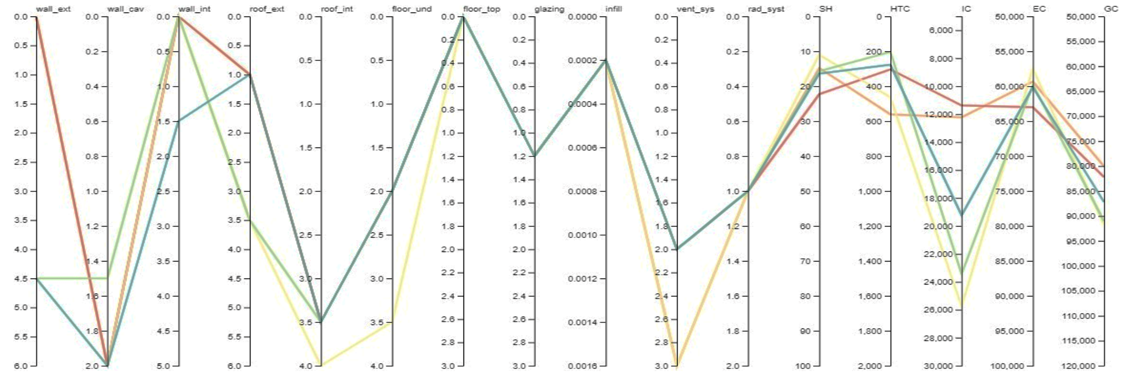


Figure 44 - Parallel cordinates plot - construction year 1920 - 1945

	Wall Rc $m^2 \cdot K/W$			Roof Rc $m^2 \cdot K/W$		Floor Rc $m^2 \cdot K/W$		W/ m^2K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	0	2	0	1	3.5	2	0	1.2	0.0002	2	1	22.3	304	11376	63022	82219
Lowest global cost	0	2	0	1	3.5	2	0	1.2	0.0002	3	1	14.8	561	12225	59341	80069
Lowest space heating	4.5	2	0	3.5	4	3.5	0	1.2	0.0002	3	1	11.0	464	25752	57482	91738
Lowest hours too cold	4.5	1.5	0	3.5	3.5	2	0	1.2	0.0002	2	1	15.7	204	23430	59806	91058
Best performing	4.5	2	1.5	1	3.5	2	0	1.2	0.0002	2	1	16.4	277	19232	60142	87196

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

Terraced house - <u>1975 – 1995</u>- Nuclear family:

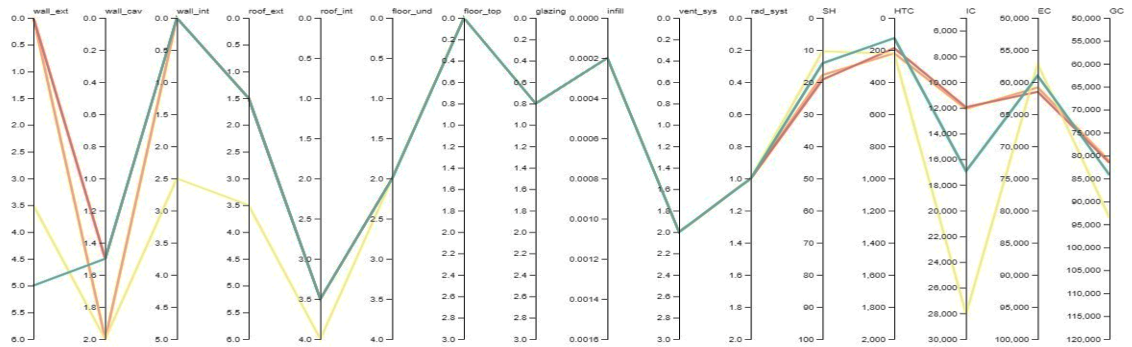


Figure 45 - Parallel coordinates plot - construction year 1975 - 1995

	Wall Rc $m^2 \cdot K/W$			Roof Rc $m^2 \cdot K/W$		Floor Rc $m^2 \cdot K/W$		W/ m^2K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	0	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	19.2	188	11945	61508	81571
Lowest global cost	0	2	0	1.5	3.5	2	0	0.8	0.0002	2	1	17.8	220	12074	60838	81210
Lowest space heating	3.5	2	2.5	3.5	4	2	0	0.8	0.0002	2	1	10.4	223	28068	57182	93548
Lowest hours too cold	5	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	14.1	126	16922	58993	84213
Best Performing	5	1.5	0	1.5	3.5	2	0	0.8	0.0002	2	1	14.1	126	16922	58993	84213

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

The results from the optimised results for both construction years demonstrate that both measures result in similar results with almost identical refurbishment measures for each construction year. By comparing the measures of both construction years, it's evident that the original external roof insulation can be maintained in its original state and is only required when considering a maximum reduction in space heating demand. Furthermore, one of the main differences is that HR++ glazing is the predominant measure for the different categories for the construction year 1920 – 1945 whereas, for the construction year 1975 – 1995, the predominant glazing suggest is triple glazing. One of the reasons for this could be the slightly better glazing specification that the dwellings between 1975 – 1995 start with as the base condition.

Terraced house - 1920 – 1945 - **Senior household:**

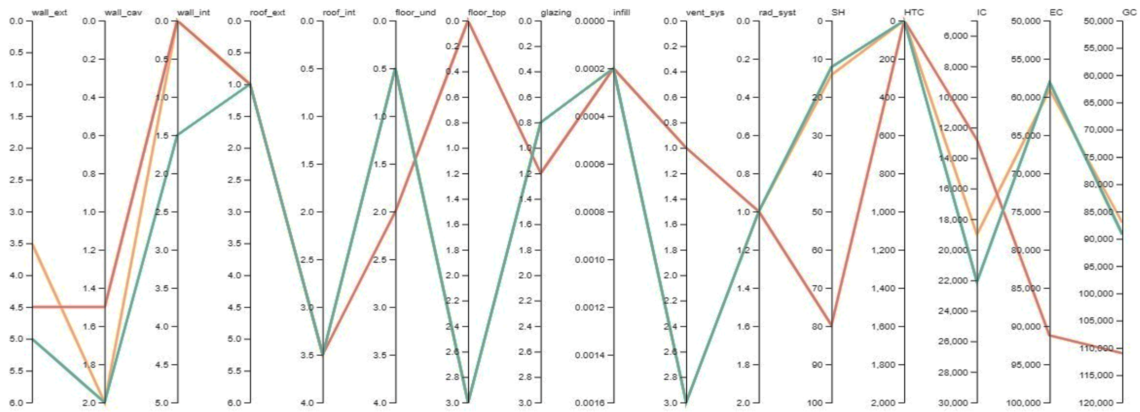


Figure 46- Parallel cordinates plot - senior household

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	4.5	1.5	0	1	3.5	2	0	1.2	0.0002	1	1	79.8	0	12796	91225	110974
Lowest global cost	3.5	2	0	1	3.5	0.5	3	0.8	0.0002	3	1	14.2	0	19003	59056	87039
Lowest space heating	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179
Lowest hours too cold	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179
Best Performing	5	2	1.5	1	3.5	0.5	3	0.8	0.0002	3	1	12.2	0	22112	58086	89179

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

When the household profile is changed to a senior couple household, the external wall insulation requires maximum external insulation values for the façade for each of the respective categories. Additionally, for this specific situation, the solutions prioritise top-floor insulation over underfloor insulation. Furthermore, D2-balanced ventilation systems are a necessity for the majority of the categories as well. Therefore, it can be concluded that the high energy consumption profile of the senior household results in an overall higher requirement for façade insulation and advanced mechanical ventilation systems to deliver sufficient energy savings and comfort. However, this results in an increase in investment cost for the best-performing scenario in comparison to a nuclear family to approximately € 22,000, an increase of nearly 14% from the nuclear family condition. This help reduces the number of hours too cold to zero and is the only scenario in which this has been evident in this study. This is because the senior households already have a high-temperature setpoint pattern which results in a complete reduction in hour exceedance once the refurbishment measures are in place.

Terraced house – 1920 – 1945 – Nuclear family – <u>Constraint: no external insulation</u>

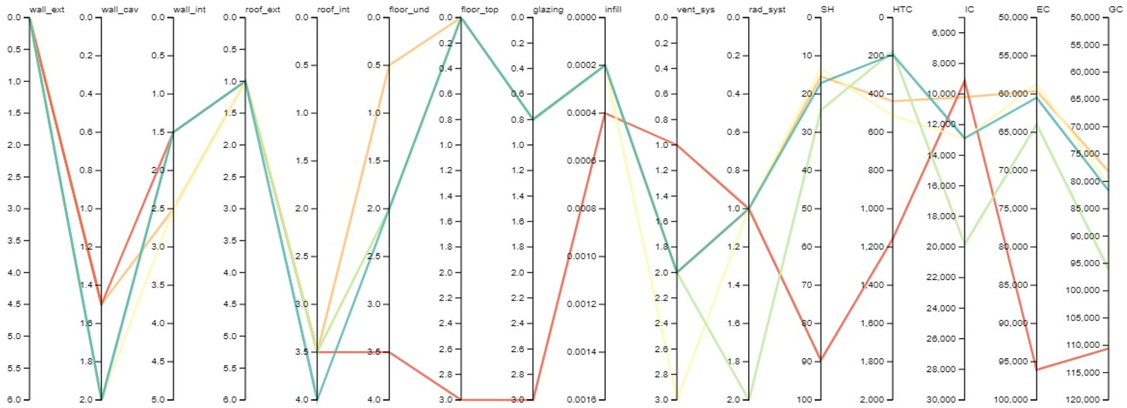


Figure 47 - Parallel cordinates plot - contraint no external insulation

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	0	1.5	1.5	1	3.5	3.5	3	3	0.0004	1	1	89.6	1156	9147	96055	110595
Lowest global cost	0	1.5	2.5	1	3.5	0.5	0	0.8	0.0002	2	1	15.4	438	10204	59633	78135
Lowest space heating	0	2	2.5	1	3.5	2	0	0.8	0.0002	3	1	13.4	513	12923	58686	80589
Lowest hours too cold	0	2	1.5	1	3.5	2	0	0.8	0.0002	2	2	24.2	177	19836	63962	96076
Best Performing	0	2	1.5	1	4	2	0	0.8	0.0002	2	1	17.1	194	12884	60481	81664

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

The addition of constraining external insulation on both the façade and roof results in solutions that limit those specific insulation layers. For example, the external wall insulation is substituted by both the cavity insulation and increased levels of internal wall insulation at maximum internal insulation of 2.5 Rc when considering the category for lowest space heating demand. Similarly, external roof insulation is substituted using internal roof insulation which has already been addressed as a preferable measure due to its lower cost and similar effectiveness. This slightly increases the energy demand for each category in comparison to the Pareto solutions determined for each category for the baseline case. For example, the scenario for the lowest space heating demand results in an increase of 2 kWh/m2 compared to the non-constrained case within the same category even after utilising triple glazing rather than HR++ glazing. Additionally, the limited external insulation can be seen as having a direct impact on the requirement of a low-temperature comfort radiator to compensate for the increase in transmission loss and achieve maximum reduction in the number of hours too cold.

Terraced house – 1920 – 1945 – Nuclear family – **Constraint: no cavity wall insulation**

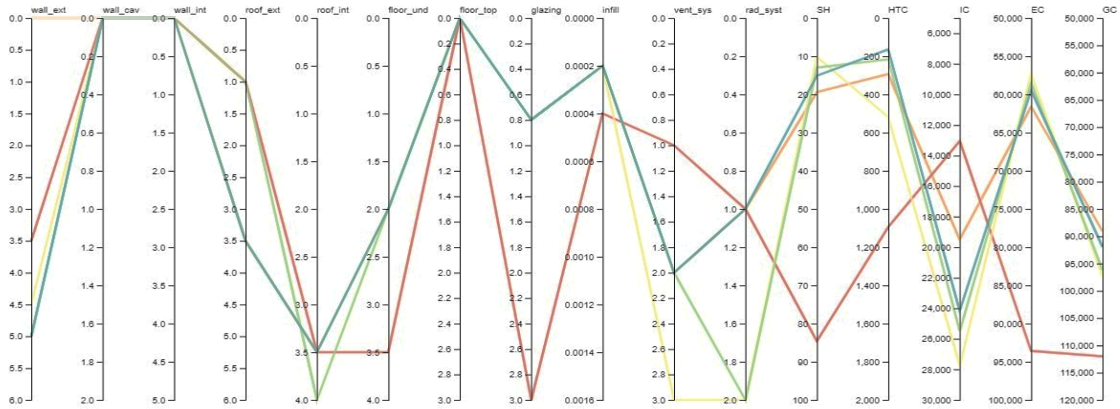


Figure 48 - Parallel coordinates plot - constraint no cavity wall insulation

	Wall Rc m²·K/W			Roof Rc m²·K/W		Floor Rc m²·K/W		W/ m²K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	3.5	0	0	1	3.5	3.5	0	3	0.0004	1	1	84.6	1094	13046	93579	112017
Lowest global cost	3.5	0	0	3.5	3.5	2	0	0.8	0.0002	2	1	19.4	293	19494	61596	89089
Lowest space heating	4.5	0	0	3.5	3.5	2	0	0.8	0.0002	3	2	10.2	519	27766	57289	97333
Lowest hours too cold	5	0	0	1	4	2	0	0.8	0.0002	2	2	13	216	25494	58478	96250
Best Performing	5	0	0	3.5	3.5	2	0	0.8	0.0002	2	1	15.1	164	24172	59480	91950

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

In this scenario the limited use of cavity wall insulation results in it being substituted by external wall insulation for all the various categories, especially when considering both the lowest investment and global cost category. This directly increases the initial investment cost for both the respective categories. For example, the lowest global cost category incurs an investment cost of nearly € 20,000 which is an increase of nearly 45% when compared to the lowest global cost measure for the base case scenario without constraints. Additionally, the prioritization of external wall insulation over internal wall insulation can be attributed to the fact that the external wall insulation measure is more effective at preventing thermal bridging with the possibility of using thicker insulation in comparison to the restricted internal wall insulation and therefore a more favourable measure in this scenario. Furthermore, like the previous scenario, the limited cavity wall insulation results in the requirement for low-temperature comfort radiators to achieve a reduced number of hours too cold. The substitution of the cavity wall insulation for the external wall insulation results in no substantial change in the overall comfort for the different categories.

Terraced house – 1920 – 1945 – Nuclear family – **Constraint: no space for D2 ventilation**

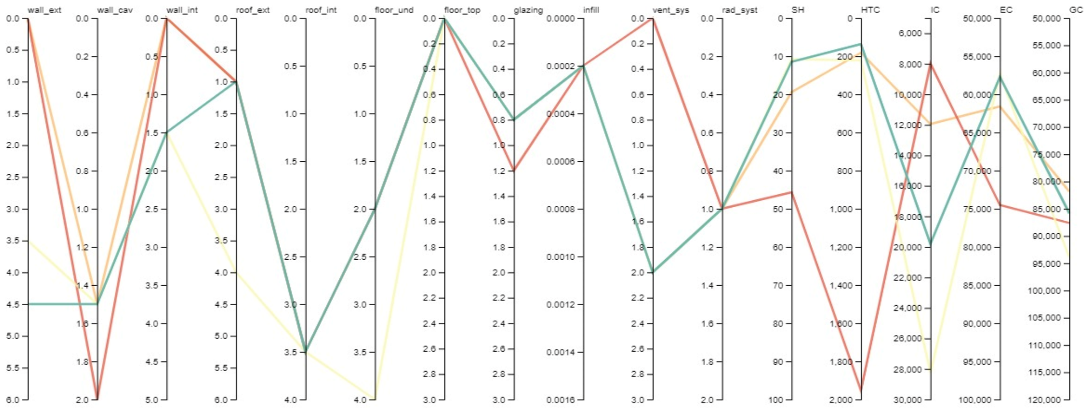


Figure 49 - Parallel cordinates plot - constraint no space for D2 ventilation

	Wall Rc $m^2 \cdot K/W$			Roof Rc $m^2 \cdot K/W$		Floor Rc $m^2 \cdot K/W$		W/ m^2K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	0	2	0	1	3.5	2	0	1.2	0.0002	0	1	45.7	1953	7991	74514	87606
Lowest global cost	0	1.5	0	1	3.5	2	0	0.8	0.0002	2	1	19.4	182	11945	61594	81837
Lowest space heating	3.5	1.5	1.5	4	3.5	4	0	0.8	0.0002	2	1	10.8	222	28251	57369	93918
Lowest hours too cold	4.5	1.5	1.5	1	3.5	2	0	0.8	0.0002	2	1	11.5	137	19801	57723	85823
Best Performing	4.5	1.5	1.5	1	3.5	2	0	0.8	0.0002	2	1	11.5	137	19801	57723	85823

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

The limited use of the D2 balanced ventilation system has a limited impact on the overall potential energy demand reductions and reduction in the number of hours too cold. It reiterates the findings by the optimised solutions that type C2 CO2 controlled ventilation systems are sufficient to achieve optimal levels of comfort and energy saving as demonstrated by the measures in the best performing category. Moreover, the lowest investment measures that were derived from this Pareto front results demonstrate that although the application of type D2 ventilation is restricted, it's not beneficial to maintain the existing natural ventilation as it can result in significantly higher energy demand and negatively impact the comfort of a space.

<u>Detached house</u> **– 1920 – 1945 – Nuclear family.**

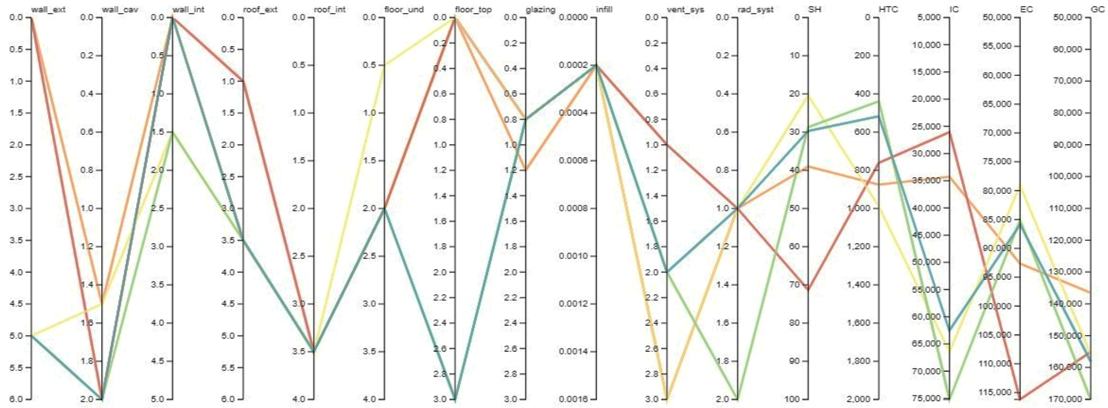


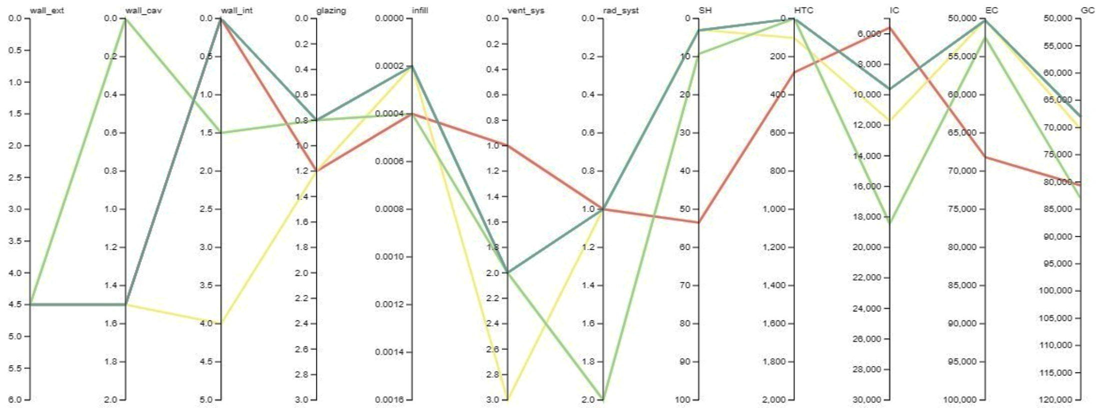
Figure 50 - Parallel cordinates plot - Detached house

	Wall Rc m²·K/W			**Roof Rc** m²·K/W		**Floor Rc** m²·K/W		**W/ m²K**	**m3/s-m2**	**Installations**		**Energy & Comfort**		**Investment, energy, global cost €**		
	w_ext	w_cav	w_int	r_ext	r_int	f_und	f_top	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	0	2	0	1	3.5	2	0	0.8	0.0002	1	1	71.3	761	26066	116188	155100
Lowest global cost	0	1.5	0	3.5	3.5	2	0	1.2	0.0002	3	1	39	875	34274	92635	136513
Lowest space heating	5	1.5	1.5	3.5	3.5	0.5	0	0.8	0.0002	3	1	20.4	989	66420	79106	155943
Lowest hours too cold	5	2	1.5	3.5	3.5	2	3	0.8	0.0002	2	2	28.7	438	75205	85127	170067
Best Performing	5	2	0	3.5	3.5	2	3	0.8	0.0002	2	1	29.7	517	62529	85855	158119

Ventilation: **0** = Type A (Natural) , **1** = Type C1 (mechanical exhaust) , **2** = Type C2 (mechanical exhaust with CO2 control),**3** =Type D2 (balanced ventilation)
Radiator system : **0** = Original (High temperature), **1** = low temperature, **2** = low temperature comfort radiators
SH = space heating demand kWh/m2 , **HTC** = hours too cold , **IC** – investment cost, **EC** = energy cost, **GC** = global cost

The measures for each category when the dwelling archetype changes to a detached dwelling are comparable to that of a terraced house of the same construction year. The main difference is that the external roof is highly insulated for scenarios except for the lowest cost category, and this can be attributed due to the larger roof area. Moreover, the lack of external wall insulation reduces the energy demand savings potential significantly when considering the lowest global cost category which is due to the significantly larger exposed façade area. Therefore, when it is introduced in the best-performing solution, lowest space heating demand and lowest hours too cold scenarios with a high Rc value, the investment cost is nearly 2.5 times that of the lowest investment cost category for the detached house. Therefore, it can be concluded that the impact on both energy savings and cost drastically increases as the exposed façade area increases. Additionally, when comparing the lowest number of hours too cold category, even though the additional low-temperature comfort radiator is added, it is nearly twice that when compared to the terraced dwellings with similar envelope refurbishment measures. Furthermore, this is the only other scenario other than the senior household scenario where the best performance scenario includes both underfloor and over-the-floor insulation. This could potentially be once again attributed to the increase in exposed envelope area overall and the high sensitivity that the roof insulation value has based on the initial sensitivity analysis. Additionally, investment cost and energy costs account for 38% and 56% of the global cost overall and therefore the weightage of the initial investment cost increases.

<u>Portiek apartment</u> – **1920 – 1945 – Nuclear family.**



	Wall Rc m^2·K/W			W/m^2 K	m3/s-m2	Installations		Energy & Comfort		Investment, energy, global cost €		
	w_ext	w_cav	w_int	Glaz	Infil	Vent	Rad	SH	HTC	IC	EC	GC
Lowest investment	4.5	1.5	0	0.8	0.0002	2	1	3.1	0	9630	50253	68043
Lowest global cost	4.5	1.5	0	1.2	0.0004	1	1	53.5	283	5596	68187	80629
Lowest space heating	4.5	1.5	4	1.2	0.0002	3	1	2.9	102	11703	50207	70307
Lowest hours too cold	4.5	0	1.5	0.8	0.0004	2	2	9.3	0	18439	52477	83055
Best Performing	4.5	1.5	0	0.8	0.0002	2	1	3.1	0	9630	50253	68043

The results demonstrate that the change in housing archetype to a portiek apartment results in comparable measures to that of a terraced dwelling. However, it must be noted that since the portiek apartment case considers a middle apartment unit, the roof and floor input parameters are excluded. The external wall requires the use of cavity wall insulation up to 1.5 Rc with a priority for external wall insulation. Additionally, in the case of portiek apartments, the use of high-value of external wall insulation of 4.5 Rc is evident across all categories. This can be explained by the minimally exposed façade which makes it financially feasible to include both the lowest investment and global cost categories as well. The higher window-to-wall ratio for portiek apartments compared to other dwelling archetype results in the triple glazing being a recurrent refurbishment measure across the respective categories. Furthermore, the lower compactness ratio of this archetype results in a 70% reduction of energy demand on average in comparison to terraced dwellings. Additionally, the number of hours too cold for the best-performing measure, for example, is zero and therefore this suggests that the measures used for portiek apartments results are more effective in improving the comfort of the users in comparison to single-family housing typologies. The reduced exposed envelope surface area directly results in on average 37% reduction in overall investment cost in comparison to terraced dwellings with similar refurbishment measures.

5.1.4 Impact of post-refurbishment occupancy behaviour

The next stage involved the analysis of the impact of post-refurbishment occupancy behaviour changes to a high or low behaviour consumption profile. The base case categories and their respective refurbishment measures for each of the scenarios include the lowest investment cost and the best-performing measure. These were assumed as potentially the most common and preferable categories within the decision-making process and therefore considered for this stage of the study.

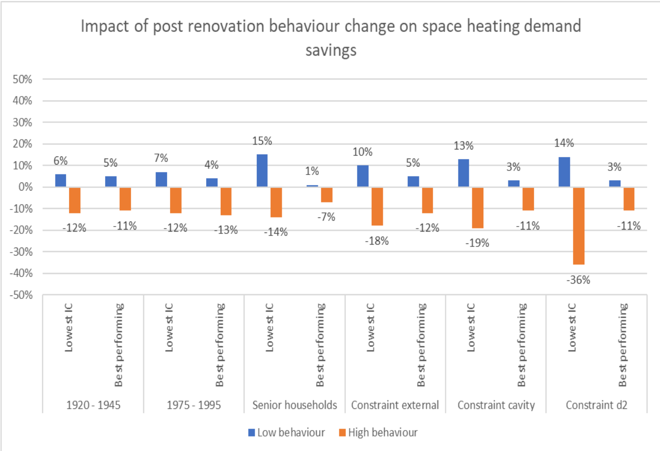


Figure 51 - post occupancy behaviour impact on space heating demand

As shown in Figure 51 as the occupant changes their behaviour to low occupancy behaviour, on average one can see a 7% increase in space heating demand savings. On the other hand, if occupants changed their behaviour to that of a high-energy consumer, space heating energy demand savings could reduce by 15%. Therefore, overall it can be concluded that the high energy behaviour has a higher impact on space heating demand than the change to low behaviour. Furthermore, the impact on space heating demand savings is higher for low-investment cost measures that include less intensive refurbishment measures.

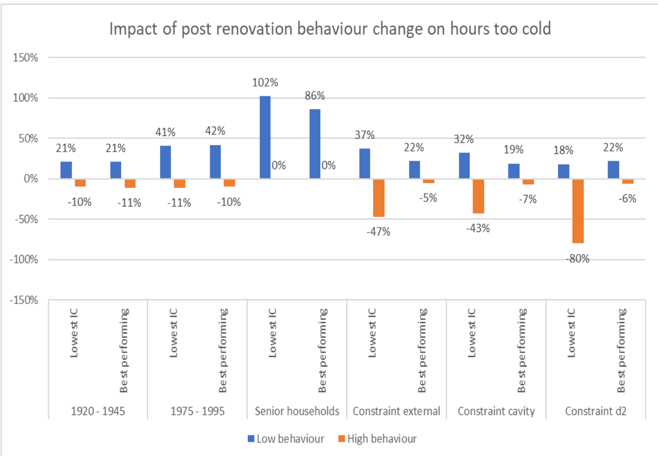


Figure 52 - post occupancy behaviour impact on hours too cold

The impact on the number of hours is the opposite of that of space heating demand. As occupants change to low behaviour, on average the number of hours to cold increases by 40% in comparison to the 22% reduction in the number of hours too cold as occupants change to high behaviour profiles. As expected, the impact of changing to low behaviour is most prominent when selecting the lowest investment measure for senior households as the setpoint temperature drastically changes. Additionally, upon further inspection of the lowest investment measure for the constrained D2 ventilation scenario, the reduced number of hours too cold significantly increases when the user switches to high behaviour. This is because the base refurbished cases for the lowest investment cost category consider natural ventilation and therefore more sensitive to a high occupancy behaviour (high setpoints) in comparison to the base case scenario with higher potential to improve thermal comfort.

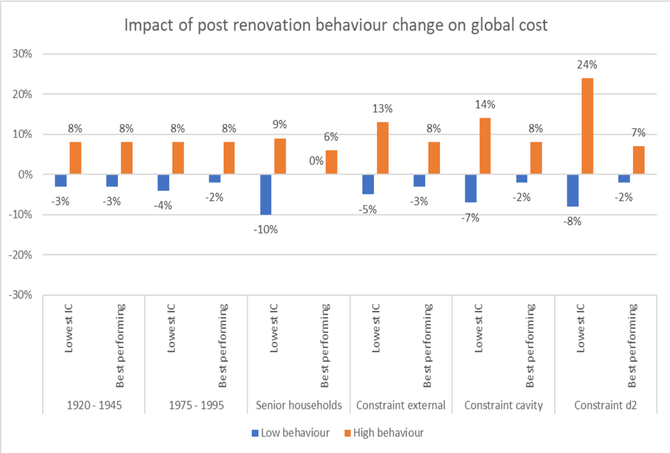


Figure 53 - post occupancy behaviour impact on global cost

The impact of behaviour changes on global cost mirrors that of the space heating demand with an additional average reduction of 4% when an occupant changes to low behaviour. On the other hand, the change to high behaviour increases global cost by 10% which is proportionate to the impact observed for space heating demand.

5.2 Results discussion

5.2.1 Pareto front solutions by Category

Firstly, the Pareto optimal solutions mentioned above **can all be classified as low-temperature ready refurbishment strategies.** This can be reasoned as the space heating demand for measures is nearly 75% lower on average than the no-regret target of 102 kWh/m2 set by the Nieman standard for terraced dwellings. Similarly, the number of hours too cold is on average nearly 85% less than the base condition. The same can be determined for the detached housing typologies wherein the categorised refurbishment measures on average require a space heating demand that is 80% less than the target of 186 kWh/m2 set by Nieman's standards and 70 % fewer hours too cold than the baseline scenario. (Cornelisse et al., 2021). The Portiek apartments measures are also considered as low temperature ready as the majority of categories present space heating demand outputs that are nearly 88% lower than the Nieman target of 45 kWh/m2. Similarly, the hours too cold for each terraced, detached and portiek apartment have reduced by 85%, 71% and 96% respectively. Therefore, it can be generally concluded that optimised measures meet the no re-regret targets comfortably.

Additionally, the lowest investment cost solutions suggest that there is a possibility to achieve considerable savings in energy reduction with a combination of refurbishment measures. The measures focus on cavity wall insulation, internal roof insulation, HR ++ glazing, minimal infiltration, and the type C1 ventilation system. However, the multi-measure strategy is still relatively expensive in comparison to previous studies considering economically feasible low-temperature refurbishment strategies suggest in previous studies *(Rutten, 2021)*. This is because the current methodology considers the global cost as an optimization objective and therefore the measures assign a higher weightage to energy cost that contributes a higher percentage to the global cost which then results in more intensive refurbishment measures overall. Therefore, as expected the lowest investment cost solutions result in a higher global cost in the long term.Furthermore, the higher contribution of energy cost to global cost results in slightly more ambitious solutions to achieve the lowest global cost. This includes the use of type C2 or D2 ventilation systems along with triple glazing windows which lead to higher initial investment costs at first but lower energy costs in the long term.

To achieve even higher levels of comfort and energy saving, the refurbishment measures include a considerably higher level of insulation on the envelope including external wall and roof insulation which is in addition to the internal insulation. Both external insulation measures contribute significantly to the increase in investment cost. Moreover, underfloor insulation is required however it's limited as its contribution overall to energy savings is not as significant. The main difference between the lowest space heating demand measures and the maximum comfort measures is that the lowest space heating demand solutions consider more ambitious measures like D2 balanced ventilation systems and higher external roof insulation value. On the other hand, the lowest hours to cold measures suggest the use of C2 CO2-controlled ventilation systems and the use of low-temperature comfort radiators to further improve comfort.

However, this highlights potential limitations when using the tool to suggest optimised results for comfort and space heating demand. For example, when considering the wall insulation measures, even though the individual layers of the external, cavity and internal wall insulations exclude the maximum value, it does not consider the insulation thermal resistance for the envelope construction as one whole where total constructional thermal resistance values are over-dimensioned in comparison to standards of new constructions.

The best-performing measures considering the three objectives and indicators are comparable to that of the measures derived from the measures with the lowest hours too cold. This is because the measures are comparably not as extreme as those determined when solely looking and energy demand reduction whilst still providing adequate savings that can help reduce global costs in the long term. Therefore, the measures still include external wall insulation combined with cavity wall insulation, triple glazing, lowest infiltration level and moderate levels of underfloor insulation. However, where the best-performing measures differ compared to the lowest space heating demand measures, is in prioritises internal roof insulation and C2 ventilation system. Additionally, it can be concluded that when transitioning to low-temperature heating, it's more effective to refurbish the dwelling using insulating measures and keep the existing radiator than replace the radiators solely with low-temperature comfort radiators. This is because by refurbishing the dwelling not only is the overall comfort improved but it results in lower global costs in the long term as proven by the results from the proposed tool.

5.2.2 Pareto front solutions by scenarios

When further examining the scenarios, the change in construction year resulted in nearly identical refurbishment measures per category. One of the reasons why this occurs is due to initial assumptions of the requirement for complete insulation replacement when undergoing a refurbishment of the dwelling. Therefore, as an optimization workflow, the measures converge to similar measures within the design space. To see a significant difference in the measures the tool would need to only consider the potential difference between additional insulating measures. The only scenario where there could be a potential difference is when the construction year is newer and that base condition has sufficient insulation value that at no additional investment cost, it would be more economically feasible to maintain the existing insulation rather than upgrade the insulating measures with minimal impact on energy savings and comfort.

Furthermore, as household behaviour increases, so does the requirement for more ambitious measures like external wall insulation and D2 balanced ventilation systems to achieve comparable reductions in energy demand whilst the number of hours too cold is completely reduced. An inconclusive occurrence is the prioritization of top-floor insulation in this specific scenario over underfloor insulation and this would need to be examined in more detail potentially critically looking at the underlying relations developed by the surrogate model. Furthermore, as constraints are added to the envelope insulation for example for the external roof and external wall insulation, alternative measures like the internal wall insulation in addition to the requirement for low-temperature comfort radiators. Similarly, when the cavity insulation is restricted the external wall insulation is substituted in its place. However, the suggested measures do bring into question why the model would select the more expensive refurbishment measure. This could be due to the limited possible thickness of the internal insulation available in the material database as it does not exceed a Rc value of 4. Moreover, an initial investigation suggested that even if the same thermal resistance of insulation is used on the internal or external wall insulation, the external wall insulation resulted in a higher reduction in space heating demand due to the additional impact on minimising thermal bridging. Similar to the constraint on external insulation, the limitation on cavity insulation also results in a requirement for low-temperature comfort radiators. Additionally, the limitation in D2 ventilation systems confirms the past conclusions that C2 ventilation systems can be sufficient to deliver space heating savings and comfort for the user and still be low-temperature ready.

Finally, the investigation into three proposed housing archetypes including terraced, detached and portiek apartments suggests a direct correlation between the compactness ratio and therefore exposed surface area and the impact on the refurbishment measures. Moreover, in comparison to more compact dwelling archetypes like terraced housing, the more ambitious categories like best-performing solutions and lowest space heating demands for detached dwellings that specifically require near maximum levels of external envelope cost nearly 2.5 times that of the lowest investment cost solution in comparison to 1.6 times for terraced housing and this reflected in the increase in the share of investment cost in the global cost for detached dwellings. Additionally, it is evident that as an occupant of high compactness ratio dwelling archetypes, selects less intensive refurbishment measures evident in the lowest investment cost categories, the potential for energy savings reduces dramatically. For example, with comparable measures, occupants of portiek apartments can benefit from an average of 70% reduction in energy consumption for the respective categories in comparison to terraced dwellings with the reduced exposed surface area resulting in a near complete reduction in the number of hours too cold for the best-performing category.

5.2.3 Post-refurbishment Occupancy behaviour change

The impact of post-occupancy behaviour change is in line with the previous study by (Ben & Steemers, 2014) wherein the impact of occupancy behaviour change post-refurbishment becomes more muted as the level of refurbishment increases and this can be concluded for all three performance indicators. However, based on the assumptions of each of the respective post-refurbishment occupancy profiles, the change to high behaviour profiles results in a larger impact for each of the indicators in comparison to the change to low behaviour profiles. Although as will be discussed ahead, the low variation in the spread of measures overall, especially demonstrated in the space heating demand indicator for example suggests that there is potential interdependency on specific measures that heighten the impact and is not being revealed within this specific Pareto optimal set of solutions. For example, this has been suggested with the refurbishment measure that kept its original natural ventilation system and in turn incurred a more drastic change in the respective indicators especially when considering the high behaviour profile post-refurbishment.

5.2.4 General results recommendations

The results determined by the optimization workflow highlight specific commonalities in relation to reoccurring refurbishment measures that are effective in each scenario and category. The majority of the measures comprise a combination of triple-glazing windows with the lowest infiltration value at 0.0002 m3/s/m2. Additionally, internal roof insulation with a high Rc value and cavity wall insulation at the maximum possible thickness within the cavity are cost-effective strategies that can be used to positively impact comfort and energy savings. Overall, it can be concluded a moderate level of underfloor insulation needs to be maintained after which there is no added value of the additional insulation especially 'on top of the floor insulation. In relation to installations, the optimal measures include the use of type C2 ventilation systems whilst maintaining the original radiators when transitioning to low temperatures. By focusing on refurbishing the dwelling rather than investing in a more expensive low-temperature comfort radiator, one can achieve similar if not better levels of comfort whilst translating the initial investment into economical savings in terms of the global cost in the long term.

Furthermore, the results overall show potential for the tool to be able to categorise and suggest optimal refurbishment measures with logical and explainable results. However, an overall observation is a limited and low range in which the overall range of measures falls within. This is potentially due to two potential factors. Firstly, all the measure converges to include the lowest infiltration level due to its cost-effectiveness and high sensitivity in impacting space heating demand. This could potentially be muting the overall impact of other refurbishment measures. Furthermore, the feasibility of achieving this level of airtightness in combination with its high sensitivity would need to be examined further. This could either be addressed by limiting the variation in infiltration level and keeping it constant and then running the optimization model to see how the results vary. Secondly, the low solution range can be attributed to the high weightage of energy cost in the overall design space because of its high contribution to the overall global cost which then inherently leads to more extensive refurbishment measures that lead to higher initial investment cost overall.

5.3 Tool Interface Development

5.3.1 Evaluation of existing refurbishment tools

The review by Seddiki et al. (2021) evaluates a range of 19 existing retrofit tools across 10 different countries. The paper suggests that existing tools primarily use empirical data either from historical measures data or pre-defined databases. Therefore the suggestions are limited to a specific building type and are dependent on an intensive pre-defined database. Another method used to generate measures is through normative calculations that are representative of building regulation norms and therefore are transparent and effective to use. However, these methods do not take into account the impact of thermal zones and user behaviour which results in inaccurate calculations.

Additionally, the current tools have the ability to determine the performance of the existing condition of the dwelling. However, the refurbishment measures suggested are mostly dependent on the user being invited to select measures from a predefine list of measures and evaluate the performance based on their judgement. Moreover, the measures are considered individually with no consideration of integrated effects. The individual measures include measures in relation to the building envelope, equipment and renewable energy. However, only a handful of tools consider indicators related to social and aesthetic aspects. This is especially relevant when considering complex refurbishment measures like upgrading building installations that can require considerably more effort and assistance from specialised installers. Additionally, the tools do provide varying levels of information regarding funding options available such as grants, loans and green financing products from banks.

A closer look is taken at two tools including the 'checkjehuis'(De Energie Centrale) , 'totalkredidt' (Totalkredit) and 'Verbeterjehuis'(Milieu Centraal). The tools have certain elements in common including the ability to access the measures on a web-based platform with an easy-to-use interface. Users are asked to input data about their dwelling through a questionnaire-like format with the most of inputs filled in by default based on the initial data provided like type of dwelling and year of construction. The users have the ability to customise their data if required or else they can keep the default values. The evaluation criteria include EPC ratings, investment cost, energy savings and CO2 reduction. Furthermore, it is relevant to note that both the 'checkjehuis' and 'Verbeterjehuis' tools provide users with the ability to gain an understanding of quantitative measures and values like the thermal resistance of measures in terms of descriptive terms or colour indicators that can be effectively used to educate and inform users during the decision-making process.

5.3.2 Proposed Decision-making tool interface

Based on the review of existing refurbishment tools above the following features have been addressed in the proposed tool.

Feature	Description
Access to background information	The tool must be part of a larger ecosystem of information sharing where information regarding properties of the individual refurbishment measures and procedures to collect the required input data for the tool is readily available both within and outside the decision-making tool.
Questionaire like input data collection	To gather data about the existing dwelling, the user can input the input parameters in a logical, step-by-step manner making it easy to use.
Prefilled, default input values that can be overridden	The default values could help reduce the barrier to using the tool and speed up the process, therefore, making it easier for users to quickly get an initial indication of their refurbishment solutions.

Ability to take into account household type and therefore behaviour with the possibility to be educated on post-refurbishment behaviour change	The tool includes a feature for users to select their household type and post behaviour profile post refurbishment and see its impact on their savings.
Descriptive indication of the effectiveness of refurbishment measures and input parameters	A descriptive categorising of refurbishment measure bands is used to give users a helpful guide when inputting and assessing the existing state of their dwelling's thermal performance.
A dashboard with integrated refurbishment measure solutions that are automatically determined	At the end, the user is able to see a clear selection of refurbishment packages with the respective performance indicators. This is automatically determined and categorised by the underlying surrogate model that comes near to modelling dynamic simulations that are quicker and easier to use through this interface.
Access to information regarding financial and material suppliers (further feature development)	Finally, once the user selects their refurbishment measure, they are guided to explore and grants and companies that can help them implement the refurbishment measures further.

Figure 54 - Introduction page to the tool LT-set

As shown in Figure 54 the landing page introduces users to the benefits and the context behind the transition to low-temperature district heating. This also demonstrates how the tool can develop to become a component of a larger ecosystem connecting various stakeholders to help reduce the barrier to the transition.

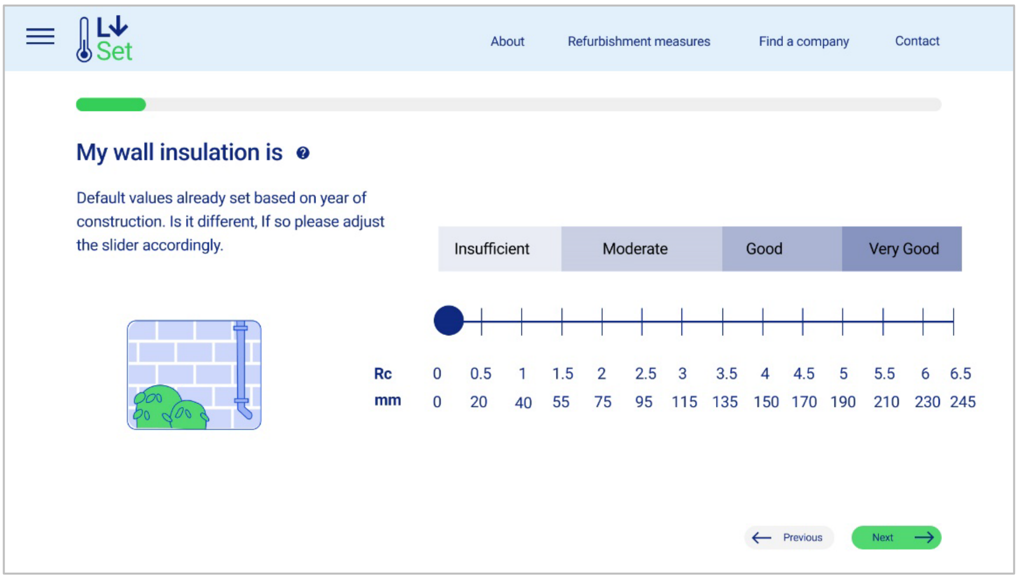


Figure 55 - Slider input paramter for existing wall insulation

The input parameters include envelope parameters including wall, roof and floor insulation. Additionally, the user can select constraints and limitations that may prevent them from undertaking certain refurbishment measures and that can be then taken into account by the tool. Additional, input parameters include the glazing and ventilation system with similar descriptive or visual indicators. Moreover, as seen above the values are indicated as being selected by default based on housing archetype and construction year.

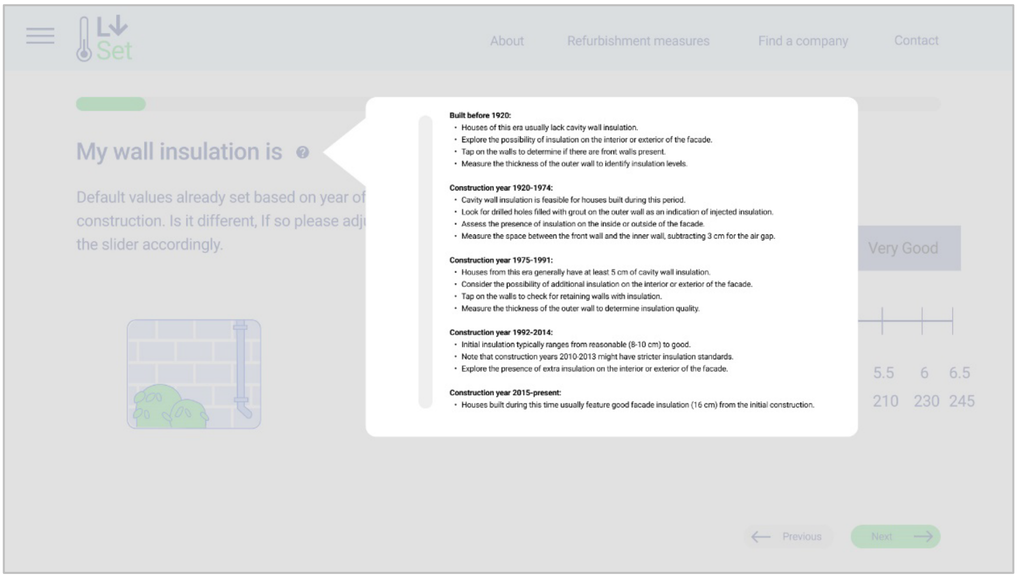


Figure 56 - Information pop up window for wall insulation input parameter.

The user interface also acknowledges that the technical knowledge is not widely known and therefore, users must be able to also embark on the process of educating themselves as they use the tool to find out more information to help supplement their process of using the tool and decision making. This includes useful tips like how insulation can be measured.

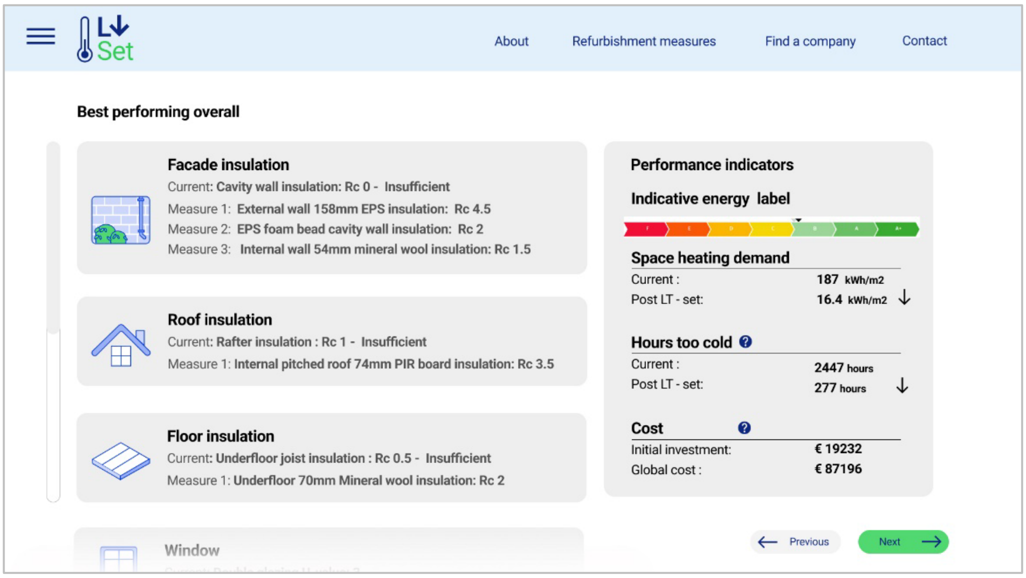


Figure 57 - Final refurbishment package dashboard

Once the input parameters are filled in then users can explore and evaluate the different categories of refurbishment measures and gain an understanding of what building products are required to achieve the respective performances. The indicators include an EPC rating before and after, current and improved space heating demand, hours too cold and finally what the package eventually costs.

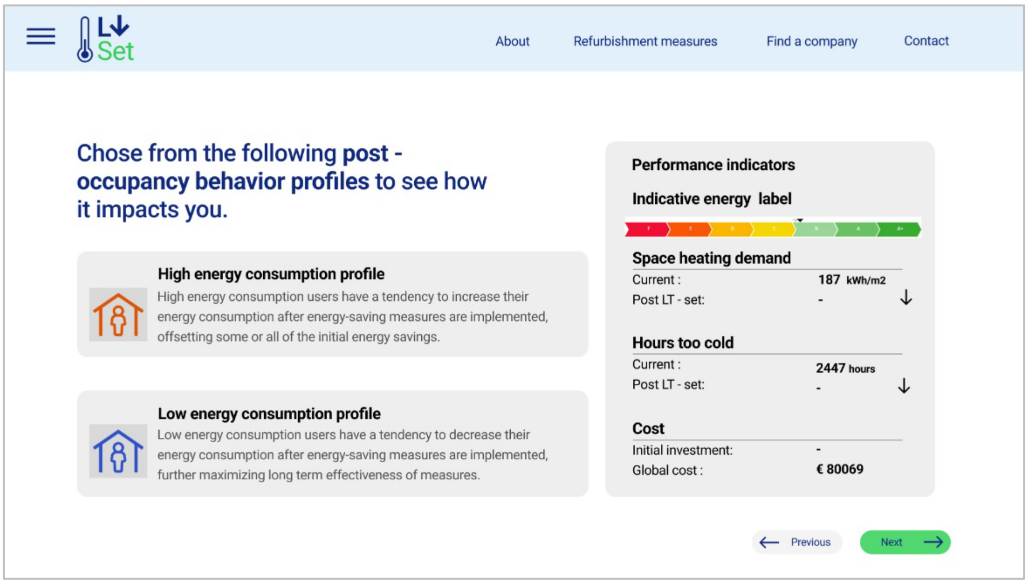


Figure 58 - Indication of occupancy behaviour change post refurbishment

Another aspect addressed in the tool is the ability to educate the users on the impact of their post-refurbishment process. If the users chose either of the profiles shown above, they are guided to a page with more details on what sub-parameters define each of the profiles like setpoint, setback temperature and use of radiator in infrequently used rooms. This provides the tool with a holistic approach by easily educating users on the impact of the behaviour on their recently selected refurbishment package with could make the tool more effective overall.

Conclusion

6. Conclusions

6.1 Answering research questions.

The aim of this thesis was to answer the following research question :

How to develop a **surrogate model**-based decision-making tool to select **combined, no-regret refurbishment measures** using **performance indicators** for **multiple Dutch housing** typologies considering **occupancy behaviour** and **lifecycle cost** to transition to **low-temperature district heating?**

In order to address this main research question the first stage of the research examines various areas of research in order to collect the relevant data inputs to train the simulation model. This helped answer the following sub-questions:

1. What defines the input and output parameters that address the transition to low-temperature district heating?

Dutch housing typologies and their respective sensitive parameters

The Dutch housing stock comprises varying housing archetypes including terraced, multi-family, detached and semi-detached dwellings with terraced housing accounting for most of the building stock. In order to define the building archetypes, window-to-wall ratio, useable floor area and overall geometrical layout including the exposed façade surface area can be used as the sensitive parameters that impact energy demand and comfort. Each of the dwelling archetypes can be further classified by construction year that falls within four construction year brackets including 1920 – 1945, 1945 – 1975, 1975 – 1995 and <1995. These construction years are reflected by the thermal building physical properties of the construction including envelope insulation levels, existing ventilation systems, glazing type and overall airtightness of the dwelling.

Dutch **household behaviour profiles** and their respective sensitive parameters

The household profiles can be classified into high energy consumption households like the nuclear family and senior coupe households and on the other hand, they can be classified as low energy consumption households such as adult couples or single-parent households. Each of these household profiles was defined in terms of their setpoint temperature schedules, use of setbacks based on occupancy schedules and thirdly the operation of radiators in the frequently used living room and sparingly used rooms like the kitchen, bedroom and bathroom when occupants are home. Additionally, the maximum and minimum levels for each of the occupancy behaviour sub-parameters from the household profiles were combined to define two post-refurbishment occupancy profiles including high and low post-refurbishment profiles.

Existing **refurbishment strategies** used to make dwellings LT – ready?

Existing literature covered a broad range of low-temperature refurbishment measures including both envelope and building installation refurbishment measures to deliver an effective combination of measures. This included upgrading glazing specifications to HR++ or triple glazing with improved airtightness and cavity wall insulation. Installation measures included the use of D2 balanced ventilation systems and the use of low-temperature comfort radiators specifically designed to enhance the capacity of radiators at low temperatures to maintain comfort standards with minimal intervention. Additionally, the literature suggests that focusing on building installations for ventilation like balanced ventilation systems can have the largest impact and secondly upgrading glazing and making them more airtight can significantly reduce energy consumption and improve comfort in a cost-effective manner.

Performance indicators that can be used to evaluate refurbishment measures to define a no-regret refurbishment strategy.

The three main performance indicators defined in this study include space heating demand, hours too cold which defines thermal comfort and global cost. Furthermore, the definition by the report by Nieman was used to define a no-regret refurbishment measure, one that would not require further modification nor interventions within the technical lifespan of the measures in anticipation of the transition to district heating and other alternative heating sources as an alternative to natural gas. Therefore, this study complies with the compactness ratio dependant space heating targets set by Nieman, wherein values under a certain threshold would be sufficient to achieve an energy label A/B with minimal additional interventions like the external insulation and adding air quality sensors in the ventilation system or replacing the radiator. Furthermore, the number of hours too cold would either need to be maintained or reduced further once the transition to low-temperature district heating. These targets helped define the baseline performance that would need to be achieved by the refurbishment measures to become low-temperature ready.

2. What are the methods used to evaluate the **life cycle cost** (LCC) of the refurbishment measures?

Current lifecycle cost assessment methods include the net present value and global cost method. The former evaluates the cost in terms of the difference between benefits and cost which is then discounted over a calculation period. However, for this specific study, the latter method is chosen which is defined primarily by cost functions like operating, investment and maintenance costs over a 30 year period with a market interest rate of 4.8%. Moreover, this is the method prescribed by the European Commission and defined by NEN norms.

3. What are the current methods used to train and evaluate **surrogate models**?

Surrogate models have been used extensively in building simulation models using nonparametric algorithms like artificial neural networks and the gaussian process. These algorithms are preferred over parametric algorithms like stepwise linear regression models because of the complex no linear nature of the thermal performance of building energy simulations. In most instances, synthetic energy simulation training data is collected and used as a supervised learning to train the models. To define an adequate sample for the training data, the Latin hypercube sampling method is the most adopted method due to its ability to uniformly sample the design space which lends itself well to training a representative surrogate model. Furthermore, the R-squared method or root mean squared error are common methods used to evaluate the fit of the model in comparison to the real data.

The next phase used the inputs, definitions, and performance indicators to define the simulation model that provided the synthetic training data for two housing archetypes including terraced and detached dwellings across the range of construction years.

4. How can the simulation model be developed **parametrically** to accurately simulate and sample the design space addressing the occupancy profiles pre- and post-refurbishment, thermal performance of refurbishment measures and performance indicators?

The simulation model defined a parametric workflow to define the various input parameters. Firstly, a base geometry was defined for each of the housing archetypes and then assigned the respective zones and programs. For each program a standard set of input parameters like the ventilation rate in accordance with the building decree. Additionally, a library of custom household schedules is defined for each of the households in Excel and then connected to the simulation model to facilitate adaptability and flexibility for the profile definitions in line with literature studies previously. Furthermore, the envelope parameters were defined by parametric sliders with a predefined step size to formulate discretised parameters with the upper and lower bounds which include both the thermal performance values of both the original envelope for each of the respective construction years as well as the refurbishment measures. The thermal resistance values specifically define the insulation layers and thus are independent of the basic construction that is assumed to be constant. This is done to be able to collect data samples to train one surrogate model that can be used to evaluate the outputs and performance of both the current constriction and the refurbished version whilst minimising the need to define a library of predefined wall constructions.

Furthermore, the novelty of this workflow is the ability to determine the radiator capacity dynamically in relation to the constructional properties of a dwelling that directly relates to the dwelling construction year in accordance with ISSO 51 standards. This provides an accurate base for defining the radiator capacity in correlation with the construction year upon which the logarithmic mean temperature difference and radiator exponent is used to calculate the radiator capacity at low temperatures. The model used this definition to dynamically change between the original high-temperature radiator scenario and the low-temperature radiator scenario. Furthermore, to toggle between different ventilation systems, a combination of percentage window operability, window opening schedule, occupancy schedule and mechanical ventilation rates per zone helped define the distinctive ventilation systems. In addition to the standard energy demand outputs that are provided by Energy Plus simulations, a custom script was defined as part of the workflow to incorporate the ATG method of assessing the number of hours too cold that is representative specifically for residential dwellings and this was specifically assessed at the living room zone level as a proxy for the entire dwelling. Finally, a calibration with the existing empirical studies and a sensitivity study helped validate the simulation model to ensure the quality and certainty of the training data used to train the surrogate model.

5. How can a building energy surrogate model be combined with LCC cost analysis to generate Pareto set results?

The simulation model is connected to mode FRONTIER, a platform that helps assist with simulation automation and optimization. It facilitated the automated sampling and processing of the synthetic simulation data which resulted in a training data set of 2000 samples with 13 input parameters. One of the novelties of this study is the use of categorical variables within the surrogate model that involved the process of one hot encoding. The data was then used to train a surrogate model using a selected set of machine-learning algorithms. After validating the performance of the models using the R-squared method, the artificial neural network model was determined to be the most accurate.

To generate the Pareto set of results, the surrogate model is integrated into an optimization workflow using Wallacei X. The workflow develops a flexible workflow to filter and translate input parameters for the surrogate model to be able to generate the building's physical performance indicators of comfort and energy demand. Additionally, a workflow to access the database of the defined set of refurbishment measures with researched cost data was developed. This helped accurately define the investment cost for the refurbishment measures. In addition to the investment cost, the energy cost is defined by the post-processed final input energy value considering system COPs in combination with energy prices and the maintenance cost is defined as a percentage of the investment cost of distribution building installations. These sub-outputs are multiplied by respective discount rates to determine the final global cost per refurbishment measure combination in a dynamic framework which is one of the novelties of this study.

The final stage involved the use of the trained surrogate model and proposed optimization workflow to understand the range measures that can be expected from the decision-making tool for a diverse range of scenarios. This helps evaluate the effectiveness of the surrogate model in comparison to previous studies whilst understanding how the workflow can be improved to better facilitate the decision-making process.

6. How can the decision-making tool prescribe categorised LT-ready refurbishment strategies to facilitate the decision-making process?

In order to generate optimal refurbishment measures to deliver low-temperature ready refurbishment measures, the Pareto front set of solutions was categorised and filtered into 5 main categories including i) lowest investment cost, ii)lowest global cost, iii) lowest space heating demand, iv) lowest hours too cold (maximum comfort) and v) best-performing measure overall which is defined as the measure that is closest to the utopian point or point of origin as it equally considers all three performance indicators or objectives.

A set of scenarios were investigated, and the initial analysis suggests that the proposed workflow defines refurbishment measures that align with previous studies. Moreover, since the solutions are Pareto optimal solutions that considered global cost as one of the optimization objectives, it was clear that the refurbishment measures proposed could be categorised as no-regret low-temperature ready refurbishment strategies as the combined measures resulted in space heating energy demand and hours too cold well below the baseline targets set by the Nieman standards.

Additionally, the tool provided insightful information regarding the share of investment cost and energy cost towards the overall global cost. It was concluded that due to the higher contribution of energy cost to the overall global cost, ambitious insulation measures like external envelope insulation are feasible in the long term with higher initial investment costs that account for the savings in global long-term cost. This is in addition to achieving the maximum level of airtightness with triple glazing. Moreover, the best-performing measures helped conclude that the type c2 ventilation systems are adequate to deliver sufficient energy savings and thermal comfort. The low-temperature radiator systems are only preferable when considering the most optimal levels of comfort.

Additionally, the initial results of evaluating the post-occupancy complied with previous literature studies with the impact in behaviour change decreasing as the refurbishment measures tend towards the best-performing category with more intensive refurbishment measures. The results suggest that based on the high behaviour profile has a more drastic impact on the space heating demand, hours too cold and global cost post-refurbishment compared to the lower consumption behaviour post-refurbishment. This can be an effective method of educating the newly LT-ready occupants on the impact of their behaviour on their saving potential after they refurbish their dwelling and

7. What methods can be used to make the proposed workflow more accessible to decision makers to facilitate the decision making process?

To address this question, further work will need to be conducted in developing a user interface as a mock up to help demonstrate how the tool can be scaled and distributed in a user-friendly manner. This will follow in the next phase of this research.

After answering the respective sub-research question the main question can be answered:

How to develop a **surrogate model**-based decision-making tool to select **combined, no-regret refurbishment measures** using **performance indicators** for **multiple Dutch housing** typologies considering **occupancy behaviour** and **lifecycle cost** to transition to **low-temperature district heating?**

In order to transition to low-temperature district heating, this thesis has demonstrated that an artificial neural network-based surrogate model can be effectively used within a decision-making process to suggest optimal refurbishment measures that can help maintain thermal comfort. The housing archetype use includes terraced, detached and portiek apartments for varying household types including nuclear, senior and adult couples. The refurbishment measures include the use of demand-driven type C2 ventilation systems, increased airtightness, triple glazing and cavity insulation as part of the envelope. These measures can form refurbishment packages that are categorised into the lowest investment, lowest global cost, lowest space heating demand, lowest hours too cold and best performing overall. In order to evaluate the refurbishment measures, the space heating demand and hours too cold is compared against the no-regret refurbishment target defined by Nieman. Additionally, the financial feasibility is also addressed using the global cost method. This is then finally made accessible to users through a user-friendly interface that can finally bring help address the challenge across neighbourhoods that can transition to low-temperature district heating at scale and therefore lead us to a more sustainable future !

6.2 Research limitations

This study acknowledges several limitations of the study that need can be addressed further and developed upon. Firstly, based on the current objectives with global cost being used instead of investment cost, the high contribution of energy cost to the global costs means that the Pareto optimal measures are limited in a range which has resulted in comparably more **intensive refurbishment measures even at the lowest investment cost category.** Furthermore, the results derived from the post-refurbishment occupancy behaviour change have been addressed for a limited set of scenarios. This in combination with the limited range of measures in relation to overall performance, results in a potential loss of information where there could be an interrelation between the refurbishment measure and the impact of post-refurbishment occupancy behaviour change.

Moreover, the dominant refurbishment measure includes significantly improving the overall airtightness of the dwelling, which is due to its high sensitivity, especially on space heating demand. This could also be a potential reason for the **relatively low energy demand** across the Pareto front solutions which could be considered as optimistic. This could be further investigated by controlling the refurbishment measures for infiltration and re-evaluating the proposed solutions within the design space for the respective scenarios and categories. This can be supported by a critical investigation into the feasibility of the proposed infiltration reduction measures.

The current method of defining radiator capacity does not consider the **oversized capacity of existing radiators** when transitioning to low-temperature district heating. Although the current methods adapt to the thermal performance for the specific construction year based on the input parameters, the radiator capacity also is inherently then dimensioned in accordance with the refurbished state. Therefore a separate, yet interconnected workflow would need to be defined to define the original radiator capacity based on the construction year whilst maintaining that same original capacity when evaluating the refurbishment measures when transitioning to low-temperature heating. This is because, in its current state, the model is trained on precise radiator capacity dimensioning for every combination of thermal input parameters and therefore lacks training data that can allow it to consider oversized radiator capacity from the original base condition that can then impact the final thermal comfort of a space.

Additionally, the although the global cost lifecycle cost assessment considers the current up-to-date energy prices and market inflation rate, there have been evident **fluctuations in energy prices** over the past couple of years. Therefore, the model can only predict the global cost with limited certainty and is used more as a comparative assessment between the current condition and the proposed measures and its impact on cost in the long term. Finally, the current methodology assumes complete replacement of the existing insulation in the envelope and thus as seen with the two construction year ranges 1920 – 1945 and 1945 – 1975, the decision model presents **similar refurbishment measures** for each of the categories. Therefore currently the workflow is well suited to make a comparison between the current base condition and the categorised refurbishment measures.

6.3 Further Areas of Research

The methodology is proven to be easily adaptable to multiple housing archetypes and construction years and therefore it would be valid to test the workflow out on multiple housing typologies further and evaluate the refurbishment measures. Moreover, previous studies have suggested that although the surrogate model can have a low error rate based on the random sample validation, there can be instances where the error rate is not evenly distributed across the design space and can potentially increase as solutions tend towards the optimal solutions that exist at the bounds of the input parameter range where small variations in output values can result in higher error rates. This could potentially be resolved by an **iterative surrogate model training process** where the model is retrained by either expanding the input parameter range or focusing the bounds on the domains where Pareto optimal solutions converge, however, this would need to be examined further. Additionally, as mentioned earlier the starting construction year has a limited impact on the final proposed measures. To address this challenge it would be relevant to **add the base condition insulation in addition to the new refurbished insulation** measures where the converged measures may be similar however, the investment costs would be lower for new construction and therefore deliver more context-specific solutions.

Additionally, it would be of interest to use the trained model and workflow to understand how the measures vary by **changing the optimization objective** to consider initial investment cost directly instead of global cost to understand how that can impact the suggested measures and this could potentially lead to less intensive refurbishment packages overall that could it make it more difficult to reach the low-temperature ready targets. Additionally, another option is to use the targets defined by the Nieman no-regret refurbishment target in the optimization objective by minimising the distance to the target performance indicator. Therefore, the objective would shift from the most optimal solutions to one that meets a set minimum target that is sufficient. Additionally, the methodology used in this research has provided a flexible framework in which the **refurbishment database can be expanded** to include more refurbishment measures with an extensive cost database that can then include accurate cost data from a manufacturer's database. Similarly, the framework can be expanded to also **include more specific housing typologies** like ground-floor apartments, gallery apartments and corner dwellings.

Furthermore, once the model has been extensively validated and tested for accuracy, it could be used in practice to test out its **effectiveness with decision-makers in practice**, understand their knowledge gaps, and interpretation of refurbishment measures to gauge an understanding of how effective the tool is from a user perspective. Additionally, the model can also be effectively used to conduct a global sensitivity analysis to gain a deeper understanding of the interdependency between input parameters and the overall impact of each parameter on the respective performance indicators. Furthermore, as an additional feature, it would be useful to add the possibility of altering the weights of each of the optimization objectives to allow the ability of users to select the importance they would give to each of the objectives. Moreover, based on the review of existing tools in the market, there is currently a focus on technical parameters like energy and comfort with **less focus on soft parameters** like aesthetic value and ease of implementation. This could be further investigated and implemented in the tool.

7. Reflection

1)How is your graduation topic positioned within the Building Technology studio?

My graduation thesis is titled " **LT-Ready: A Surrogate Model-Based Decision Tool for Low-Temperature District Heating Refurbishment**". This research topic falls under the domain of façade & climate design in combination with computational design. The topic addresses the pressing challenges of implementing complex, multi-objective refurbishment strategies that include various building physical and performance aspects including comfort, energy, and materiality. In order to be able to examine multiple refurbishment strategies that meet the set objectives in both a computational and time-efficient manner whilst enhancing the capabilities of existing tools, a surrogate model based on machine learning principles is developed to help assess a large number of possible refurbishment strategies to arrive at an optimised solution. Therefore, the thesis bridges the gap between the two disciplines in an integrated manner.

***2**) How did the research approach influence your design/recommendations?*

The research considers a broad range of challenges, specifically addressing the need of delivering low temperature-ready refurbishment strategies whilst also exploring the broader context of refurbishment challenges that currently hinder the transition to a sustainable built environment. This includes the challenge of scalability across housing typologies, life cycle cost and occupancy behaviour.

Therefore, the initial research phase involves the collection of existing data from previous studies regarding the individual themes. For example, the study of the housing typologies and their typical, sensitive parameters formed the bases for developing the base simulation model from which synthetic training data is collected. Additionally, an in-depth study was conducted of the existing methodologies currently being used to effectively train surrogate models in the context of building energy simulation and studying effective workflows to effectively manage and train the surrogate models. The initial literature study provided crucial building blocks for developing the tool as it made sure that the data that the model was trained on was a valid representation of existing dwelling conditions and refurbishment practices in the industry.

3) How do you assess the chosen approach and methodology?

To develop a surrogate model that considers a variety of interdependent parameters, it proved crucial to develop the model within a flexible, parametric framework. This facilitated the iterative development of the tool where custom components and helped maintain more control whilst improving the efficiency of the overall development process. However, this also resulted in a longer development process in comparison to traditional building simulation tools like Design Builder wherein the in the basic architecture of the tool is predefined in a methodological application. This was not taken into consideration during the initial development stage which could have been foreseen. Furthermore, I believe a deeper discussion on the building energy performance input assumptions during the initial development stage could have resulted in further improvement of the accuracy of the training data used to train the simulation model. However, the initial calibration process and sensitivity analysis helped validate the initial assumptions made.

Furthermore, in the context of running building simulations that are time-consuming and complex, especially in the context of parametric tools, a crucial learning outcome was to run periodic tests along the development process before increasing the overall complexity to prevent extended debugging procedures. Furthermore, one of the main challenges was establishing the computational architecture to run the many iterations of training data required to train the surrogate model parallelly across multiple computer nodes. However, this proved crucial to being able to quickly test and iterate through various training algorithms.

Additionally, I believe the feedback from mentors was particularly helpful in refocusing and zooming out to see the development process in a larger context, especially during the initial stages of setting up the simulation and computational workflow. Additionally, interviews with experts in the field, provided deeper insights into the potential pitfalls when using a relatively novel methodology.

The overall approach helped effectively answer the research question and the positive aspect of the research approach was taking relatively well-established, individual research themes in the field of low-temperature refurbishment and piecing it together using a new approach.

4) How do you assess the academic and societal value of your graduation?

Within the academic field, this thesis has helped build on existing research, especially in relation to the integration of occupancy behaviour and life cycle cost within the context of low-temperature heating refurbishment within a larger scalable, computational approach to address multiple housing archetypes and construction years. Furthermore, the majority of previously studied methodologies primarily considered a limited set of quantitative building simulation input parameters, and this research demonstrates a method to address qualitative, categorical data like occupancy behaviour. Additionally, the decision-making tool can be potentially used in the academic domain within sensitivity studies and further examination of the impacts of input parameters in a time-efficient manner.

In the larger context of societal impact, I believe the development of decision-making tools helps make complex, computational building simulation models more accessible to the decision-makers where the optimization process prescribes categorised potential refurbishment strategies rather than demanding users to explore a broad range of refurbishment measures without understanding which potential solutions are the most effective and optimal. However, I believe the tool can be improved further in order to reduce the number of technical input parameters and instead take into account a deeper understanding of the limitations and existing knowledge base of the users. Furthermore, I ability of the tool to assess post-refurbishment behaviour change could be an important method to educate users on their behaviour from an energy consumption point of view in order to engage with users and present a more holistic approach to dwelling refurbishment in general as it can have a significant impact on potential savings from the chosen refurbishment measures.

5) How do you assess the value of the transferability of your project results?

The aspect of transferability and scalability is pertinent, especially to this graduation topic. The goal of this research was to develop a scalable, decision-making tool, helping homeowners and the respective homeowner associations across neighbourhoods transition to low-temperature district heating. Therefore, the tool currently makes broad assumptions concerning the most common typical building archetypes and their respective constructional properties. However, the building stock is still quite varied and thus the model currently provides some degree of flexibility to adjust default input parameters for the initial condition. However, this is limited to the envelope and installation parameters of a dwelling and does not provide the ability to change the underlying dwelling geometry which can become a challenge especially when considering the increase in variation in detached dwellings and apartments. It would be interesting to define a method to capture that variability by defining a single parameter like compactness ratio for example. Furthermore, the methodology used still requires a significant amount of data and time to train and validate each of the surrogate models and would require intensive testing before it can be rolled out at scale. An interesting feature or subcomponent of the studied methodology is the use of an editable refurbishment measure database within the workflow, and I think as more UpToDate data becomes available, with potential economies of scale or local sourcing of materials, this could help improve the scalability of the tool in the future.

6) What are the potential challenges limiting the use of the applied methodology in practice?

The tool has theoretically proven to be able to provide useful insights when deciding the low-temperature district heating refurbishment strategies. However, before it can be implemented in practice in the industry certain limitations of the approach need to be addressed. When developing recommendation-based tools with optimized solutions, the research shows that the interpretability of the results is only as good as the fundamental framework and objectives built into the tool. Therefore, it's difficult to completely factor in all the practical limitations in relation to the implementation of refurbishment solutions. For example, certain solutions may be optimised, however, it's practically unfeasible due to limitations on material availability or inefficiencies that could potentially have been avoided by choosing a slightly less optimised solution but with more logistically efficient procedures. The single solution-based approach limits the possibility of evaluating the broader range of solutions and therefore brings to discussion the role of building technologists as facilitators within the decision-making process in harmony with the tool. It potentially makes the tool a more engaging, insightful facilitator within a larger framework of decision-making that still involves traditional experts that analyse and develop the final solutions. However, the tool makes decision-makers less dependent on the limited set of measures that are defined by the experts.

Furthermore, it's widely known that there can exist large performance gaps in the initial building simulation energy savings proposed by conventional simulation tools in comparison to the real building energy consumption. Moreover, the accuracy and certainty of the prescribed solutions from a surrogate mode are highly dependent on the availability and quality of the training data used to train the models. Thus, the application of such tools is also dependent on the development of the accuracy of building performance simulations in the wider context before it can be utilised with a certain level of confidence. Additionally, such models require extensive validation and use-case-based testing of the tool to discover underlying accuracies of the model especially when considering complex, multi-variate problems like the one addressed in this research. Therefore, the overall process of training, pre-processing and validating the models brings into question the net time savings overall. To be able to justify the time invested in developing the tool, it must be developed considering the scalability and adaptability of the models which can potentially come at the expense of accuracy for specific scenarios.

7) How does this approach relate to the larger context of innovation within the broader industry?

Recent advancements in natural language-based machine learning models like chat GPT can provide an interesting synergy to such decision-making tools. Current tools are primarily text-based with a static line of information delivery. An interesting concept could be a more collaborative, initiative-based line of information where the decision-maker can interrogate the solutions and ask questions while using the tool to help the decision-makers expand their knowledge base and become active learners through the process. This does bring into question the role of experts as facilitators within the decision-making process. However, it's interesting to understand if such approaches could reduce the friction involved in sustainability decision-making processes.

Additionally, I think such tools have a large potential to be combined in a larger network of data-driven insights in the built environment. For example, the Netherlands is one of the countries with a significant amount of geospatial data on their built environment that is accessible in an open-source environment. As this data infrastructure is strengthened with more detailed and accurate data regarding the building physical properties of the dwellings, it can be combined with such decision-making tools to integrate accurate data seamlessly.

Furthermore, in the context of low-temperature district heating, it thinks the research currently addresses the refurbishment challenges at the building context level. However, I believe the existing infrastructure needs to also be refurbishment with interesting developments in the field including projects like "TEMPO" with innovations in district heating fault detection and decentralised buffers that help make the networks more efficient and resilient. Therefore the scope of this research could potentially examine further research verticals that extend to the existing network infrastructure.

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Appendix 1 - Housing typologies characteristics(Agentschap NL, 2011; Cornelisse et al., 2021)

Parameters	Terraced housing				Semi Detatched				Detatched				Apartment			
Construction year	<1945	1945 - 1975	1975 - 1995	**>1995**	**<1945**	1945 - 1975	**1975 - 1995**	**>1995**	**<1945**	**1945 - 1975**	**1975 - 1995**	**>1995**	**<1945**	1945 - 1975	**1975 - 1995**	**>1995**
Area (median)	109	108.5	113.5	124.8	120.4	115.8	119.5	140.9	155.7	162.7	161.8	185.2	80.8	76.6	73.3	89
Compactness ratioAls/Ag	1.6	1.5	1.4	1.4	2.0	1.9	1.9	1.9	2.3	2.3	2.2	2.2	1.3	1.0	1.2	1.0
WWR (back and front façade)	34%	39%	32%	30%	21%	23%	21%	21%	17%	18%	19%	21%	48%	50%	36%	39%
Ground floor Rc	0.77	0.57	1.16	2.68	0.73	0.6	1.25	2.63	0.94	0.66	1.35	2.64	0.56	0.48	1.16	2
Closed façade Rc	0.7	0.84	1.53	2.68	0.82	1.06	1.61	2.59	0.99	1.10	1.69	2.56	0.58	0.67	1.66	2.61
Flat/pitched roof Rc	1.24	1.22	1.5	2.75	1.2	1.23	1.59	2.69	1.42	1.40	1.82	2.68	1.00	0.96	1.66	2.67
Glazing Rc	0.34	0.37	0.35	0.48	0.33	0.37	0.37	0.46	0.34	0.38	0.36	0.47	0.32	0.35	0.34	0.46
Glazing U-value	2.96	2.73	2.82	2.1	3.06	2.69	2.72	2.16	2.98	2.66	2.74	2.14	3.11	2.87	2.91	2.16
Airtightness level 1 (original) dm3/s/m2	3.0	3.0	3.0	1.5	3.6	3.6	3.6	1.8	4.2	4.2	4.2	2.1	1.8	1.8	1.8	0.9
Ventilation system	System A	System A	System C1	System C1	System A	System A	System C1	System C1	System A	System A	System A	System C1	System A	System A	System C1	System C1
Heating power output level 1 W	18,887	12,074	14,241	10,287	21,509	14,413	18,531	11,069	25,503	30,508	32,070	12,661	5,639	9,704	9,006	7,675
Energy Label	G	E-F	D	C	F	E-F	C	B	G	E-F	D	B	G	E	C	B
Avergae WWR	33.7%				21.6%				18.7%				43.4%			
Average floor area m2	114.0				124.2				166.4				79.9			
Average compactness ratio	1.5				1.9				2.3				1.1			
Closed façade	42.3	40.5	40.6	49.9	97.8	104.7	96.6	108.5	136.7	164.7	144	150.9	20.8	21.2	23.7	24.7
Single/ Double glazing m2	6.5	4.3	3.1	7	6.5	6.7	3.4	25.9	8	5.8	2.9	18.1	4.5	6.9	1.2	4.7
Double Glazing/HR++ m2	14.9	21.3	16.2	14.8	19.5	24.6	23	3.1	20.3	29.5	31.58	21.5	14.8	14.4	12.4	11.1
Total façade m2	63.7	66.1	59.9	71.7	123.8	136	123	137.5	165	200	178.48	190.5	40.1	42.5	37.3	40.5

Appendix 2 - Variables contributing to behaviour factors (Guerra-Santin & Silvester, 2016)

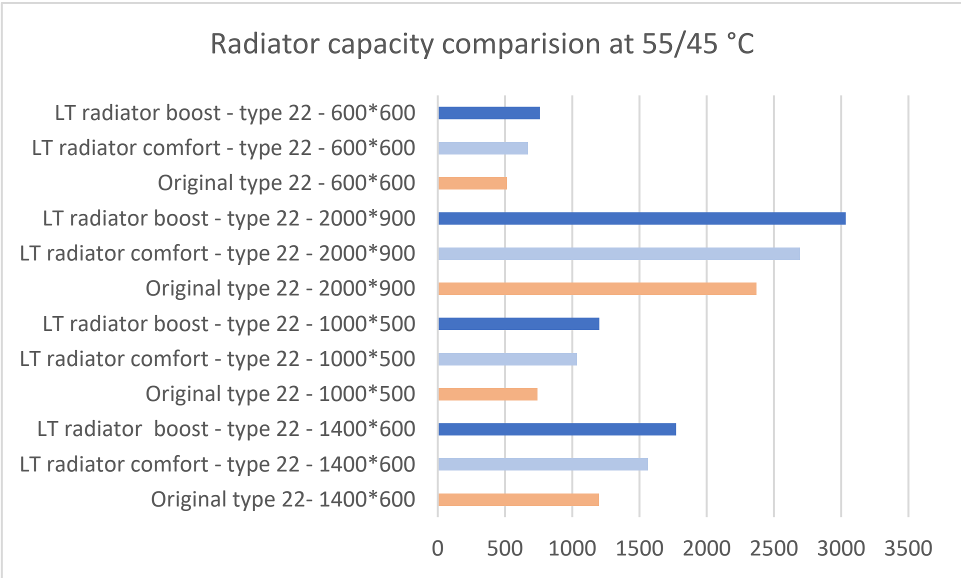
Factor and name	Variable contributing
Factor 1. Presence home factor score	Presence at home, 06:00–09:00 Presence at home, 09:00–12:00 Presence at home, 12:00–15:00 Presence at home, 15:00–18:00 Presence at home, 18:00–23:00 Presence at home, 23:00–06:00
Factor 2. Temperature day factor score	Thermostat settings, 09:00–15:00 (°C) Thermostat settings, 15:00–18:00 (°C) Thermostat settings, 18:00–23:00 (°C)
Factor 3. Temperature setback factor score	Thermostat settings, 06:00–09:00 (°C) Thermostat settings, 23:00–06:00 (°C)Thermostat settings, when nobody home (°C)
Factor 4. Bedroom radiators factor score	Radiators on in the main bedroom Radiators on in other bedrooms
Factor 5. Ventilation factor score	Natural ventilation in the living room while heating Natural ventilation in other rooms while heating
Factor 6. Other rooms' radiators factor score	Radiators on in the kitchen Radiators on in the bathroom

Appendix 3 - ANNOVA test : factor scores for each household test (Guerra-Santin & Silvester, 2016)

Factor	Lower scores	*u*	Higher scores
1. Presence home factor score $F(6, 1224.5) = 28.74$, $p < .001$	Single adult Two adults *(less often)*	3 adults Single parent	Two seniors Single senior Nuclear family *(more often)*
2. Temperature day factor score $F(6, 1211.5) = 49.20$, $p < .001$	Single adult *(lower)*	Two adults 3 adults Nuclear family Single parent	Two seniors Single senior *(higher)*
3. Temperature setback factor score $F(6, 1216.9) = 9.1$, $p < .001$	Single adult Single parent Two seniors Two adults *(lower setting)*	n.a.	3 adults Single senior Nuclear family *(higher setting)*
4. Bedroom radiators factor score $F(6, 1223.9) = 5.0$, $p = .001$	Single parent Nuclear family *(more frequently)*	Single adult Single senior Two adults Two seniors	3 adults *(less frequently)*
5. Ventilation factor score $F(6, 1226.5) = 1.86$ n.s.	*(more)*	Single senior Single adult Nuclear family 3 adults Two adults Two seniors	Single parent *(less)*
6. Other rooms' radiators factor score $F(6,1232.8) = 24.1$, $p < .001$	Two seniors 3 adults *(more frequently)*	Nuclear family Single senior Two adults	Single parent Single adult *(less frequently)*

Note: n.a. = Not available; n.s. = not statistically significant.

Appendix 4 - Radiator capacity comparison between original high temperature and LT comfort/ boost radiators.(RADSON)



Appendix 5 - Senior household base schedule

Living room	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	-1	-1	-1	-1	-1	-1	-1
1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	-1	-1
3	-1	-1	-1	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	6	6	6	6	6	6	0
7	6	6	6	6	6	6	0
8	6	6	6	6	6	6	0
9	9	9	9	9	0	0	0
10	9	9	9	9	0	0	0
11	9	9	9	9	0	0	0
12	12	12	12	12	0	0	0
13	12	12	12	12	0	0	0
14	12	12	12	12	0	0	0
15	15	15	15	15	0	0	0
16	15	15	15	15	0	0	0
17	15	15	15	15	0	0	0
18	18	18	18	18	18	0	0
19	18	18	18	18	18	0	0
20	18	18	18	18	18	0	0
21	18	18	18	18	18	0	0
22	18	18	18	18	18	0	0
23	-1	-1	-1	-1	-1	-1	-1

Appendix 6 - Senior household setpoint inputs for base schedule

Senior couple Heating setpoint values in living room

Hours	Heating setpoint
-1	19
0	20
6	21
9	22
12	22
15	22
18	23

Senior couple Heating setpoint values in bedroom (semi-open)

Hours	Heating setpoint
-1	19
0	20
6	21
9	21
12	21
15	21
18	21

Senior couple Heating setpoint values in kitchen and bathroom (open)

Hours	Heating setpoint
-1	19
0	20
6	21
9	22
12	22
15	22
18	23

Appendix 7 - Adult couple household base schedule

Living room	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
0	-1	-1	-1	-1	-1	-1	-1
1	-1	-1	-1	-1	-1	-1	-1
2	-1	-1	-1	-1	-1	-1	-1
3	-1	-1	-1	-1	-1	-1	-1
4	-1	-1	-1	-1	-1	-1	-1
5	-1	-1	-1	-1	-1	-1	-1
6	6	6	6	6	6	0	0
7	6	6	6	6	6	0	0
8	6	6	6	6	6	0	0
9	9	9	9	0	0	0	0
10	9	9	9	0	0	0	0
11	9	9	9	0	0	0	0
12	12	12	12	0	0	0	0
13	12	12	12	0	0	0	0
14	12	12	12	0	0	0	0
15	15	15	15	0	0	0	0
16	15	15	15	0	0	0	0
17	15	15	15	0	0	0	0
18	18	18	18	18	18	0	0
19	18	18	18	18	18	0	0
20	18	18	18	18	18	0	0
21	18	18	18	18	18	0	0
22	18	18	18	18	18	0	0
23	-1	-1	-1	-1	-1	-1	-1

Appendix 8 - Adult couple household setpoint inputs for base schedule

Adult couple Heating setpoint values in living room

Hours	Heating setpoint
-1	15
0	16
6	17
9	18
12	18
15	19
18	20

Adult couple Heating setpoint values in bedroom (semi-open)

Hours	Heating setpoint
-1	15
0	16
6	17
9	18
12	18
15	18
18	18

Adult couple Heating setpoint values in kitchen and bathroom (semi-open)

Hours	Heating setpoint
-1	15
0	16
6	17
9	18
12	18
15	18
18	18

Appendix 9 - Building simulation grashopper pseudo code