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A Parametric Modelling Approach for Energy Retrofitting Heritage Buildings: The Case of Amsterdam City Centre

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Abstract: The city of Amsterdam has ambitious goals to achieve a 95% reduction in carbon emissions by 2050 and to phase out natural gas by 2040. Disconnecting the building stock from natural gas requires well-ventilated and well-insulated buildings and a switch to renewable energy sources, making optimal use of heat pumps and sustainable heating solutions available locally. Most buildings in the historical city centre are protected and often insufficiently insulated, leading to increased energy use and a poor thermal environment. Standard retrofitting interventions may be restricted, requiring new approaches to balancing the need for energy efficiency and the preservation of heritage significance. With the case of the Amsterdam City Centre, the goal of this research is to present a parametric modelling approach for energy retrofitting heritage buildings and to identify minimum requirements for preparing the residential stock to lower temperature heat (LTH). Using parametric design and bottom-up energy modelling, the research estimates that a 69.1% of natural gas reduction could be achieved when upgrading the buildings to lower temperature (LT). Results of this paper also demonstrate how the applied approach can be used to guide decisions on the improvement in energy performance of the historic built environment.

Keywords: built heritage; energy retrofitting; parametric modelling; simulation; low-temperature heating

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1. Introduction

1.1. Context

In the Netherlands, energy use for heating in the built environment accounts for nearly 15% of the national energy consumption [1]. According to the Dutch Central Bureau of Statistics, about 89.5% of Dutch households use a natural gas boilers for heating [2]. In Amsterdam, emissions from the built environment represent about 28% of the total carbon dioxide (CO_2) emissions [3]. Phasing out the use of natural gas for all existing and new homes by 2040 would enable a carbon reduction of around 370 kilotons, almost 30% of the current emissions in the built environment [3]. The Transition Vision Heat (in Dutch: Transitie visie Warmte), published by the Municipality of Amsterdam in 2020, outlines the lowest cost alternatives to moving from fossil fuels to sustainable heating sources for housing and non-residential buildings. By the year 2050, the city aims to reduce CO_2 emissions by 95% compared to 1990 and to be natural gas-free by 2040 [4]. Amsterdam is composed of nine city districts ('stadsdelen'), which are the link between the neighbourhoods ('buurten') and the town hall ('stadhuis'). The Transition Vision Heat specifies the steps for each district to achieve the heat transition goals, while highlighting the importance of making this transformation affordable for citizens and with a reliable heat supply. Every 5 years, the Transition Vision Heat of Amsterdam is revised. Clear goals were established, but the pathways to achieve these targets remain vague, especially for the historic inner city, or 'Centrum'. Due to the listed heritage in the area (a lot of monuments), the municipality decided to keep buildings connected to the gas grid, focusing on 70% natural gas reduction by 2040, and to use biogas, hydrogen, and hybrid solutions for the remaining energy demand [4].

Radical renovation schemes seem non-viable since Amsterdam would jeopardise its United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage status and a large part of its tourism attractiveness [5]. At present, there is currently no intention to expand the existing high-temperature (HT) district heating networks towards the city centre. Switching to sustainable gas types through the existing grid used for natural gas is unambitious because it may give the impression to homeowners that little efforts are expected from them to achieve the decarbonisation of their building [6]. Moreover, the availability of hydrogen and green gas is limited, and their production is not always as environmentally friendly as perceived. Recent studies demonstrate that using hydrogen for heating is economically or environmentally unfavourable and more expensive than using heat pumps and district heating [7,8]. Research emphasises the optimistic expectations of the Dutch government for application of green gas in the residential sector, but the production and deployment of green gas for a large-scale implementation are not ready in the Netherlands [9]. Climate-neutral hydrogen is hardly available, and there is still little experience with its use for heating homes and buildings. In the coming years, therefore, attention will mainly be focused on a limited number of pilot and demo projects to gain knowledge and experience about the maximum safe and efficient application of hydrogen in the existing built environment [10]. When sufficiently insulated, buildings can be efficiently heated using a heat pump in combination with local LTH from open water, air, soil, or anthropogenic residual heat sources [11]. With the prominent presence of water in the canals, coupled with residual heat from cooling processes and exhaust air, utilising LT sources emerges as an alternative strategy for decarbonising Amsterdam Centrum. However, there is still a great deal of uncertainty about which combinations of measures are required to prepare heritage buildings to a LT level.

1.2. Energy-Efficiency Measures for Heritage Buildings

Raising awareness about the importance of managing and preserving built heritage is integral to the idea of urban sustainability [12,13]. Around 20% of the European buildings were constructed before 1945, usually with low energy performances [14,15]. Historic centres in Europe have a key role to play in the journey towards a natural gas-free future, and interest in the topic of energy efficiency in heritage buildings has been growing in the last decade [14,16,17]. The inner city of Amsterdam is the district with the highest heat demand density, and heritage buildings constitute the largest share of the building stock, with 86% of the buildings being protected [5]. Post-insulation measures for heritage buildings are limited by a list of rules and regulations, and architectural interventions must respect aesthetic and historic conservation principles. The buildings usually have poor thermal insulation and suboptimal thermal comfort, which may lead to increased energy demand. Natural ventilation via window openings and air infiltration, which are the traditional means of air exchange between indoor and outdoor spaces in historic buildings, causes significant heat losses in cold months.

In practice, implementing energy retrofitting measures in historic buildings is a challenge [13]. Some buildings may be too fragile to withstand the installation of energy-efficient services or the introduction of renewable energy sources. Enhancing energy efficiency leads to a more air-tight building envelope; thus, interventions must be carefully executed due to the risks of damages, such as condensation, mould growth, and moisture. Only limited technical standards are made available, and owners are much in need of expert guidance and upfront insights on the technical and financial feasibility of measures to make well-informed energy investments. Solutions need to be planned well in advance and custom-designed, making the process expensive and often unattractive. Specific knowledge and an integrated approach that considers both the need for energy efficiency and the preservation of heritage significance add an extra layer of complexity [18]. Permit processes to upgrade heritage buildings are not always logical processes: a more transparent identification process of "what" parts of heritage buildings can be modified and to what degree is needed [19]. The complexity of evaluating the costs of retrofitting measures and the uncertainty about the energy-saving potentials are additional barriers that hinder the uptake and investment in energy retrofitting. This constitutes a considerable task for the municipality to reach its sustainability targets, while conserving this built heritage and keeping the historic inner city attractive for locals and visitors. So, the question arises as to whether the target of 70% natural gas reduction by 2040 is realistic for the city centre of Amsterdam and what retrofitting measures need to be carried out on the building stock, while maintaining an appropriate equilibrium between energy efficiency objectives and heritage protection.

1.3. Modelling District-Scale 'Retrofittability'

Developing heat demand models is a challenging task given the heterogeneity of the building stock and the diversity of energy patterns associated with different functions [20]. Bottom-up energy models are widely used to estimate district-scale heat demand for building stocks [21–24]. These models help estimate high-level spatial-temporal demand by calculating energy use on building archetypes and extrapolating the results to represent a larger group of buildings at a neighbourhood or district scale [25,26]. Outputs inform planners on the feasibility of current policy goals and provide spatial information on the potential reduction of operational CO_2 emissions in different retrofitting scenarios [26].

Spatial modelling for the energy retrofit of historic urban areas has been explored in previous research, mainly focussing on categorising buildings, assessing the impact of retrofit solutions on heritage value, and finding a balance between energy efficiency and historical preservation [27–29]. Fabbri et al. [30] study both qualitative aspects, such as building conservation, and quantitative aspects, including potential energy savings at a neighbourhood level in Ferra, Italy. Similarly, Egusquiza et al. [31] compare various refurbishment strategies in Santiago de Compostela in Spain using a CityGML model and considering indicators such as energy performance, negative heritage impact, applicability of measures, and economic assessment. However, these studies evaluate retrofit measures either individually or a set of predefined packages, thereby restricting the exploration of diverse combinations. Selecting suitable strategies is complex given the multitude of retrofitting options on both the envelope and the building systems, as highlighted by Wu et al. [32]. To make well-informed decisions, it is important to consider measures simultaneously and to evaluate combined effects and potential trade-offs [32,33]. The range of options greatly varies based on the building typology, construction date, occupancy, and the ambitions of the building owners [34]. Maintaining a high level of detail and customisation is particularly important for heritage buildings.

This research aims to fill this gap by identifying suitable and feasible energy retrofit combinations. This involves utilising parametric design alongside energy simulation engines to assess, compare, and select optimal solutions within a diverse range of combinations. Following such logic, the present approach uses Ladybug Tools 1.6.0 in Rhinoceros 3D 6 software tools to iterate all combinations of measures for building archetypes against energy use, peak heating demand, or feasibility (monumental status). The objective is to assess the optimal trade-offs between different objectives and establish minimum requirements, with a focus on preparing buildings for a LT level. The article has three primary goals:

- present a parametric modelling approach for energy retrofitting of heritage buildings;
- identify opportunities for preparing the buildings for LTH by defining retrofitting packages, including minimum requirements and potential SH demand reduction;
- reflect on the interrelationships between heritage conservation principles and energy efficiency in Amsterdam city centre.

The results of the research also showcase how the parametric model can serve as a valuable tool for informing decisions in planning energy-efficient measures for similar historic urban environments.

2. Materials and Methods

The research follows the New Stepped Strategy: Research (the local circumstances), Reduce (the energy demand), Reuse (residual energy), Produce (from renewable energy sources), which is based on the Rotterdam Energy Approach and Planning (REAP) and the Amsterdam Guide to Energetic Urban Planning (in Dutch: LES-Leidraad Energetische Stedenbouw) [35,36]. The framework proposes a step-by-step plan indicating when, how, and to what extent specific energy measures can be applied to new and existing buildings. The present article focusses on strategies for the first step of the framework by proposing a generic approach to energy retrofit decisions for Amsterdam Centrum. The approach was tested on the residential building stock of Amsterdam Centrum, which counts about 12,500 buildings. Generating non-residential building typologies is challenging and highly relevant for future work, but was excluded from the present research. The approach developed consists of 4 different steps, as summarised in Figure 1.

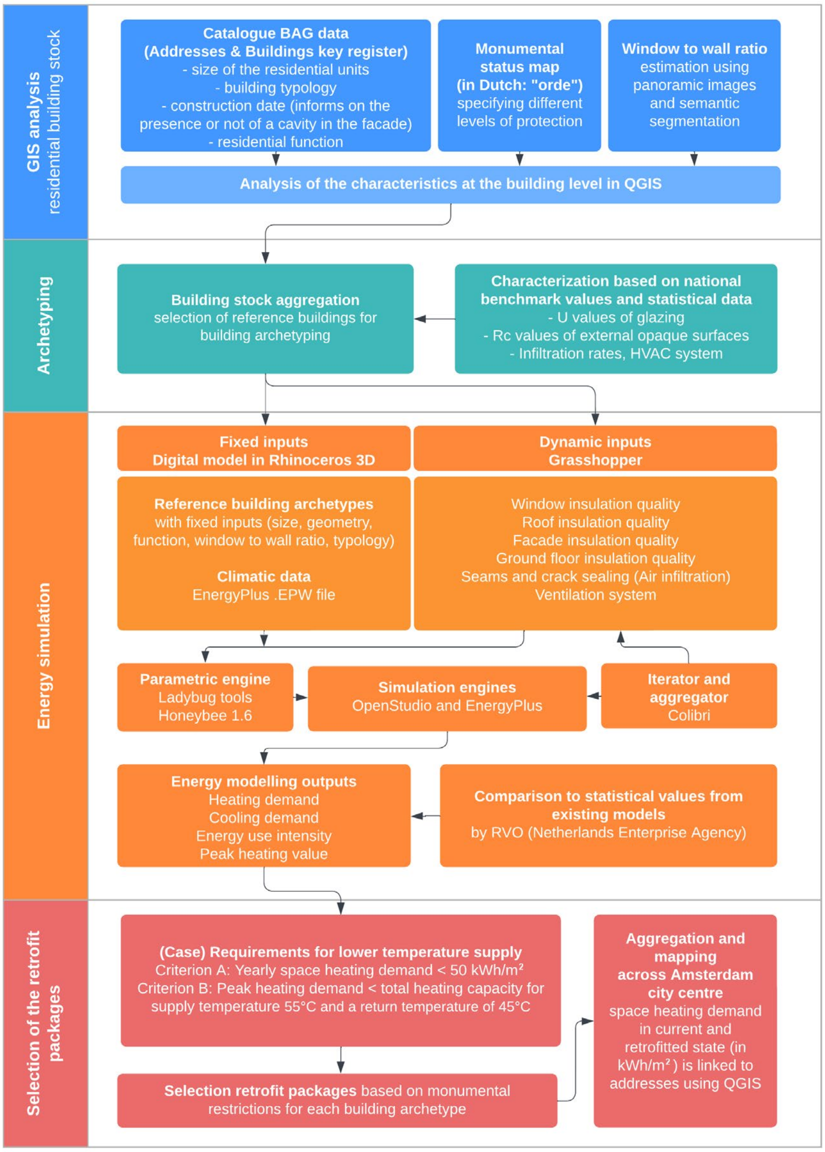

Figure 1. Flow chart of the parametric modelling approach for energy retrofitting.

2.1. Step 1: Geographical Information Systems (GIS)-Analysis of the Residential Building Stock

The following GIS-analysis focuses on the residential building stock in Amsterdam Centrum. Spatial data was collected from multiple resources to conduct the statistical analysis:

- 'Atlas class map: valuation urban and architectural quality' provided by the municipality of Amsterdam [37]. Three protection levels were assigned to the building stock. Orde 1 is the most restrictive and is assigned to buildings that have the status of a national or municipal monument or which are eligible for it. At this protection level, retrofitting activities should use the same materials, colours, and shapes as the original design. Orde 2 is for 'high-value' buildings that make an important contribution to the townscape. Interventions at this protection level should preserve the original façade visible from public space and the roofscape. Orde 3 is assigned to 'medium-value' buildings. An analysis of buildings in orde 3 should be conducted to determine whether retrofitting activities should consider the preservation of the building elements [38]. For both orde 1 and 2, all retrofitting activities must be approved by the municipal architectural committee 'Commissie Omgevingskwaliteit', before building owners can begin the process [39]. The data show that 49% of the buildings in Amsterdam Centrum have a protection level of 1, 28% have a level of 2, 9% have a level of 3, and 14% of the buildings have an undefined status. As shown in Figure 2, most buildings built before 1946 are highly protected with a level 1 or 2.

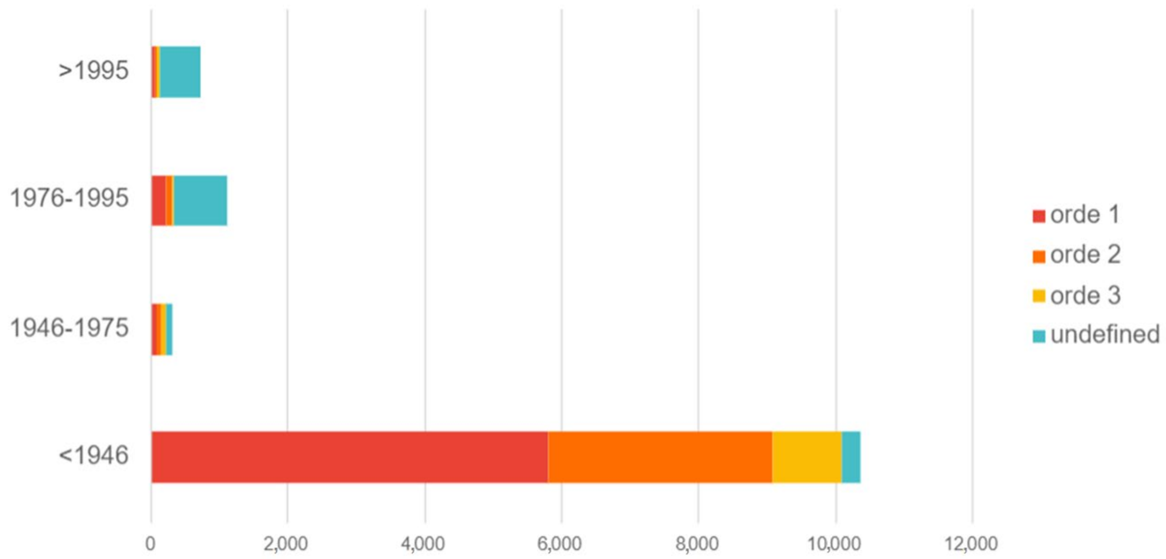

Figure 2. Number of buildings classified per construction period and level of protection in Amsterdam Centrum.

- 'National Register of Addresses and Buildings' (in Dutch: BAG-Basisregistratie Adressen en Gebouwen) on the address and building level with construction date, useable area, and typology [40]. The construction periods were defined based on national standards and used as an indicator of the building characteristics [41]. The typology 'detached' was not further considered since it represents only 0.2% of the residential building stock in Amsterdam Centrum. The typologies 'corner house' and 'semi-detached' (in Dutch: 'hoekwoning' and 'twee-onder-een kapwoning') have similar amounts of surface area exposed to the exterior. For this study, these two types were merged into the same typology 'semi-detached';
- Data on window-to-wall ratio (WWR), defined as the percentage area of a building façade that is glazed, was calculated by extracting façade textures from panoramic images [42]. Figure 3 shows a sample of images used for the calculation.

Figure 3. Sample of panoramic images captured in Amsterdam Centrum [42].

The WWR dataset covers approximately 48% of the front facades of all buildings in Amsterdam Centrum. It shows that the average WWR is 46% for buildings constructed before 1946, 46% between 1946 and 1974, 44% between 1975 and 1995, and 48% for buildings built after 1995. For different typologies, the WWR remains within similar ranges, with an average WWR of 45% for apartments, 47% for terraced buildings, and 41% for semi-detached buildings. Due to the low variability of the WWR, reference buildings were modelled with a WWR of 45%.

2.2. Step 2: Identification and Characterisation of the Building Archetype Stock

The GIS data of Amsterdam Centrum previously described was aggregated into 33 building archetypes based on construction year, protection status, presence of a cavity in the façade, and building typology. Each building typology was represented by a reference object with typical building geometry from the historic inner city. The buildings were chosen based on available datasets of the ongoing and past research projects on sustainable heritage, 'Collect Your Retrofits' and 'Green Light District,' within the Faculty of Architecture and Built Environment at Delft University of Technology [39,43]. Both buildings have a level of protection of 1. The front facades of the two reference buildings are shown in Figure 4.

Figure 4. Front facades of the two reference buildings for energy calculation [43].

Parametric tools are able to condense into a single workflow the design logic, the simulation engines, and the optimisation indicators. It allows the computation and iteration of all possible retrofit packages for each archetype as well as their associated impact on energy performance. The energy model developed combines the geometry of the reference buildings in Rhinoceros 3D 6 with the parametric interface of Grasshopper, a graphical algorithm editor. The plug-in Ladybug Tools allows data transfer between Rhinoceros 3D and the simulation engines OpenStudio 3.5.0 and EnergyPlus 22.2.0 [44]. Building layouts were reproduced and divided into different energy zones. For the multi-storey building, actual energy data were provided to calibrate the model. The terraced archetype used the same reference building layout as the semi-detached archetype, apart from having only the front and back facades exposed. The apartment archetype was considered an average apartment of the 23 residential units in the multi-storey building. The energy demand modelled therefore is the average of all units located on the different floors of the building (on ground, mid, and top levels). No sensitivity analysis was conducted for the effect of the orientation of the buildings on energy performance. A recent report shows that this parameter has a minimum impact on the modelled energy demand [41]. The orientation of the reference buildings was set to north–south. For all reference buildings, the attic floor was conditioned. The compactness ratio is defined as the ratio between the external envelope surface and the heated volume. Table 1 gives a summary of the attributes of the modelled archetypes.

Table 1. Overview of the attributes of the building archetypes.

Building Type	Surface Conditioned (m^2)	Number of Floors (-)	WWR (%)	Average Floor Height (m)	Compactness Ratio (m^2/m^3)
Semi-detached	124	2	45	2.8	0.7
Apartment	65	1	45	2.8	0.3
Terraced	124	2	45	2.8	0.5

Table 2 shows the initial thermal transmittance for external opaque surfaces Rc values in m^2K/W and U values for glazing in W/m^2K, and further specifications for each construction period. These values were deduced from national benchmark values [41,45].

The value of gap sealing is defined as the intensity of air infiltration in m^3/s per square metre of exterior surface area. At a typical building pressure of approximately 4 Pa, 'minimal' gap sealing corresponds to an air infiltration rate of 0.0005 m^3/m^2 façade and 'none' to a rate of 0.0007 m^3/m^2 façade. Ventilation C is a ventilation system with a natural supply and mechanical exhaust. Ventilation type 'C1' is the basic system with ventilation roosters in the façade for the air supply and mechanical ventilation outlets placed in the kitchen, bathroom, and toilet. Ventilation type 'C2' is a similar system combined with CO_2 sensors. For occupancy and ventilation schedules, the Open Studio standard programme 'Midrise Apartment' was assigned to the energy model. Interior building elements such as walls, floors, and ceilings were given generic values from the Open Studio library for residential buildings. The heating set point temperature was set to 21 °C and the cooling set point to 25 °C, which is the same value as the upper outdoor temperature limit at which to ventilate. This setting prevents ventilative cooling when outdoor temperatures are too high. Similarly, the minimum outdoor temperature at which to ventilate was set to 12 °C. An ideal load air system object, which is a function in EnergyPlus, was used to study the energy demand for each energy zone.

Table 2. Building envelope properties assumed per period of construction.

Rc Values of External Opaque Surfaces (m^2K/W) and U Values for Glazing (W/m^2K)					Infiltration	Ventilation
	Facade	**Roof**	**Ground Floor**	**Windows + Frame**	**Gap Sealing**	**Type**
<1946	0.19	0.22	0.15	5.2	none	natural
1946–1975	0.36	0.39	0.32	2.8	none	natural
1976–1995	1.3	1.3	0.52	2.8	minimal	C1
>1995	2.53	2.53	2.53	2.8	minimal	C1

2.3. Step 3: Energy Simulation Using Parametric Modelling Tools

Current states were simulated using the values defined in step 2 and compared to statistical values for the same building archetypes to check consistency. The SH demand simulated for each building archetype was compared to existing model calculations from the Netherlands Enterprise Agency (in Dutch: Rijksdienst voor Ondernemend RVO) [45]. Per construction period, the average deviations for the construction periods <1946, 1946–1975, and 1975–1995 across all building typologies ranged from 0% to −15%, meaning that the parametric model tends to estimate greater SH demand than the RVO model. For constructions built after 1995, the model showed an average deviation of −27%, which could be explained by the fact that the reference objects have geometry and characteristics that coincide with typical heritage buildings and not recent constructions. Further research should be conducted with a larger building sample with different compactness ratios to test and improve the accuracy of the model. The parametric energy model was then used to simulate different levels of refurbishment and to evaluate the impact of all retrofitting packages on energy performance. Table 3 gives an overview of the tested values for the energy retrofitting packages.

Table 3. Overview of the retrofitting measures tested on each building archetype.

Rc Values of External Opaque Surfaces (m^2K/W) and U Values for Glazing (W/m^2K)				Infiltration	Ventilation
Facade	**Roof**	**Ground Floor**	**Windows + Frame**	**Gap Sealing**	**Type**
1.7	1.3	3.5	2.8	minimal	C1
2	2.5		1.8	good	C2
3	4		1.1		D1 HRV 90%
4	8		0.7		
6					

The insulation levels and ventilation types were defined based on common retrofitting measures in the Netherlands for both protected and non-protected buildings [39,41,45]. 'Good' gap sealing is defined as an air infiltration rate of 0.0005 m^3/m^2 façade. The type 'D1 HRV 90%' corresponds to a balanced ventilation system with mechanical supply and exhaust combined with a heat recovery rate of 90%. The EnergyPlus Weather (EPW) file for Amsterdam contains data collected from the weather station at Schiphol airport and was used as input for the energy simulation. For each individual or combination of interventions, the model provides insights on the potential impacts of the selected retrofit package on the building's energy performance.

2.4. Step 4: Identification of Retrofit Packages and Potential Performance

The objective of this step is to assess the 'retrofittability' of each archetype and link it to a suitable retrofit package. The goal is to obtain better insights on the most consuming archetypes and serve as a base for the selection of retrofit packages. For each of the three building typologies, the model computed 3024 retrofitting packages, totalling 9072 retrofitting combinations. There are more options for retrofitting buildings constructed before 1946 (1200 combinations) since these buildings have far less of such measures in place than buildings from other construction periods. For example, newly constructed buildings (built after 1995) had only 288 retrofitting packages. By computing all these scenarios, it is possible to compare their impact and narrow down solutions from a very broad range of interventions. Design Explorer was used to explore the multi-dimensional parametric alternatives [46]. The scope of the present article is to identify minimum requirements to make archetype buildings suitable for LTH, as described in the following chapter. However, the parametric nature of the model allows the user to explore which different optimisation paths are possible based on various objectives, for instance, maximising energy savings, minimising the initial budget, or minimising operational CO_2 emissions. The goal is to find the insulation upgrade really needed, which level would be overkill, and which solutions are most realistic. Figure 5 illustrates this general method with the example of an 'apartment' typology.

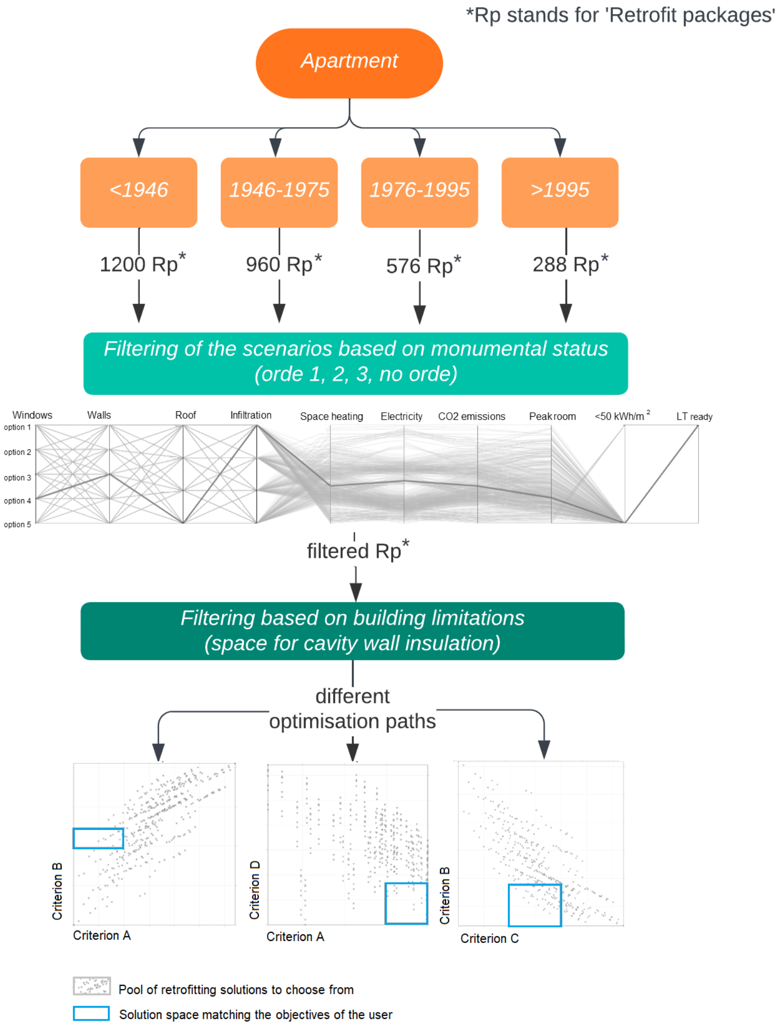

Figure 5. Example process of filtering and selecting best-performing retrofit packages for apartment typology.

3. Results

3.1. Defining Retrofitting Packages to Prepare the Amsterdam Centrum to LTH

Insulating buildings can reduce the heat demand, resulting not only in a reduction of CO_2 emissions for SH [47,48] but also allowing buildings to use LTH supplied by sustainable systems [23,49]. Lowering the temperature level improves the potential for using local and sustainable heat sources [50]. Previous studies on retrofitting strategies for using LTH focused primarily on measures on the building envelope (e.g., window and door replacement, improved insulation level and air infiltration) [51]. Further solutions for LT systems include upgrading existing space heating equipment (such as LT radiators, underfloor heating systems, or infrared panels), improving ventilation (such as mechanical ventilation with heat recovery), or adapting the heat generation system (for example, switching to a heat pump, integrating solar thermal collectors, or installing photovoltaic (PV) panels) [51].

For each package, the model evaluates if the archetype would be ready for LT based on a simplified logic using two criteria, which were integrated into the model. Criterion A requires that the annual SH demand be below 50 kWh/m^2, as given by the Municipality of Amsterdam as the target value for LT heat strategies [23]. Criterion B requires that the peak heating demand of the living room space be less than the total heating capacity for a supply temperature of 55 °C and a return temperature of 45 °C. This condition is set to ensure that the living room will still be comfortable when heated at LT. The study used existing datasets from the reference buildings, including an inventory of the dimensions and the types of radiators present in the living rooms of the reference cases. Calculations of the heating capacity of the rooms were conducted using the 'LT-ready tool' developed at Delft University of Technology and the calculation method provided by Østergaard [52,53]. The filtering process among the pool of retrofitting packages is shown in Figure 6.

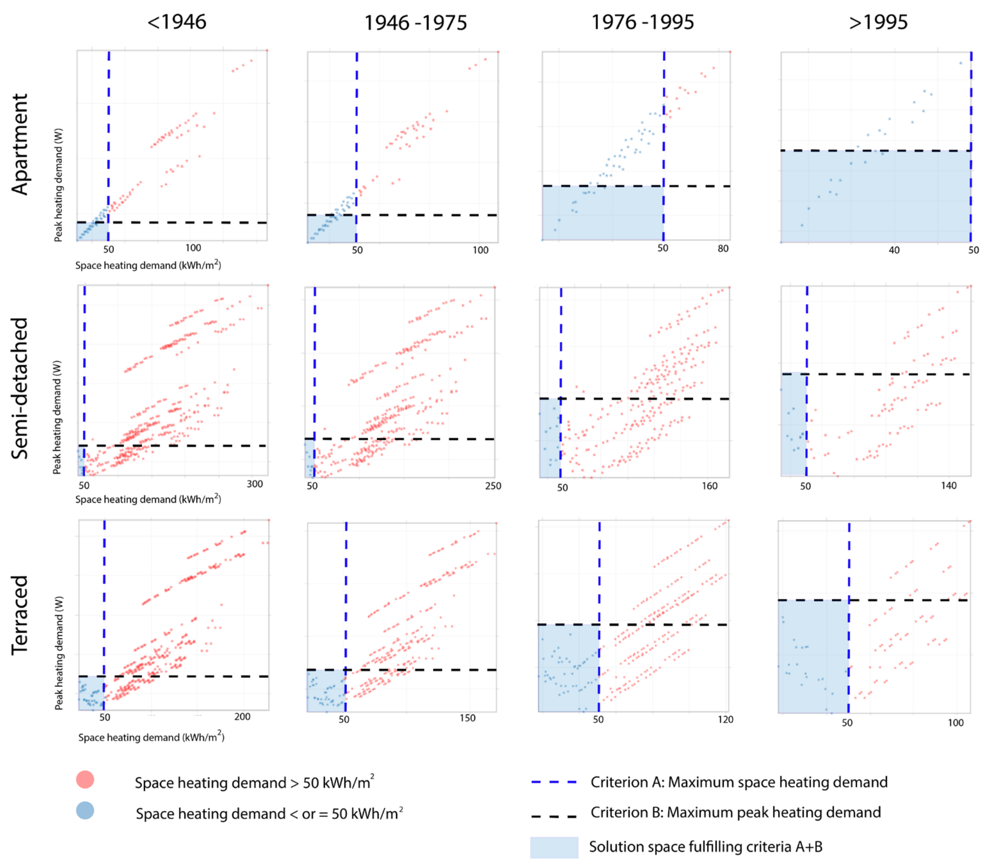

Figure 6. Defining solution spaces where the retrofitting packages fulfil both criteria A and B, classified per building typology and construction period.

Each point represents a retrofitting package (e.g., a combination of measures), tested against criteria A and B. The solution space is the area where packages fulfil both criteria. From this solution space, one package is selected based on technical feasibility (e.g., minimum assumed efforts to implement the solutions considering monumental restrictions) and the presence or not of a cavity in the wall. For protected buildings (orde 1, 2, and 3), double wall construction (with a maximum Rc of 2) was selected to minimise the risk of internal condensation after retrofitting. A condensation check is necessary to ensure that the selected retrofit package will not cause the deterioration of historic elements. When a cavity is available in the wall, cavity wall (CW) insulation is considered the most favourable option since it can be easily implemented in most cases. Figure 7 shows the outcomes of the parametric model for different building types and across multiple construction periods. For each building archetype, minimum requirements were translated into a Retrofit package (Rp).

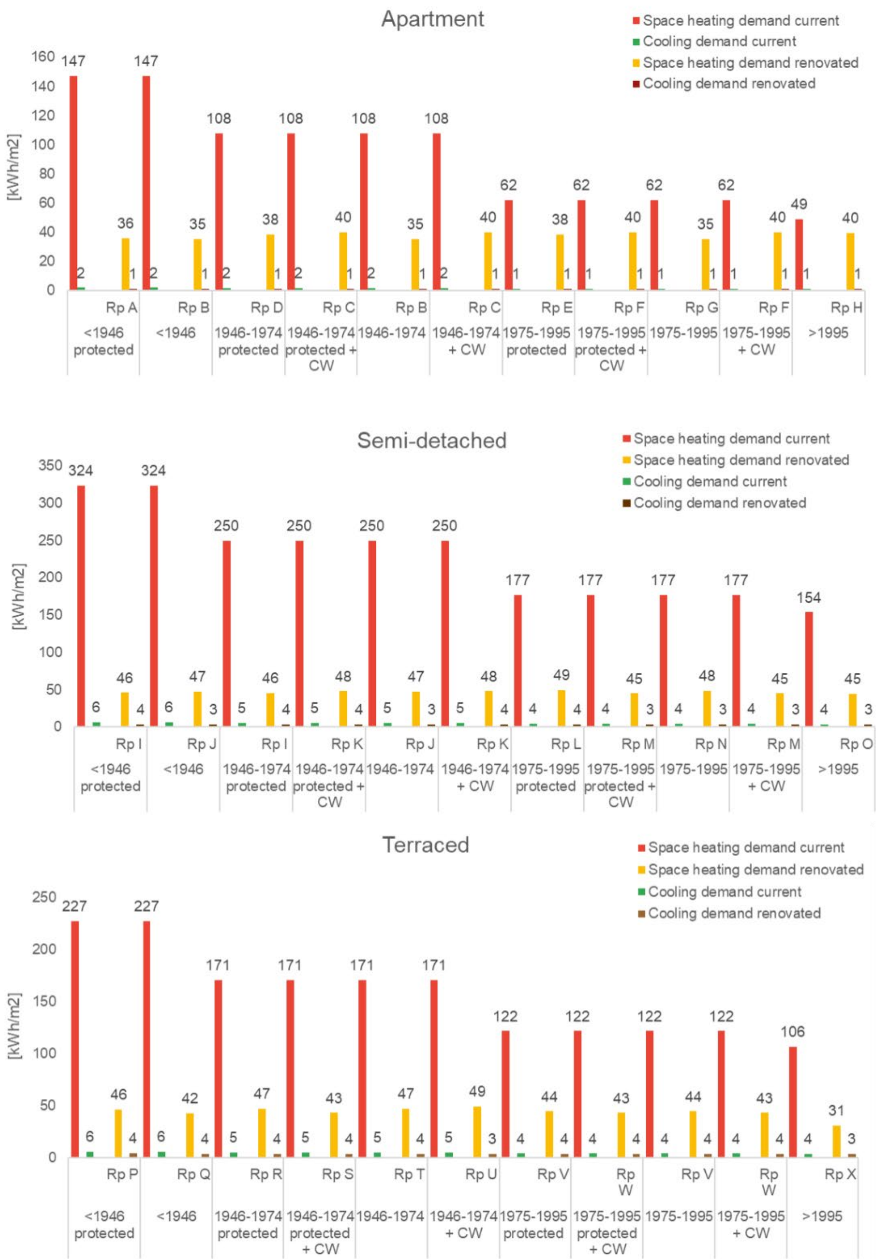

Figure 7. SH and space cooling demand in current and renovated states for different construction periods and to prepare buildings for LTH.

As expected, the SH demand increases with the age category of the building archetypes and decreases with the compactness ratio. The semi-detached house is the most energy-consuming type for SH and space cooling, followed by terraced houses and apartments. This can be explained by the fact that semi-detached houses have a larger envelope surface exposed to the exterior, allowing greater heat transfer between the house and the outdoors. The results suggest that the cooling demand is not significantly influenced by the retrofitting packages compared to the current state. The resulting energy savings for SH demand are summarised in Table 4.

Table 4. Resulting energy savings for SH compared to the current state and categorised per period of construction, protection status, presence of a cavity in the wall (CW), and building type.

Construction Period	Protected Building	Cavity in the Wall	SH Savings Compared to Status 'Current'		
			Apartment	Semi-Detached	Terraced
<1946	✓		76%	86%	80%
<1946			76%	85%	81%
1946–1974	✓		64%	81%	75%
1946–1974	✓	✓	63%	82%	72%
1946–1974			67%	81%	72%
1946–1974		✓	63%	81%	71%
1975–1995	✓		38%	72%	64%
1975–1995	✓	✓	36%	75%	65%
1975–1995			43%	73%	64%
1975–1995		✓	36%	75%	65%
>1995			19%	71%	71%

The greatest energy savings are expected for semi-detached and terraced buildings constructed before 1946, with a reduction ranging from 80% to 86%. For more recent buildings (constructed after 1995), fewer retrofitting measures are required, and the SH savings range from 19% to 69%. Across the same construction period and typology, the variability of the savings is low.

3.2. Spatial Distribution of Building Energy Use and Neighbourhood-Scale Mapping

There are no data available for the presence of cavities in the walls of buildings. Therefore, it was considered that a cavity in the wall was always present for the construction periods 1946–1975 and 1975–1995. The retrofitting packages to get to LTH level were applied to all housing addresses in Amsterdam Centrum and aggregated over the 70 neighbourhoods. The current situation is evaluated at 486.7 GWh per year for SH of residential buildings in Amsterdam Centrum. The neighbourhoods 'Elandsgrachtbuurt' and 'Felix Meritusbuurt' are the most consuming ones, with more than 21 GWh per year. Figure 8 shows the spatial distribution of SH demand for residential buildings per neighbourhood in Amsterdam Centrum.

By applying all retrofit packages to the building archetypes, the potential SH savings to prepare buildings to LTH are illustrated in Figure 9.

The mean value of SH savings across the district is around 67.6%, with the minimum savings of 19.4% for 'Westerdokseiland' (excluding 'Stationsplein', where there is no dwelling) and the maximum savings of 76.7% in 'Leidsegracht Zuid'. If the buildings are retrofitted to be prepared for LTH, 336.3 GWh per year of natural gas could be saved from SH demand reduction. This represents a total energy-saving potential of 69.1% for SH demand of the residential building stock in Amsterdam Centrum. An overview of the distribution of the retrofit packages is shown in Figure 10.

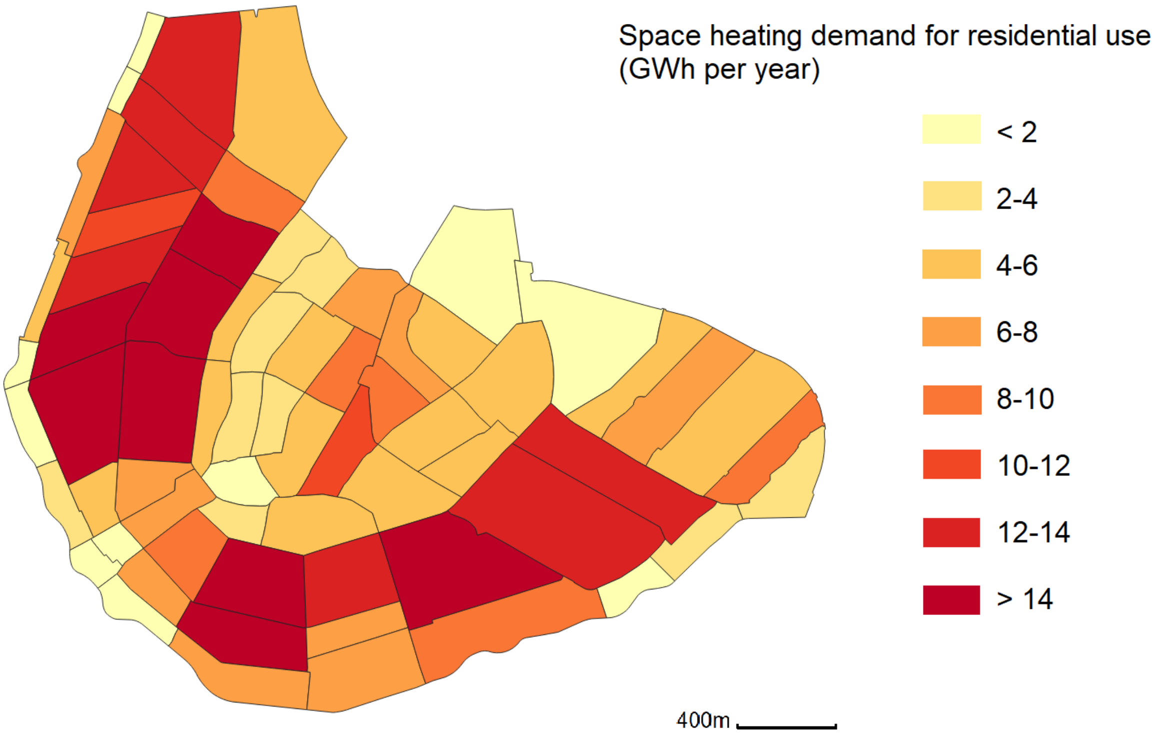

Figure 8. Total SH demand for residential buildings before retrofitting in Amsterdam Centrum.

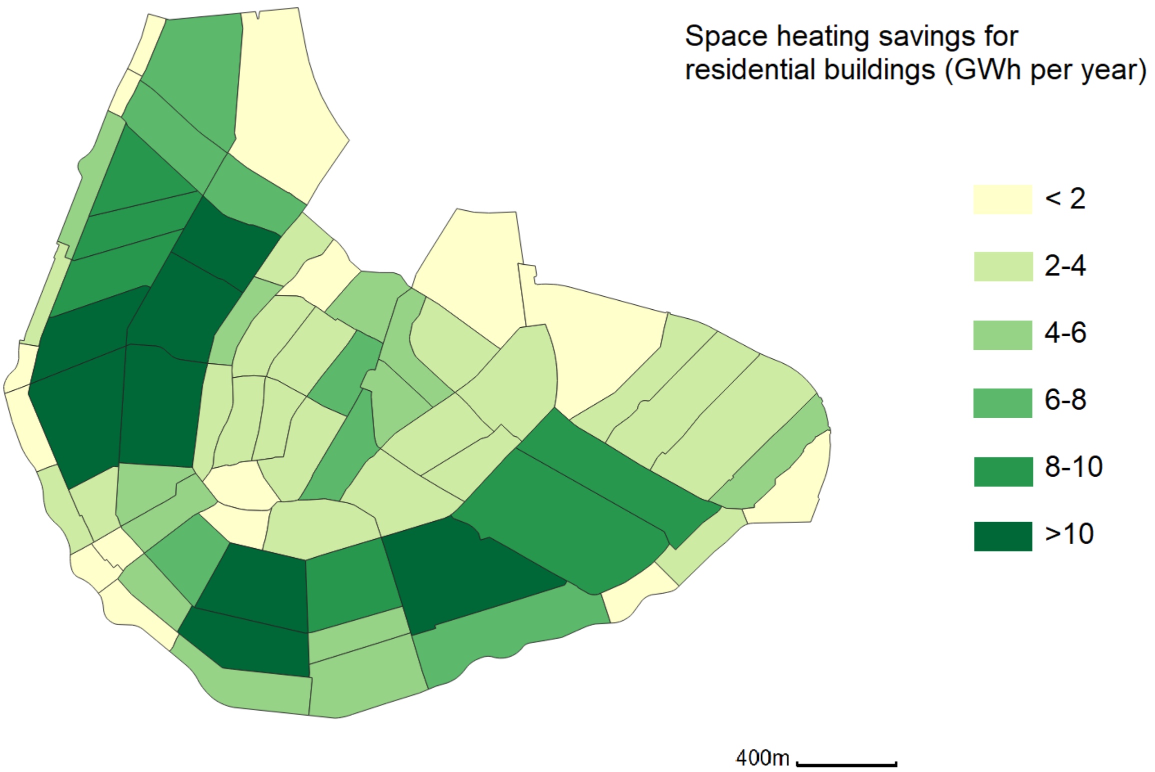

Figure 9. Savings potential for SH compared to the status 'current' of residential buildings in Amsterdam Centrum.

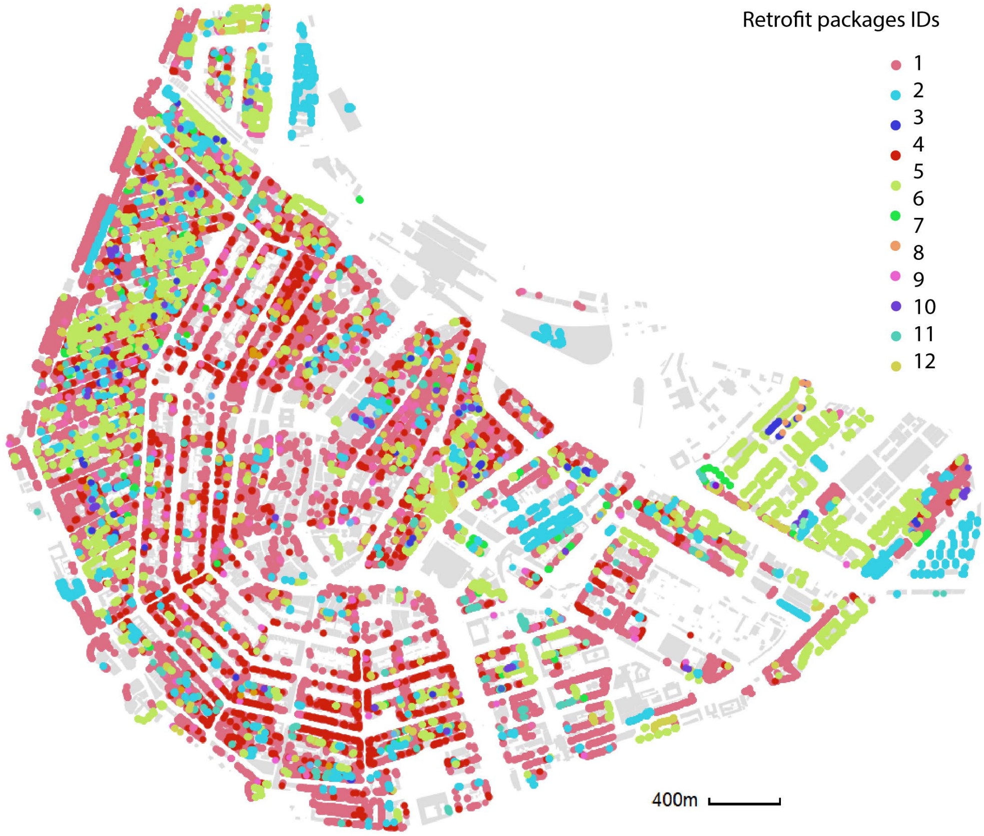

Figure 10. Spatial distribution of the different retrofit packages towards LTH across Amsterdam Centrum.

The map reveals that the most recurring retrofit package is for the 'apartment built before 1946 in a protected multi-storey building', accounting for 58% of all addresses. This package consists of changing existing windows and frames with vacuum glass (U = 0.7), implementing interior wall insulation construction (Rc = 2), insulating the roof (Rc = 4) and the ground floor (Rc = 3.5), improving the airtightness with minimal gap sealing, and installing a ventilation system (C1). Retrofitting semi-detached and terraced houses in protected buildings constructed before 1946 requires a similar combination of measures with higher requirements on air tightness (e.g., 'good gap sealing') and a more performing ventilation system (e.g., D with 90% heat recovery). However, these solutions are challenging to implement since vacuum glass is usually about 3.5 times more expensive than HR++ glass, and interior wall insulation takes valuable space from the living area. Placing HR++ glass as a rear window could be a smart way to bypass restrictions, while preserving the authenticity of the façade. If buildings are orde 2 or 3, an alternative solution would be to insulate the back façade on the exterior, if not visible from public view. Across all tested archetypes, ground floor insulation (Rc = 3.5), improving the air tightness with minimal gap sealing, and good ventilation are the minimum requirements. In contrast, changing windows with monumental glass (U = 2.8) or installing a rear window with foil (U = 1.8) are never sufficient if the ambition is to go off natural gas.

In order to pinpoint residential units that are almost prepared for LTH, an intermediary category was set with the conditions that the SH demand should be below 65 kWh/m^2 and the peak heating demand of the living room should be less than 1.5 times the total heating capacity of the room. The building archetypes 'apartment in a multi-storey building' built during the construction periods '1975–1995' and 'after 1996' fit these requirements, showing that little changes must be made to these archetypes. Research should be conducted to evaluate if upgrading heat delivery systems with low-temperature radiators, heat reflective foil, add-on fan radiators, infrared panels, or floor heating systems could be sufficient measures to get these buildings prepared for LTH.

From these findings, identified patterns were derived and compiled into recommendations (Figure 11). The recommendations are naturally limited to the tested retrofitting solutions presented in Table 3 and should be used as indications for buildings with similar characteristics to the modelled building archetypes.

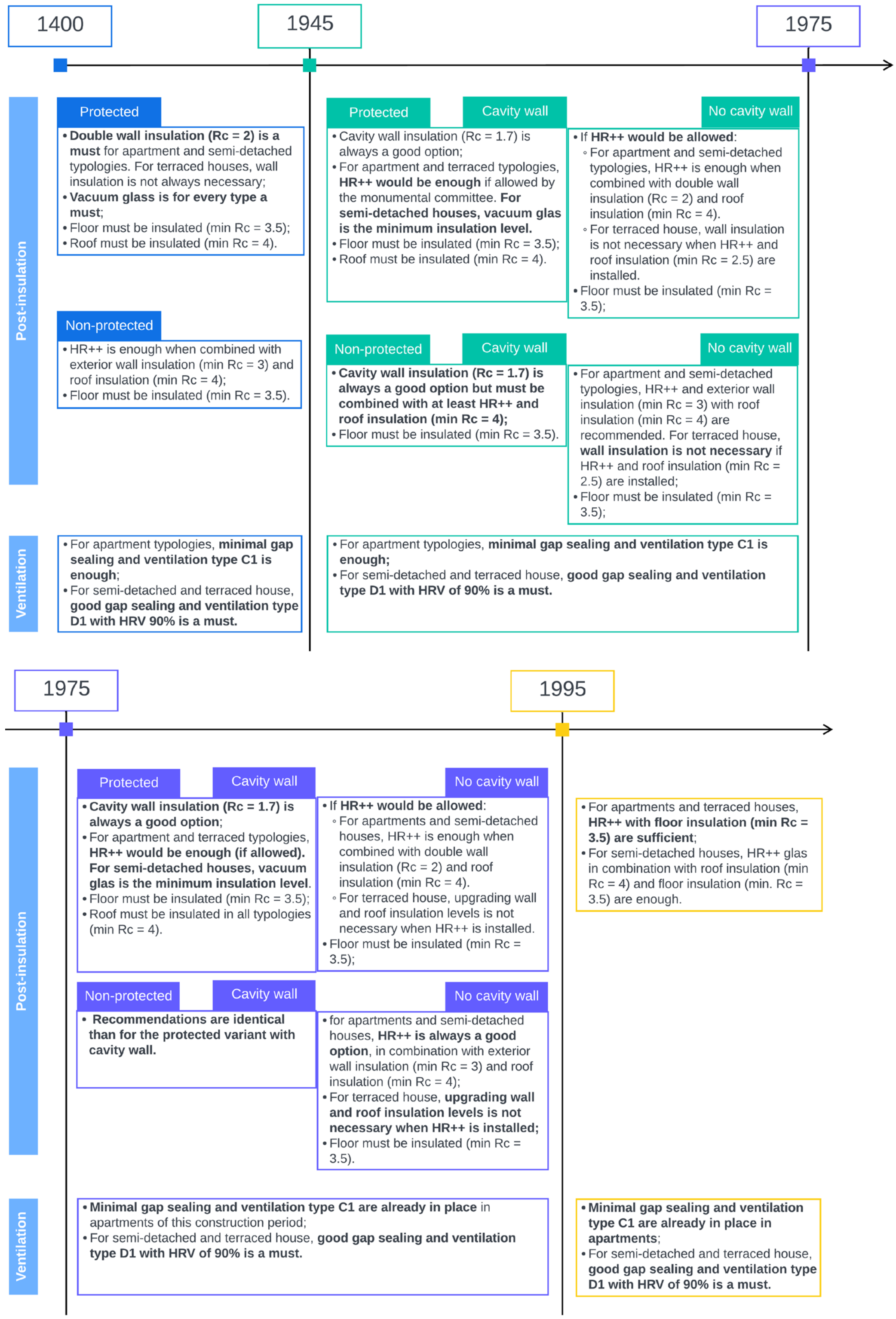

Figure 11. Recommendations for buildings in Amsterdam Centrum to be prepared for LTH.

4. Discussion

The study described a generic approach for the design of a parametric model that can be used to design retrofitting strategies for residential buildings in historic city centres. Retrofitting strategies need to be integrally assessed as a sustainable alternative to natural gas. With these premises, the presented model used a systematic solution space search approach, starting with the energy modelling of reference residential buildings, and concluding with the creation of a solution space and retrofit packages based on two design criteria defining the preparedness of the buildings to LTH. Identifying energy retrofit packages based on a multi-parametric analysis is an initial step towards a standardised approach to conducting historic building energy retrofits. This process sheds some light on the number of options available for each building archetype and helps to pinpoint existing buildings that are most challenging to upgrade.

Thanks to the model versatility, the parametric modelling approach can be used to quickly identify and prioritise the most impactful combination of options and draw stepped retrofitting plans, where energy-saving measures are gradually implemented by homeowners based on budget availability. This helps identify a shared energy strategy for multi-owner building blocks, particularly in situations where top-down coordination is lacking or challenging. It allows users to actively discover natural investment opportunities and reduce carbon emissions, while keeping an eye on the alternative collective use of sustainable heat sources. The generated energy cost savings can then be retained to make further investment steps. The results of the design can also be refined by building owners and used as support to discuss the acceptance level of interventions between users and with the monument protection committee. While the criteria for energy retrofits may vary depending on stakeholders, in the realm of transitioning an entire city's building stock to sustainable heating and according to the New Stepped Strategy, individual investment criteria and associated benefits must be balanced with societal goals, such as CO_2 emissions savings and societal costs [35]. The parametric model presented in this research highlights the constraints faced by individual users when optimising for the collective use of low-temperature heat sources in the surrounding area.

It is important to carefully consider a series of limitations associated with the presented approach. The models are dependent on several assumptions regarding input parameters, such as the geometry of buildings, the thermal properties of the envelope, setpoints, ventilation schedules, or occupant behaviour. Using a bottom-up approach with building archetyping is a 'one size fits all' logic and does not fully capture the complexity and variability of features of heritage buildings (e.g., some parts of the envelope may have been renovated, some specific elements may be monumental). Although the archetyping models were calibrated and validated using reference values or collected monthly energy data when made available, Majcen [54] highlights that large deviations can be observed between the theoretical and actual demands, especially for buildings with low energy labels, which are common in Amsterdam Centrum. Additional research on occupant behaviour and using detailed measured data related to the indoor thermal environment would be beneficial for further improving the calibration of the model. Despite these limitations, the research contributes to a better understanding of the variability in SH demand across various building types in the entire city centre, as well as the potential impacts of different retrofitting strategies on a large scale. Such models are essential to support policy makers in monitoring the effects of current climate policies and setting realistic targets for the future development of an urban region.

Cost optimisation strategies are of limited value in the model, as investment costs are highly dependent on material availability, installation capacity, or workforce. Retrofitting strategies for entire districts would require more than 10 years to be executed, altering business cases significantly. Costs also vary depending on the implementation of the measures (as a package or individually) or if combined with maintenance and repair works [55]. The use of specific materials and technologies (e.g., vacuum glass, original material, and details) requires a higher investment than for non-protected buildings. The value of properties in Amsterdam Centrum is generally high, due to the significance of the district as a cultural, historic, and touristic hub. Considering its economic value for the municipality, a new model is highly needed where homeowners are not the only ones investing in the maintenance and upgrade of the heritage buildings. Specific subsidies and incentives could support widescale retrofit initiatives, connecting fast and cost-effective solutions for protected buildings with the private market.

5. Conclusions and Future Work

Based on the presented research, the following conclusions can be drawn and used for future work on developing energy retrofitting strategies for similar housing stock:

- The parametric modelling approach is applied to the inner city of Amsterdam, in the Netherlands. The model outputs were translated into recommendations for the building stock, emphasising the transition to LTH and highlighting minimum requirements.
- Across all tested archetypes, ground floor insulation (Rc = 3.5), improving air tightness with minimal gap sealing, and good ventilation are the minimum requirements.
- In contrast, changing windows with monumental glass (U = 2.8) or installing a rear window with foil (U = 1.8) are never sufficient if the ambition is to go off natural gas.
- The most common package consists of changing existing windows and frames with vacuum glass (U = 0.7), implementing interior wall insulation construction (Rc = 2), insulating the roof (Rc = 4) and the ground floor (Rc = 3.5), improving the airtightness with minimal gap sealing, and installing a ventilation system (C1).
- Retrofitting measures on semi-detached and terraced buildings constructed before 1946 to LT level achieve the most significant SH demand reduction, ranging from 80% to 86%. For more recent buildings (constructed after 1995), fewer retrofitting measures are required, and the SH savings range from 19% to 69%.
- Outputs of the model were aggregated at the neighbourhood level across Amsterdam Centrum using GIS tools. Major savings could be achieved by retrofitting the existing residential buildings to a lower temperature level in the neighbourhoods around the canal belt, namely 'Herengracht', 'Keizersgracht', and 'Prinsengracht'. On the district scale, the parametric model evaluated a total annual SH saving potential of 336.3 GWh per year of natural gas, leading to a reduction of operational CO_2 emissions of 60 kilotons. If we consider that all households use natural gas for SH, this is equivalent to 69.1% of natural gas reduction. When applying the proposed retrofit packages, the buildings could switch to LTH and be efficiently heated using a heat pump. Considering that more and more sustainable electricity will be fed into the grid, all-electric systems will score even better in terms of operational CO_2 emissions in the future.
- Due to the relative broad range of strategies, defining a parametric model can prove its value as it can facilitate various investment purposes, design objectives, and timeline constraints, while clearly identifying critical measures like vacuum glass to stay within monumental restrictions. The proposed model is a good starting point for effectively guiding local stakeholders in the early stage of the decision-making process, as motives for needed investments vary between owners and tenants and their positioning in the building.

Future development steps include integrating the embodied carbon of insulation into the model, testing the retrofit packages against overheating risks, and evaluating the robustness of the measures for future climate scenarios. A generic approach to retrofitting non-residential buildings in Amsterdam Centrum is still a grey area, and it would be challenging to implement scalable and comprehensive strategies in Amsterdam City Centre if these buildings are not incorporated into future recommendations. It would also be beneficial to conduct research on the participation of various stakeholders involved in the energy retrofitting process and the qualitative aspects of selecting retrofitting measures in heritage buildings. For example, the desirability of the solution, available subsidies, or an ongoing maintenance plan are key elements in the decision-making process. By limiting time spent on case-to-case projects and with the reuse of standardised solutions from the parametric model, large-scale retrofitting of heritage buildings, conducted by multiple building owners, housing corporations, or large private investors, could reduce person-hours-related costs and the overall cost of retrofitting. Along with this approach, it is essential to better integrate energy and sustainable issues into cultural heritage legislation to trigger more transparency and prevent inconsistent and subjective permitting decisions. Finally, energy planning strategies for historic areas should not be only focused on the building level; it is important to connect small-scale solutions for historic buildings to existing opportunities for exchanging heat and cold on a neighbourhood scale. Future research efforts will be dedicated to linking the parametric model to local opportunities to reuse energy waste streams (e.g., residual heat from cooling processes and possibilities for underground storage) and to produce renewable energy from local sources with, for instance, solar collectors on roofs or aquathermal energy systems extracting heat from the canal water.

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List of Abbreviations

BAG	Basisregistratie Adressen en Gebouwen (National Register of Addresses and Buildings)
CW	Cavity Wall
EPW	Energy Plus Weather
GIS	Geographical Information Systems
HRV	Heat Recovery Ventilation
HT	High Temperature
LTH	Lower Temperature Heating
LT	Lower Temperature
PV	Photovoltaic
REAP	Rotterdam Energy Approach & Planning
RP	Retrofit Package
RVO	Rijksdienst voor Ondernemend Nederland (Netherlands Enterprise Agency)
SH	Space Heating
UNESCO	United Nations Educational, Scientific and Cultural Organization
WWR	Window-to-Wall Ratio

References

1. Segers, R.C.; Niessink, R.; Van Den Oever, R.; Menkveld, M. Warmtemonitor 2019 CBS, CBS and TNO. Available online: https://www.cbs.nl/nl-nl/achtergrond/2020/35/warmtemonitor-2019 (accessed on 2 April 2023).
2. Centraal Bureau voor de Statistiek (CBS), 92 Procent Woningen op Aardgas Begin 2019. Available online: https://www.cbs.nl/nl-nl/nieuws/2021/07/92-procent-woningen-op-aardgas-begin-2019 (accessed on 2 April 2023).
3. Gemeente Amsterdam Ruimte en Duurzaamheid, Nieuw Amsterdams Klimaat—Routekaart Amsterdam Klimaatneutraal 2050 (Policy Document). Available online: https://www.amsterdam.nl/bestuur-en-organisatie/volg-beleid/coalitieakkoord-uitvoeringsagenda/gezonde-duurzame-stad/klimaatneutraal/ (accessed on 2 April 2023).
4. Gemeente Amsterdam, Transitievisie Warmte Amsterdam (Policy Document). 30 September 2020. Available online: https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/duurzaamheid/aardgasvrij/ (accessed on 2 April 2023).

5. Dobbelsteen, A.v.d.; Broersma, S.; Fremouw, M.; Blom, T.; Sturkenboom, J.; Martin, C. The Amsterdam energy transition roadmap–introducing the City-zen methodology. *Smart and Sustainable Built Environment* **2020**, *9*, 307–320. [CrossRef]
6. Dobbelsteen, A.; Gehem, S. Er Zijn Meer Duurzame Alternatieven Dan Biogas, Zoals Zomerhitte. 10 September 2020. Available online: https://www.parool.nl/columns-opinie/er-zijn-meer-duurzame-alternatieven-dan-biogas-zoals-zomerhitte~bce8e07b/?referrer=https://www.google.com/ (accessed on 2 April 2023).
7. Korberg, A.D.; Thellufsen, J.Z.; Skov, I.R.; Chang, M.; Paardekooper, S.; Lund, H.; Mathiesen, B.V. On the feasibility of direct hydrogen utilisation in a fossil-free Europe. *Int. J. Hydrogen Energy* **2023**, *48*, 2877–2891. [CrossRef]
8. Weidner, T.; Guillén-Gosálbez, G. Planetary boundaries assessment of deep decarbonisation options for building heating in the European Union. *Energy Convers. Manag.* **2023**, *278*, 116602. [CrossRef]
9. Miedema, J.H.; Van der Windt, H.J.; Moll, H.C. Opportunities and Barriers for Biomass Gasification for Green Gas in the Dutch Residential Sector. *Energies* **2018**, *11*, 2969. [CrossRef]
10. Weeda, M.; Niessink, R. Waterstof Als Optie Voor Een Klimaatneutrale Warmtevoorziening in De Bestaande Bouw. 2020. Available online: https://www.tno.nl/nl/duurzaam/systeemtransitie/energietransitie-wijken/waterstof-alternatief-aardgas/ (accessed on 2 April 2023).
11. Averfalk, H.; Werner, S. Novel low temperature heat distribution technology. *Energy* **2018**, *145*, 526–539. [CrossRef]
12. Nocca, F. The Role of Cultural Heritage in Sustainable Development: Multidimensional Indicators as Decision-Making Tool. *Sustainability* **2017**, *9*, 1882. [CrossRef]
13. Stanojević, A.D.; Milošević, M.R.; Milošević, D.M.; Turnšek, B.A.J.; Jevremović, L.L. Developing multi-criteria model for the protection of built heritage from the aspect of energy retrofitting. *Energy Build.* **2021**, *250*, 111285. [CrossRef]
14. European Commission. EU Buildings Factsheets. 2014. Available online: https://ec.europa.eu/energy/eu-buildings-factsheets_en (accessed on 2 April 2023).
15. Tadeu, S.; Rodrigues, C.; Tadeu, A.; Freire, F.; Simões, N. Energy retrofit of historic buildings: Environmental assessment of cost-optimal solutions. *J. Build. Eng.* **2015**, *4*, 167–176. [CrossRef]
16. EU. *EU Directive 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency*; EU: Brussel, Belgium, 2018.
17. Martínez-Molina, A.; Tort-Ausina, I.; Cho, S.; Vivancos, J.L. Energy efficiency and thermal comfort in historic buildings: A review. *Renew. Sustain. Energy Rev.* **2016**, *61*, 70–85. [CrossRef]
18. Lidelöw, S.; Örn, T.; Luciani, A.; Rizzo, A. Energy-efficiency measures for heritage buildings: A literature review. *Sustain. Cities Soc.* **2019**, *45*, 231–242. [CrossRef]
19. Havinga, L.; Colenbrander, B.; Schellen, H. Heritage significance and the identification of attributes to preserve in a sustainable refurbishment. *J. Cult. Herit.* **2020**, *43*, 282–293. [CrossRef]
20. Voulis, N.T.D. Harnessing Heterogeneity: Understanding Urban Demand to Support the Energy Transition. Ph.D. Thesis, Delft University of Technology, Delft, The Netherlands, 2019. [CrossRef]
21. Streicher, K.N.; Padey, P.; Parra, D.; Bürer, M.C.; Schneider, S.; Patel, M.K. Analysis of space heating demand in the Swiss residential building stock: Element-based bottom-up model of archetype buildings. *Energy Build.* **2019**, *184*, 300–322. [CrossRef]
22. Hedegaard, R.E.; Kristensen, M.H.; Pedersen, T.H.; Brun, A.; Petersen, S. Bottom-up modelling methodology for urban-scale analysis of residential space heating demand response. *Appl. Energy* **2019**, *242*, 181–204. [CrossRef]
23. Kaandorp, C.; Miedema, T.; Verhagen, J.; van de Giesen, N.; Abraham, E. Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation. *Appl. Energy* **2022**, *325*, 119759. [CrossRef]
24. Fleiter, T.; Worrell, E.; Eichhammer, W. Barriers to energy efficiency in industrial bottom-up energy demand models—A review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3099–3111. [CrossRef]
25. Aksoezen, M.; Daniel, M.; Hassler, U.; Kohler, N. Building age as an indicator for energy consumption. *Energy Build.* **2015**, *87*, 74–86. [CrossRef]
26. Swan, L.G.; Ugursal, V.I. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. *Renew. Sustain. Energy Rev.* **2009**, *13*, 1819–1835. [CrossRef]
27. Prieto, I.; Izkara, J.; Egusquiza, A. Building stock categorization for energy retrofitting of historic districts based on a 3D city model. *DYNA* **2017**, *92*, 572–579. [CrossRef]
28. Ulu, M.; Durmuş Arsan, Z. Retrofit Strategies for Energy Efficiency of Historic Urban Fabric in Mediterranean Climate. *Atmosphere* **2020**, *11*, 742. [CrossRef]
29. Egusquiza, A.; Brostrom, T.; Izkara, J.L. Incremental decision making for historic urban areas' energy retrofitting: EFFESUS DSS. *J. Cult. Herit.* **2022**, *54*, 68–78. [CrossRef]
30. Fabbri, K.; Zuppiroli, M.; Ambrogio, K. Heritage buildings and energy performance: Mapping with GIS tools. *Energy Build.* **2012**, *48*, 137–145. [CrossRef]
31. Egusquiza, A.; Prieto, I.; Izkara, J.L.; Béjar, R. Multi-scale urban data models for early-stage suitability assessment of energy conservation measures in historic urban areas. *Energy Build.* **2018**, *164*, 87–98. [CrossRef]
32. Wu, R.; Mavromatidis, G.; Orehounig, K.; Carmeliet, J. Multiobjective optimisation of energy systems and building envelope retrofit in a residential community. *Appl. Energy* **2017**, *190*, 634–649. [CrossRef]

33. Wang, Q.; Ploskić, A.; Holmberg, S. Retrofitting with low-temperature heating to achieve energy-demand savings and thermal comfort. *Energy Build.* **2015**, *109*, 217–229. [CrossRef]
34. Nagy, Z.; Rossi, D.; Hersberger, C.; Domingo Irigoyen, S.; Miller, C.; Schlueter, A. Balancing envelope and heating system parameters for zero emissions retrofit using building sensor data. *Appl. Energy* **2014**, *131*, 56–66. [CrossRef]
35. Tillie, N.; Dobbelsteen, A.; Doepel, D.; Joubert, M.; Jager, W.; Mayenburg, D. Towards CO_2 Neutral Urban Planning: Presenting the Rotterdam Energy Approach and Planning (REAP). *J. Green Build.* **2009**, *4*, 103–112. [CrossRef]
36. Dobbelsteen, A. Towards closed cycles—New strategy steps inspired by the Cradle-to-Cradle approach. In Proceedings of the PLEA2008, Dublin, Ireland, 22–24 October 2008.
37. Gemeente Amsterdam. Atlas Ordekaarten—Waardering Stedenbouwkundige en Architectonische Kwaliteit. Available online: https://maps.amsterdam.nl/ordekaart/?LANG=nl (accessed on 2 April 2023).
38. Gemeente Amsterdam. Waarderingskaart Beschermd Stadgsgezicht Centrum. Available online: https://www.crk.amsterdam.nl/welstandsnota/criteria-erfgoed/waarderingskaart_beschermd_stadsgezicht_centrum (accessed on 2 April 2023).
39. Blom, T.; Dobbelsteen, A. WP1.2—D1.2 Reduce Report (T1.2.): Energy Reduction Potentials of the Green Light District. Available online: https://openresearch.amsterdam/en/page/78641/energy-reduction-potentials-of-the-green-light-district (accessed on 16 February 2024).
40. Basisregistratie Adressen en Gebouwen BAG Dataset. Available online: https://data.overheid.nl/en/dataset/basisregistratie-adressen-en-gebouwen--bag- (accessed on 2 April 2023).
41. Cornelisse, M.; Kruithof, A.; Valk, H. *Rapport Standaard en Streefwaardes Bestaande Woningbouw (Tech. Rep.)*; Netherlands Enterprise Agency, Niemand Raadgevende Ingenieus B.V.: Zwolle, The Netherlands, 2021.
42. Eijgenstein, C. 3D Building Reconstruction. Available online: https://github.com/chrise96/3D_building_reconstruction (accessed on 7 February 2024).
43. Dang, M.; Van den Dobbelsteen, A.; Voskuilen, P.; Cunin, M.; Poolman, H.R. Towards a Future without Natural Gas for Monumental Buildings (Tech. Rep.). 2022. Available online: https://openresearch.amsterdam/en/page/92433/towards-a-future-without-natural-gas-for-monumental-buildings (accessed on 2 April 2023).
44. Ladybug Tools, a Collection of Computer Applications That Support Environmental Building Design and Planning. Available online: www.ladybug.tools (accessed on 2 April 2023).
45. Agentschap, N.L. *Voorbeeldwoningen2011 Bestaande Bouw*; Agentschap NL, Department Energie en Klimaat: Den Haag, The Netherlands, 2011.
46. Design Explorer Core Studio Thornton Tomasetti, Design Explorer, an Open-Source User Interface and Tool for Exploring Multi-Dimensional Parametric Studies. Available online: http://tt-acm.github.io/DesignExplorer/ (accessed on 2 April 2023).
47. Sarihi, S.; Mehdizadeh Saradj, F.; Faizi, M. A Critical Review of Façade Retrofit Measures for Minimizing Heating and Cooling Demand in Existing Buildings. *Sustain. Cities Soc.* **2021**, *64*, 102525. [CrossRef]
48. Jezierski, W.; Sadowska, B.; Pawłowski, K. Impact of Changes in the Required Thermal Insulation of Building Envelope on Energy Demand, Heating Costs, Emissions, and Temperature in Buildings. *Energies* **2021**, *14*, 56. [CrossRef]
49. Asdrubali, F.; Desideri, U. (Eds.) *Chapter 9—Energy Efficiency in Building Renovation, Handbook of Energy Efficiency in Buildings*; Butterworth-Heinemann: Oxford, UK, 2019; pp. 675–810. ISBN 9780128128176. [CrossRef]
50. Rämä, M.; Sipilä, K. Transition to low temperature distribution in existing systems. *Energy Procedia* **2017**, *116*, 58–68. [CrossRef]
51. Wahi, P.; Konstantinou, T.; Tenpierik, M.J.; Visscher, H. Lower temperature heating integration in the residential building stock: A review of decision-making parameters for lower-temperature-ready energy renovations. *J. Build. Eng.* **2023**, *65*, 105811. [CrossRef]
52. Rutten, S. Affordable Renovation Concepts That Provide Thermal Comfort with Low-Temperature Heating. Available online: http://www.ltreadytool.nl/ (accessed on 2 April 2023).
53. Østergaard, D.S. Heating of Existing Buildings by Low-Temperature District Heating. Ph.D. Thesis, Technical University of Denmark, Department of Civil Engineering, Kongens Lyngby, Denmark, 2018.
54. Majcen, D. Predicting energy consumption and savings in the housing stock: A performance gap analysis in The Netherlands. *A+BE | Archit. Built Environ.* **2016**, *6*, 1–224. [CrossRef]
55. Buildings Performance Institute EUROPE (BPIE). Prefabricated Systems for Deep Energy Retrofits of Residential Buildings. Brussels, Belgium. Available online: https://bpie.eu/wp-content/uploads/2016/02/Deep-dive-1-Prefab-systems.pdf (accessed on 2 April 2023).