Future-Proof Energy-Retrofit strategy for an existing Dutch neighbourhood
Soheil Alavirad a, Saleh Mohammadi b,c,⇑, Pieter-Jan Hoes a, Luyi Xu a, Jan L.M. Hensen a

a Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands
b Sustainable Building Technology Research Group, School of Business Building & Technology, Saxion University of Applied Sciences, P.O. Box 70.000, 7500 KB Enschede, the Netherlands
c Witteveen+Bos N.V., Leeuwenbrug 8, 7411 SC Deventer, the Netherlands

Abstract
In the EU, buildings account for about 40% of the final energy consumption. Space heating (SH) accounts for 65% of the energy demand in buildings. There is thus a large potential in energy savings, simply by focusing on the reduction of space heating demand. In the Netherlands, there are about 6 million residential buildings constructed before 2005 where thermal performance is far from optimal. All these buildings need to reduce their demand as the first step to meet nZEB requirements. For large scale energy retrofit of buildings, the main challenge is to classify each housing type by the severity of the demand reduction.

A Dutch district in the city of Apeldoorn has been chosen to investigate the energy-saving potential and the robustness of different retrofit packages. Using a bottom-up approach, the energy-saving potential of the existing building types in the mentioned district was analysed by the parametric study of building energy performance simulations in IES VE. Subsequently, the uncertainty in building (energy) performance was assessed using a minimax regret method to compare the robustness of designs. For the covered building types and construction periods, the results suggest that after the upgrade to insulation level from current regulations, implementation of Heat Recovery Ventilation (HRV) reduces the space heating demand by 50–65% while insulation upgrade to passive house standards on yields an average heat demand reduction of only 15%. In contrast, provided with sufficient ventilation, the results suggest that sufficient ventilation eliminates the demand for space cooling in passive building envelopes (excluding climate change effects). In this regard, detached housing is the most and semi-detached is the least prone to the overheated indoor environment. Relying on natural ventilation as the only source of cooling in the summer increases the risk of overheating. Furthermore, upgrading to the nZEB standard building envelope appears to be around 40–50% less economical (€/unit saved energy) than current requirements for building envelope. Lastly, the results show that packages with HRV are about twice as robust as packages without HRV thus highlighting its optimal cost.

© 2022 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1. Introduction
Increasing energy demand and limitations on available fossil fuel use are leading to energy scarcity. These natural energy resources cause international political debates when the countries located on the most global oil and gas fields have a hold on the energy supply to the rest of the world. Global warming and its side effects have led to the internationally binding climate agreement, such as COP21 in Paris [1] so that all countries are obliged to reduce their contribution to climate change.

In addition, not only the use of fossil fuels is damaging the environment, but also their extraction is intrusive and can have irreversible effects. With the increased number of earthquake-related damages in the province of Groningen in the Netherlands, there have been movements against gas extraction recently. Although the extraction of natural gas has played a considerable role in the Dutch economy and welfare since its discovery [2], in March 2018, the Dutch Ministry of Economic Affairs and Climate announced that “the consequences of gas extraction are no longer acceptable in society” and called for a “gas-free Netherlands” [1]. A recent study by [2] also claims the link between gas extraction and frequent earthquakes in Groningen to be “not a new phenomenon” and “proven by many studies” which adds more support to the previous claims. However, a gas-free Netherlands requires Dutch
households to switch to alternative energy sources or the import of gas must continue [2].

On the other hand, the reduction of demand is the first step towards sustainability according to Trias Energetica (Fig. 1). A three-step Trias Energetica is one of the best-known and most widely used methods for the energy-efficient built environment developed by [3]. The other two steps in Trias Energetica cover the remaining share of energy demand as much as possible from renewables and eventually increase the efficiency in the remaining share of fossil fuel usage. Due to the current limit in the generation capacity of Renewable Energy Sources (RES) compared with the demand, the reduction of the energy demand is highlighted more as the primary step. Accordingly, the focus of this research is reducing energy demand.

### 1.1. Building sector

In the EU, approximately 40% of the energy demand and 35% of the CO₂ emissions originates from the building sector [3]. In residential buildings, space heating and domestic hot water count for the major share, namely about 65% and 14.5% [4]. The final energy consumption in the households consists of 72% gas, 19.2% electricity which shows a high dependency on gas [4]. Meanwhile, the Dutch government has stated that the gas extractions will reduce to less than 12 billion cubic meters per year by 2022 and the Dutch cabinet announced the urgency in focusing on existing building renovations as much as newly built buildings [5]. According to them, energy retrofits should not affect the affordability of the buildings yet improve the indoor life quality [5]. According to them, energy retrofits should not affect the affordability of the buildings yet improve the indoor life quality [5].

Realizing the renovation of 200,000 dwellings per year to cover the whole Dutch building stock is a complex and rather expensive task. In this research, the aim is to gain insight into the potential of a range of energy-retrofit measures for a typical Dutch district by simulating the energy performance of its constituent housing typologies before and after energy retrofit. The outcome of this research can guide the Dutch government and policymakers in terms of subsidizing specific energy retrofit package per building type or the use of prefabricated measures, helping with the realization of regional/national climate goals. Other advantages of large-scale energy-retrofits are benefits from economies of scale as well as less CO₂ footprint in the case of setting up the prefabrication factory close to the district with high demand/potential for retrofit.

#### 1.1.1. Status and future goals

A recent study on the energy retrofit rate in Dutch housing stock proves the same trend and claims that with the current rate realizing the national climate goals are not possible [4]. Meanwhile, the Dutch cabinet announced the urgency in focusing on existing building renovations as much as newly built buildings [5]. According to them, energy retrofits should not affect the affordability of the buildings yet improve the indoor life quality of occupants. The aim for the renovation rate of the existing building sector is estimated to be 200,000 [building/year] so that by 2050 all 6 million old buildings are covered [6].

Realizing the renovation of 200,000 dwellings per year to cover the whole Dutch building stock is a complex and rather expensive task. In this research, the aim is to gain insight into the potential of a range of energy-retrofit measures for a typical Dutch district by simulating the energy performance of its constituent housing typologies before and after energy retrofit. The outcome of this research can guide the Dutch government and policymakers in terms of subsidizing specific energy retrofit package per building type or the use of prefabricated measures, helping with the realization of regional/national climate goals. Other advantages of large-scale energy-retrofits are benefits from economies of scale as well as less CO₂ footprint in the case of setting up the prefabrication factory close to the district with high demand/potential for retrofit.

#### 1.1.2. nZEB or BENG in the Dutch context

In the Dutch context, the concept of nearly Zero Energy Building (nZEB) is translated to Bijna EnergieNeutrale Gebouw (BENG). BENG or nZEB is a building that uses as little energy as possible and locally generates a part of its demand from RES. Net Zero Energy Buildings (or NOM in the Dutch context) is a building that produces as much energy as it demands during a year. The BENG regulations in the Netherlands have become effective since 2019 for governmental buildings and from January 2021 for all newbuilt buildings [7]. There are three BENG indicators:

- **BENG 1**: Primary energy demand for heating, cooling in [kWh/m²/year] of floor area
- **BENG 2**: Primary fossil energy use for heating, cooling, and ventilation in [kWh/m²/year] of floor area
- **BENG 3**: Share of renewable energy use in percentage [%] (Share renewable energy) / (share renewable energy + primary fossil energy)

![Trias Energetica](image)
BENG 1 is the energy needed for space heating and cooling. BENG 2 is the energy for space heating and cooling and domestic hot water and ventilation and BENG 3 is the energy used from renewable resources divided by that added to primary fossil energy use [5]. For residential buildings, the above-mentioned criteria are BENG 1 ≤ 55 [kWh/m²/year], BENG 2 ≤ 30 [kWh/m²/year] and BENG 3 ≥ 50 [%]. For utility, educational, healthcare buildings, different limits apply.

1.1.3. Cost optimal energy-retrofit

The concept of large-scale energy retrofit within the EU has been covered by many studies. An Italian case study regarding the office buildings suggests that condensing gas boilers, water-cooled chillers, and full roof PV systems are the most cost-optimal measures [6]. In the same region, another case study for a hospital showed heat recovery systems, solar shading and cool roof, energy-efficient gas boiler, CCHP and non-collective solar collectors to be optimal for cost-optimal energy-saving measures [7]. Another case study in the south of Spain regarding city-level analysis of residential building stock has compared the micro economic (private) with a macro economic analysis [8]. An example from Vilas in arid climate (UAE), has shown on average an increase in the energy efficiency of 25% by application of low to medium cost techniques [9]. Using IEA Annex 75, [10] suggests that collective measures such as district heating can also be a cost-effective large-scale solution reducing district-scale CO2 emissions. [11] analysed two reference buildings in the category of single-family housing constructed in 1961–1980 and compared renovating to passive house level and regulation level. The conclusion was that cost-effectiveness largely depends on the heat generation system which in the case of direct electric heating makes renovation to passive house level the most cost-effective. In terms of individual measures, however, [11] claims exhaust air heat pumps to be the most effective and installing new windows the least cost-effective measure. [12] has analysed typical Finnish brick apartment buildings built in the 1960 s and using simulation-based multi-objective optimization aiming for minimum primary energy consumption and net present value over a 25-year discounted period, concluded that the cost-optimal renovation solution is an improvement to the national minimum energy performance requirements of new apartment buildings. Another Finnish case study for office buildings built in the late 70 s and 80 s, using multi-objective optimization aiming for least CO2 emission and best indoor thermal comfort suggests that ground sourced heat pump delivers the most cost optimum energy production and yields as high as 65% return on investment and 63% reduction in operational CO2 emissions [13]. From a top down perspective, [14] has analysed a single-family detached house built in 1935 in Cattolica-Italy, and using a novel stochastic life cycle cost analysis while considering different economic scenarios determined the dependency of investment gap between cost optimal and nZEB solutions to the micro-economic context. [15] developed a district level automated analysis procedure where energy simulation, 3D data modelling and simulation are combined. They concluded for a Finnish case study that for 6 realistic refurbishment measures compared in terms of operational cost, energy usage and CO2 scenarios can have conflicting desirable impacts. [16] analysed a Swedish multifamily building built in 1961 and using a Life Cycle Cost (LCC) analysis and considering and assuming a life cycle of 40 years suggested that balanced mechanical ventilation is only cost efficient when a minimum energy saving target of 40% is introduced. For lower targets a better building envelope is more cost efficient. [17] has studied three Toronto urban archetypes and concluded that furnace and building envelope parameters are cost-effective retrofit measures while improvements in windows are not. [18] has investigated an educational building in south Spain and showed that improving thermal bridges and using an air-to-air heat recovery system is more energy-saving compared to an improvement in windows. It was suggested for the summer period to use an air change of 4 ACH in daytime and night-time ventilation and avoid installation of air conditioning system. A summary of all suggested measures is given in the table below.

1.2. Scope

The focus of this research is the reduction of energy demand, primarily for space heating, of an existing Dutch district, which is in line with the 1st principle of Trias Energetica. A district in the city of Apeldoorn has been chosen [8]. Within the city of Apeldoorn, the district of De Maten seems the least diversified while being dominated by the most common building type in the Netherlands - terraced housing (Table 1 and Fig. 4). In the mentioned district, there is also diversity in the construction year of buildings which added to diversity in building type making it a suitable population. It should be noted that from the chosen district, only the diversity in building types and the construction year are considered and for simplification, other aspects such as building orientation and, Urban Heat Island Intensity (UHII) are ignored.

Stakeholder

A homeowner is the main stakeholder of this project as the building typologies are not representative of single buildings but a group of buildings. Overheating is also covered as a homeowner Key Performance Indicator (KPI) since overlooking such a criterion could change the strategy for the policymaker while the homeowner is the party mainly affected by building energy-retrofit [19]. The trade-offs and interactions between the optimum strategy for each stakeholder are also discussed [20]. This is to aid the policymaker in subsidizing a retrofit package that is likely to be implemented by the homeowner as well.

Robustness

Theoretically, building energy performance is analysed by a set of assumptions. These assumptions include the external conditions (like climate, irradiation) and system characteristics (building physics, installations, etc.) as well as occupant behaviour (heating/-cooling setpoints, usage profiles, etc.). Due to deviations between the assumptions made in the design phase of the building and realized condition, the building performance could potentially deviate from predictions. In the case of low energy buildings, this deviation becomes more important [21]. One deviation source is occupant behaviour. According to [22], occupant behaviour is the main source of performance deviation. This increases the uncertainty in building performance for rental housing while the private sector is not fully immune from it either. Accordingly, robustness analysis is performed to find the most robust package for the analysed building types. This mainly helps rental housing owners (social housing for instance) or Energy Service Companies (ESCos) to have more certainty in energy bills, making the investments in energy retrofits more reliable in terms of Payback Periods (PPB). [23] has conducted a comprehensive study on different methods for performance robustness and compares them based on the risk-taking attitude of decision-makers. The same author has suggested the mini-max Regret method in [21] for performance robustness analysis of decision-makers (such as homeowner/policy maker) where a certain range of performance variation is accepted.

Research question

The focus of this paper is to provide a methodology in developing a future-proof energy-retrofit strategy for Dutch building types. To realize this, the following research questions have been formed.

- RQ1: In the selected district, what are the most common building types? How does that relate to the whole building stock?
### Table 1
Summary of literature regarding energy retrofit measures.

| Literature | Country | Case study | Suggested measure |
|------------|---------|------------|-------------------|
| [6]        | Italy   | office buildings | Condensing gas boilers, water-cooled chillers, and full roof PV systems |
| [7]        | Italy   | hospital | Heat recovery systems, solar shading and cool roof, energy-efficient gas boiler, CCHP and non-collective solar collectors |
| [8]        | Spain   | residential building | Compared microeconomic and macro-economic analysis |
| [9]        | UAE     | Vilas | Energy efficiency of 25% by application of low to medium cost techniques |
| [10]       | –       | –       | Collective measures such as district heating for lowering CO2 emissions |
| [11]       | Finland | single-family housing constructed in 1961–1980 | Management cost-effectiveness largely depends on the heat generation system which in the case of direct electric heating makes renovation to passive house level the most cost-effective. In terms of individual measures, exhaust air heat pumps the most and new windows the least cost-effective. |
| [12]       | Finland | Typical brick apartments | Suggests that the cost-optimal renovation solution is an improvement to the national minimum energy performance requirements of new apartment buildings |
| [13]       | Finland | office buildings built in the late 70s and 80s | Suggests that ground sourced heat pump delivers the most cost optimal energy production and yields as high as 65% return on investment and 63% reduction in operational CO2 emissions |
| [14]       | Italy   | a single-family detached house built in 1935 | Analyses dependability of investment gap between cost-optimal and nZEB solutions to the micro-economic context |
| [15]       | Finland | case district | Concluded that various refurbishment measures can have conflicting desirable impacts in terms of operational cost, energy usage and CO2 scenarios. |
| [16]       | Sweden  | multifamily building built in 1961 | Suggested that balanced mechanical ventilation is only cost-efficient when a minimum energy saving target of 40% is introduced. For lower targets, a better building envelope is more cost-efficient. |
| [17]       | Canada  | Toronto urban archetypes | Furnace and building envelope parameters are cost-effective retrofit measures while improvements in windows are not. |
| [18]       | Spain   | Educational building | Improving thermal bridges and using an air-to-air heat recovery system is more energy-saving compared to an improvement in windows. The paper also suggested that in summertime ventilation rate of 4 ACH and night-time ventilation can eliminate the need for air conditioning. |

- RQ2: How are energy retrofit packages defined in the literature? Define a range of energy retrofit packages from least to most extensive.
- RQ3: What is the effect of each energy-retrofit package on the chosen building types in terms of space heating demand reduction, overheating risk introduced and investment cost?
- RQ4: What retrofit package is optimum for policymaker/homeowner per building type? Are there any overlaps?

The outline of this research is as follows. In Section 4 the methodology is explained. Section 5 presents the results and discussions. Finally, Section 6 concludes the results and suggests future work.

### 1.3. Methodology

The research method of this paper is based on building performance simulation to compare the effectiveness of various energy retrofit measures. To realize this, the following steps as depicted in Fig. 2, are taken:

- Modelling approaches: compare and select a modelling approach.
- Stakeholder and KPI selection: define various possible stakeholders and select KPI for performance comparison.
- Define case study: Select case-study area, scan for building types, select stakeholders and KPIs.
- Base-case modelling and validation: Compare BPS software packages, model case study, compare with reference values from UMGO.
- Design modelling and simulation: Retrofit packages are defined and modelled, compare with requirements from UMGO, compare KPIs.
- Robustness assessment: Define future scenarios, assess retrofit packages across defined scenarios, analyse spreads and maximum regrets.
- Energy strategy guidelines: Propose guidelines for the energy strategy of the case study.

The abovementioned steps are explained in depth in the following sections.

#### 1.3.1. Modelling approaches

Developing a robust energy-retrofit strategy for large groups of buildings requires knowledge about energy analysis approaches, building types, possible stakeholders, and performance robustness. The research literature review is laid out accordingly.

According to [24,25], there are two main models for energy demand analysis of building stocks and determining its energy-saving potential: top-down and bottom-up models. Each modelling method has its own approaches as schematically shown in Fig. 3.

As said by [24], top-down models find the relationship between the (historical) aggregated energy consumption of housing stock and socio-economic and socio-technical drivers. The correlations are found using national statistics. There are two main approaches for top-down models [25]:

- Econometric approaches: They find the relationship between energy consumption and macro-level variables such as inflation rate, general climate, energy price etc. [26]
Technological approaches: They seek the relationship between energy consumption and societal trends, such as trends on the ownership of appliances [24].

Top-down approaches are relatively easy to develop; as the modelling approach is mainly based on the limited historical data on energy use patterns or macro-socioeconomic parameters [25]. The main drawback of the top-down modelling according to [10], is that they lack resolution in what the potential savings for individual end-users are and this disables them in specifying key areas for improvement.

In bottom-up modelling, the sum of individual end-uses forms the total end-use energy [24]. There are three main approaches within bottom-up modelling:

- Statistical methods (SM): According to [26] they “rely on historical information and types of regression analysis which are used to attribute dwelling energy consumption to particular end-use”.
- Building-physics based/Engineering methods (EM): Most frequently used approach in the literature, According to [26] EMs “explicitly account for the energy consumption based on power ratings and use of equipment and systems and/or heat transfer and thermodynamic relationships”.
- Energy-economic methods: According to [24] this method considers “technology uptake options” as well as “user behaviour and investment behaviour of the homeowner” which makes it a hybrid bottom-up approach.

The main drawbacks of bottom-up models were mentioned in [27] to be:

- Available data for many countries is limited.
- The sensitivity of input parameters is not appropriately described.
- The effect of user behaviour and its changes through retrofitting is not completely known.

Due to the high level of details used in engineering methods compared with statistical methods, only engineering method can advise on the effect of technology breakthroughs, large scale refurbishment or change in occupant behaviour [28]

Since this research aims to find the most suitable combination of energy retrofit measures and Dutch buildings, a building physics-based method is chosen as the modelling approach. To do so, knowledge of building archetypes is necessary.

1.3.2. Key performance indicators (KPIs)

The homeowner is the main stakeholder in this study. According to [29], the homeowner looks for the energy retrofit strategy that brings the most comfort and requires the least investment. The following KPIs are considered:

- Investment cost (EUR): For each energy retrofit package, an investment cost is determined.
- Heating and cooling load (kWh/m²/yr.): The effect of each package on the building energy performance is shown in terms of heating and cooling load variation.
- Overheating risk in terms of cooling load (kWh/m²/yr.): Regarding the comfort aspect of energy retrofitting, overheating is assessed by applying a robustness assessment method suggested by [29] on cooling demand.
- Investment cost per MWh reduced demand (EUR/MWh): Investment cost per MWh thermal energy saved per year is also covered to compare how economical are the investments for different renovation levels.

To a homeowner, savings from other buildings in the neighbourhood or even the CO₂ emissions of their own building are often not the main concern. Hence, KPIs for this stakeholder are defined at the building level. In contrast, the bottom-up EM approach uses building archetypes to calculate the energy-saving potential in the building stock. This is because the creation of building archetypes
was aiming at bottom-up quantification of group-scale goals and therefore simplifications were applied to find averaged archetypes that are representative of the whole housing stock.

Often there are deviations between the predicted performance of the building and the operational performance. In deep energy retrofits to achieve low energy buildings, this deviation becomes more important. To analyse such uncertainties in building energy performance, performance robustness assessment methods have been introduced by [21] which is explained later in this section.

1.3.3. Case study

1.3.3.1. Building types. The use of building typologies in Urban Energy Simulation (UES) is common in Europe, Canada and the United States [27,30–33]. In the case of the Netherlands, [34] is a reliable source as it has been frequently used in the literature and also have been referred to in a larger building stock categorization project across Europe called Project TABULA [9].

Dutch building typologies from [34] use references from 2001 to 07. According to them, the defined building typologies are example buildings and not reference buildings. This means that the typologies cannot be used to advise on energy saving on the building level, but for larger scales such as the building sector. Accordingly, the smaller the analysis group of buildings is, the less representative the defined building typologies become. The reason for that is not only that these typologies are defined supporting large-scale decision making, but also that on the building level other effective factors such as occupant behaviour become more dominant which disallows averaging to represent aggregated behaviour. Nevertheless, these building typologies allow for the implementation of the EM approach on the district level since many houses allow for the averaging out of occupant behaviour.

According to [34] Dutch building stock divides into 7 typologies and up to 5 construction periods yielding 30 example buildings (for some typologies the oldest construction period is not divided into two as shown in Table 1). Each example building is assigned the following:

- Used floor area
- The average number of occupants
- Area of building envelope components (roof, wall, floor, window)
- Thermal properties of building envelope components
- Heating, ventilation system

Despite being outdated, a basic analysis of the energy retrofit strategy per building type has already been provided in the name of a “besparingspakket” (saving package) by [34]. However, only one energy retrofit package towards a better energy label is given while the concept of energy labels is recently replaced by nZEB. In addition, it also does not include any overheating analysis because of the improved building envelope. In 2018, the 4.2 version of a calculation model called Uniforme Maatlat Gebouwde Omgeving or UMG (uniform measuring tool for the built environment) was introduced by the Netherlands Enterprise Agency (RVO) in which the effect of different thermal systems can be quantified for typical Dutch building types for large-scale analysis [5]. The calculations in the UMG model are also based on the Dutch standard (i.e., NEN 7120) and predicts the total primary fossil fuel consumption and CO₂ emissions for a group of buildings. Nevertheless, no cost element has been added to this model and it is not adjustable in terms of building envelope thermal quality while being highly flexible in terms of building installations and heating systems.

In this research, not only different levels of building envelope thermal quality are considered (from current regulations up to passive standards), but also their performance robustness is analysed.

The results aid with simultaneous assessment of savings in space heating and resulted in overheating risk per building type.

Looking at the number of buildings across archetypes and construction periods in Table 1, there are 4 to 5 main construction periods that aid with assigning thermal properties. As mentioned above, some building typologies such as detached housing are categorized into 4 construction periods. For them, the two oldest construction periods are combined into one (being before 1964), shown between the two periods in Table 1. Comparing the numbers, terraced housing is the most populated archetype covering more than 40% of the Dutch building stock. Later in methodology, the focus has been given to this archetype as it is the most representative. Adding detached and semi-detached housing, the coverage increases to about 70% of the building stock, simply by analysing these 3 typologies.

Using the building archetypes from [34] and following a bottom-up EM method, the effect of renovation measures per example building can be computed. However, in building stock there are different stakeholders with different KPIs.

1.3.3.2. Case study selection. Due to time/energy/computation power limits, it was decided to limit the covered building types and analyse each type in more detail. This is also in line with choosing a bottom-up engineering approach in energy modelling which allows for analysing retrofit measures on building level. As such, detached, semi-detached and terraced housing have been chosen as common Dutch building typologies. This is because they cumulatively cover more than 4.6 million dwellings (out of 6 million buildings to be renovated). In addition, the coverage of all building types parallel to robustness assessment was timely, not possible. Consequently, the chosen Dutch district of De Maten in the city of Apeldoorn is chosen for further analysis which is dominated by these three typologies (specifically Terraced housing being the most common building typology in the Netherlands).

The district of De Maten does not contain all but the most common building types in the Netherlands, such as terraced, semi-detached and detached buildings (Fig. 4). After terraced housing (blue and grey), the following building types are spotted the most: Detached (green), semi-detached (red). Some apartments (black) and a few other buildings are also spotted in this district as well which are out of the scope of this research.

The colour shaded GIS map on the right in Fig. 4 shows that the construction years 1960–75 (white) and 1975–85 (the lightest blue) are the most common construction periods of the buildings in the investigated district [15]. To find the related building envelope characteristic, the construction periods from this GIS map is compared to the known construction periods from Table 1. As a result, the construction period of 1960–75 and 1975–85 have been respectively translated to 1965–75 and 1975–91.

To sum up, the typologies included in De Maten are detached, semi-detached and terraced housing built between 1964 and 1991. Next, the modelling of these base-case buildings is explained.

1.3.4. Base-case modelling and validation

There are two main approaches in modelling the energy demand of the building stock: top-down and bottom-up. To answer the research question, data on disaggregated level (building level) is required. Since the top-down approach is defined for the aggregated level, it is not a suitable choice. Within the bottom-up models, there are statistical and engineering/building physics-based models. The statistical model, according to [27], requires large data samples and is limited in covering energy-saving measures. Building a physics-based/engineering model on the other hand can model technical measures which makes it suitable in answering the defined research questions. For such purpose, several commercial software packages are available. Since
Integrated Environment Solution Virtual Environment (IES VE) is a widely used tool for BES in literature and is also able to perform parametric studies, it was chosen to execute both the gain and the robustness calculation.

1.3.4.1. Assumptions. A set of assumptions are required to perform a dynamic BES. They count both for building physics, occupant behaviour and climate. Most building physics and some occupant behaviour assumptions are given by [34] which defines Dutch building typologies. For the assumptions, due to lack of data per building type, a set of assumptions is assumed and kept constant to calculate the performance improvement. However, in robustness assessment, they alter.

Geometry
For each building typology, a reference plan is provided by [16] which is brought in Appendix A. Although these reference plans are for the newly built buildings, since they have been used in the UMGO calculations for reference demands [5], it is assumed that they hold for the old buildings within each typology. It is noted that the floor maps are not modelled in this research and only the outer part of the building that interacts with outside temperature is modelled. As a result, the internal walls and floors are not changed from what is automatically modelled by IES VE. Accordingly, for each floor, only one thermal zone is modelled. For the rooftop, the heating, cooling, and ventilation are off. For geometries like Terraced-side and semi-detached, the average performance of the sides is analysed.

Building envelope properties
For each building type, the U-values and Rc-values are assumed to be given by [35]. The older the building within a typology is, the worse its thermal properties become as the building regulations has generally become stricter in time. Table 2 includes reference thermal properties for the chosen building types. In terms of the thermal mass of the buildings, Typical Dutch constructions have been considered.

Heating and cooling setpoint
For comparison of base-case with UMGO reference values, it was attempted to match as many assumptions as possible which allow for better comparison quality. Since UMGO uses a static monthly calculation method some of the assumptions could not be the same because IES VE follows dynamic hourly BES. Therefore, despite the possibility of using an hourly heating setpoint profile, the same constant set points in UMGO calculations were taken, namely 16.5 °C for the heating from [5] and 24 °C for the cooling from [36].

Occupancy
Each building type has a reference occupancy from [34]. The occupancy for all building types represented in Table 2 is 3 persons except for Detached housing constructed in 1975–91 which is 3.2 persons. Note that this only affects the internal heat gain where a reference heat gain per person is defined later.

As for the occupancy profile, working occupants are chosen. The main effect of these assumptions is internal heat gains which are off from 8 am until 4 pm. The reference occupancy given in the reference is equally divided into two floors. This also only represents the heat gain from occupants to be divided equally between the two floors. Following the same logic, occupant presence in the attic is neglected.

Infiltration and ventilation
For the old buildings, mostly there is no mechanical ventilation system. However, typically small fans are installed in the bathrooms/kitchens which dumps aged air outside to be replaced by fresh air and adds to the air exchange between the building and environment. Therefore, the air exchange in general consists of

Table 2
Number of existing buildings per building typology [34]

| Construction year | 1945 | 1946–64 | 1965–74 | 1975–91 | 1992–2005 |
|-------------------|------|---------|---------|---------|-----------|
| Detached          | 441,000 | 119,000 | 221,000 | 178,000 |
| Semi-detached     | 285,000 | 142,000 | 224,000 | 173,000 |
| Terraced          | 523,000 | 478,000 | 606,000 | 879,000 | 353,000 |
| Maisonnets        | 226,000 | 22,000  | 94,000  | 40,000  |           |
| Common staircase-with galleries | 69,000 | 174,000 | 109,000 | 113,000 |
| Common staircase-no galleries | 256,000 | 112,000 | 142,000 | 70,000  |
| Apartment         | 99,000  | 125,000 | 125,000 | 136,000 |           |
two parts: infiltration and ventilation. Infiltration is the air that passes through the cracks in the wall, below the door, etcetera and is unavoidable while ventilation is intentionally added to keep inside air fresh.

In the case of infiltration, the older a building is, the less airtight and therefore the more its infiltration rate becomes [37]. Considering the infiltration rate in current regulations being 0.4 \( \frac{\text{l}}{\text{m}^2 \cdot \text{s}} \) (based on floor area) and a worsening trend for air tightness towards older buildings, infiltration rates of 0.8 \( \frac{\text{l}}{\text{m}^2 \cdot \text{s}} \) and 0.6 \( \frac{\text{l}}{\text{m}^2 \cdot \text{s}} \) for the construction year of 1965–74 and 1975–91 respectively are assumed. This is based on the findings of [38] which has analysed 300 Dutch dwellings where most of the measured specific leakage rates were between 0 and 1 \( \frac{\text{l}}{\text{m}^2 \cdot \text{s}} \).

For ventilation in the base case and packages, a minimum of 0.7 \( \frac{\text{l}}{\text{m}^2 \cdot \text{s}} \) through natural ventilation or mechanical ventilation in the packages with Heat Recovery Ventilation (HRV) are assumed. Besides, it is assumed that ventilation is always on therefore modelled in IES VE as infiltration rate together named total air exchange.

Internal gains

Three main sources for internal heat gains are considered. First, from the occupancy and the metabolism, second from lighting and third from the appliance. In IES VE, the sensible value of internal gain adds to the temperature and the latent value adds to the water vapour content of room air [21]. The corresponding values are brought in Table 3.

Weather data

For weather data of the base case, the weather data from energy plus for the location of Amsterdam is used which is a Typical Meteorological Year. Reference heat demands from UMG0 is calculated plus for the location of Amsterdam is used which is a Typical Meteorological Year. Reference heat demands from UMG0 is calculated for the location of Amsterdam.

In addition, the cost calculations are based on the area required which in the case of the external wall often is the highest.

### 1.3.5.1. Design space definition

Following a literature review on how the energy retrofit package is defined, the following combinations are selected (Fig. 5). The building-envelope properties start from current regulations (P1 & P4) up to passive standards (P3 & P6) [3934]. The first three packages still use the natural ventilation system while the second three are equipped with a Heat Recovery Ventilation (HRV) system. The insulation thickness of the same constructions as in the base case is increased to meet these resistance values. To give a sense of how thick the insulation becomes in the packages, the largest insulation thickness for Rc-value of 10 \( \text{m}^2 \cdot \text{K} / \text{W} \) for the roof in Package 3 and 6 is about 30 \( \text{cm} \) and for Rc of 8 \( \text{m}^2 \cdot \text{K} / \text{W} \) in the same cases for the external wall, it is about 20 \( \text{cm} \). The total roof thickness and wall thickness in such extreme cases are 35 \( \text{cm} \) and 40 \( \text{cm} \) respectively.

The U-value of the windows including the frame are from [33]. In [21], Rc-values of up to 10 \( \text{m}^2 \cdot \text{K} / \text{W} \) for a passive house is mentioned. However, since in general, the heat loss through the roof is more than external walls (more wind speed above the building and more radiative loss during night facing sky), and external walls more than the floor (presence of convective/radiative heat loss), least thermal resistance was assigned to the floor and the highest to the roof. The same trend can also be seen in the current regulations [16]. In addition, the cost calculations are based on the area required which in the case of the external wall often is the highest.

### 1.3.5.2. Modelling method

As for the heat transfer equations, the same software package is used in the designs as in the base cases (IES VE). However, to model the HRV and PV, which did not exist in the base case, additional assumptions are required.

**Heat recovery modelling method**

The HRV allows for the exhaust air to pre-heat the fresh air intake from outside and save up to 90% of the heat that was otherwise thrown away through ventilation. Considering the heat transfer equation for the air in the HRV system \((Q = m \cdot C \cdot \Delta T)\), the 90% efficiency of the HRV can be modelled in two ways:

- Increase in air-source temperature: In this approach, the 90% efficiency of HRV is translated into a 90% temperature increase between indoor and outdoor temperature \((\Delta T)\) so that only the remaining 10% of temperature difference is to be supplied for fresh air inside (+10%\(\Delta T\)).
- Modelling ventilation as infiltration with a lower rate: Another approach in modelling HRV is that instead of increasing the source temperature for ventilation by +90%\(\Delta T\) (compensating for the effect of 90% efficiency), reduce ventilation rate by 90% with no increase in source temperature so that only the remaining 10% of ventilation is heated providing fresh air \((m_{\text{HV}} = 0.1 \times m_{\text{vent}})\). This way, ventilation can be modelled as additional infiltration (source temperature same as outside) which is used to model HRV in IES VE.

| Table 3 | Building envelope properties for chosen building types [34] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Building type   | Construction year | Floor Rc-value \(\text{m}^2 \cdot \text{K} / \text{W}\) | Wall U-value \(\text{W} / \text{m}^2 \cdot \text{K}\) | Roof U-value \(\text{W} / \text{m}^2 \cdot \text{K}\) | Window + Frame U-value \(\text{W} / \text{m}^2 \cdot \text{K}\) | Infiltration \(\frac{\text{l}}{\text{m}^2 \cdot \text{s}}\) |
| Detached        | 1975–91         | 0.52            | 1.30            | 1.30            | 2.90            | 0.6             |
|                 | 1965–74         | 0.17            | 0.43            | 0.86            | 2.90            | 0.8             |
| Semi-detached   | 1975–91         | 1.30            | 1.30            | 1.30            | 2.90            | 0.6             |
|                 | 1965–74         | 0.17            | 0.43            | 0.86            | 2.90            | 0.8             |
| Terraced        | 1975–91         | 0.52            | 1.30            | 1.30            | 2.90            | 0.6             |
|                 | 1965–74         | 0.17            | 0.43            | 0.86            | 2.90            | 0.8             |

*Based on floor area
Following this logic, the total air exchange with outside for the packages with natural ventilation modelled as infiltration is:

\[
\text{Infiltration}_{\text{total}} = 0.15(\text{airtightness}) + 0.7(\text{natural ventilation}) = 0.85\left(\frac{1}{\text{s.m}^2}\right)
\]

while for the packages with HRV the total air exchange is modelled as

\[
\text{Infiltration}_{\text{total}} = 0.15(\text{airtightness}) + 0.7 \times 0.1(\text{HRV}) = 0.22\left(\frac{1}{\text{s.m}^2}\right).
\]

PV modelling method

In all packages (as shown in Appendix B), the rooftop is assumed to be filled with monocrystalline solar panels of with nominal efficiency of 13% (at 45 °C and 800 W/m²) and electrical conversion efficiency of 0.85, sized of 1640*992 mm² and tilted 40° from the horizon towards the south. This is to calculate the generation capacity on the rooftop of each building typology with the assumed reference orientation.

1.3.5.3. Simulation setup. The simulation software calculates the heat balance and dynamic BES per time unit. IES VE allows modifying both the report time step and simulation time step. The report simulation step can be smaller than the simulation time step using interpolation at cost of interpolation errors in return for smaller computation time. As the climate data is per hour, a report time step of 1 h has been chosen while the simulation time step varies. In general, the more the dynamic of heat transfer in the building, the shorter the required simulation time step to enable capturing the transient effects. In IES VE, a certain limit for the simulation time step exists such that if larger time steps are selected, discontinuity in output variables happens. IES VE avoids the simulation to complete if such discontinuities occur through errors such as “instability in wall temperature”. Accordingly, for each design, the time step was reduced until IES VE allows the simulations to be executed. To make sure the output results are independent of reducing the time steps, the simulation time step has been reduced one more step and when the results were similar, the larger time step was chosen for a shorter computation time. Following simulation time steps in minutes were eventually selected (Table 4).

1.3.5.4. Gain calculations. After the energy retrofit of a building typology to the defined packages, for the calculation of average gains from energy retrofitting, one of the assumptions used in the validation phase is changed to a more realistic one resulting in more practical energy saving. The heating setpoint, to which the BES is overly sensitive, is changed in the gain calculations to a value of 20 °C which is referred to in NEN 7120 as well as being in between the extremes in robustness assessment conditions.

1.3.5.5. Cost calculations. Since the main stakeholder of interest in this report is the policymakers, Investment Cost (IC) has been chosen for the financial KPI. For wall/roof/floor insulation, airtightness, and PV the ICs are from [21]. For glazing, the IC is from [19]. Lastly, for the HRV system, the reference price is [20]. Although the HRV price is given for 95% efficiency, the same price for 90% efficiency has been assumed. The breakdown of total investment cost per renovation package is brought in the next section.

In addition, the savings in space heating demand are compared to the required investment cost to provide insight into the return from reduced energy bills and the relevant PBP.

1.3.6. Robustness assessment

1.3.6.1. Performance robustness. Assessing the energy performance robustness of a building requires the formulation of so-called “future scenarios”. Subsequently, the KPI of interest for designs in all future scenarios is recorded in a performance matrix. After having the performance matrix, there are three methods to find a robust design based on the performance matrix as said by [29]. A comparison of these methods with respect to the indicator, robust design and a key aspect is given in Table 5. The mini-max regret method is suggested where “the decision-maker (homeowner or policymaker) can accept a certain range of performance variation”[29]. How this method works in detail is explained in the methodology section.

1.3.6.2. Performance robustness in the case study. In the literature review section, it has been pointed out that the mini-max regret method is suitable for this study. Before implementing this method, future scenarios are first formulated concerning 2 categories (energy usage and climate) as defined in [21]. The effect of policy scenarios has not been investigated as only the annual yield from PV are considered. The effect of occupancy has also not been considered as it marginally (due to working hour profiles) affects internal heat gain (60 W for 1 person and 240 W for 4 persons) which is considered more intensity (through appliance and lighting gain cumulatively ranging from about 200 W to 600 W) in the category of usage. Considered variables which formulate future scenarios are given in Table 6.

The occupancy category performs the same way as the other internal gains considered. Policy scenarios also deal with tariffs which is not related to the main objective of this research to be
minimizing the heating demand while generating the least risk of overheating.

Following the procedure of applying the regret method from [21], after the performance indicator ($P_{Imn}$) of each design ($d_m$) in each scenario ($s_n$) is computed and recorded in performance matrix (upper part of Table 7), following steps need to be taken:

- Regret calculation: "Regret" for each design in each future scenario ($R_{mn}$) is computed by subtracting its performance ($P_{Imn}$), from the best performing design in each scenario ($A_n$) as shown in the lower part of Table 7, following steps need to be taken:

- Maximum regret per design: The maximum regret for each design across all future scenarios is found: $R_{max} = \max(P_{Imn})$.
- Lastly, the design that has the least maximum-regret would be ranked as the most robust and least prone to future scenarios: $\text{robustdesign}_m = \min(R_{max})$.

For easier comparison, maximum regrets are normalized which is the maximum regret of a design divided by the largest maximum-regret across analysed typology. Normalized maximum regret of 1 shows the most robustness and 2 shows half the robustness and so forth. Such variable aids with a simple comparison of robustness in designs without the knowledge of robustness assessment methods and how they are calculated.

In the result section, designs are also compared in terms of performance spread not to find the most robust design (as the regret method has been chosen) but to provide the uncertainties in building performance across harsh conditions formulating future scenarios for robustness assessment.

1.4. Result and discussion

1.4.1. Results

Results are divided into 4 sections: Base-case modelling and validation, design performance, robustness assessment and investment analysis. Each part is executed based on a set of assumptions previously discussed in the methodology section. Since the reference demands and BENG indicators are per floor area, the total calculated demands are converted to the same unit for easier comparison. The floor area for each building is as follows: Detached = 122.4 [m²]; Semi-detached = 113.4 [m²]; Terraced-middle/side = 104.8 [m²].

| Internal gain assumptions. | Fluorescent lighting | Appliance | Occupancy |
|----------------------------|---------------------|-----------|-----------|
| Profile                    | 6–8 and 16–24       | on continuously | Not present 8:00–16:00 |
| Sensible value             | 2 [W/m²] [21]       | 2 [W/m²] [21] | 90 [W/person] |
| Latent value               | 0                   | 0         | 60 [W/person] |

Table 4

| Simulation time step per design scenario. | Base1965–74 | P1 | P2 | P3 | P4 | P5 | P6 |
|------------------------------------------|------------|----|----|----|----|----|----|
| Detached                                 | 6          | 30 | 30 | 30 | 30 | 30 | 30 |
| Semi-detached                            | 6          | 30 | 30 | 30 | 30 | 30 | 30 |
| Terraced-side                            | 6          | 10 | 10 | 10 | 10 | 10 | 10 |
| Terraced-middle                          | 6          | 10 | 10 | 10 | 10 | 10 | 10 |

Table 5

| Comparison of robustness assessment methods [29] | Performance spread across all scenarios | lowest median value with minimum performance spread | Extreme scenarios for a design highly steer the chosen robust design (conservative) |
|------------------------------------------------|----------------------------------------|---------------------------------------------------|--------------------------------------------------------------------------------|
| Max-min                                        | Performance deviation = worst-case design performance - Best performing case across all designs and scenarios | Lowest performance deviation | Considers all scenarios robust design selection (Extremely conservative) |
| Best-case & worst-case                         | Regret = design performance - best performance within that scenario | Lowest maximum-regret | feasible when a certain range of performance deviation is acceptable |

Table 6

| Future scenarios considered in this research [21] | Value |
|---------------------------------------------------|-------|
| Usage Heating setpoint                            | 18–20–22 [°C] |
| Lighting heat gain                                | 1–3 [W/m²] |
| Appliance heat gain                               | 1–3 [W/m²] |
| Climate W+                                        | 2 [°C] increase in global temperature by 2050 and change in air circulation patterns |
1.4.1.1. Base-case modelling and validation. In Fig. 6, the simulated annual space heating demand for base cases are compared with UMGO reference values [5]. The converted simulated space heating demands are demonstrated in Fig. 6. Looking at the results per construction period, the results for the older construction period (1965–74) across all building types on average show a deviation of –5% from UMGO while for the newer construction period (1975–91) the average deviation is +15%. Considering the differences in calculation methods and assumptions which will be discussed later in this research, the simulation outputs are in good agreement with UMGO reference values using a heating setpoint of 16.5 °C.

1.4.1.2. Design performance. In this part, first, the energy savings from each package is presented in terms of savings in space heating demand. Afterwards, the overheating risks in terms of cooling demand are presented to show the trade-off between savings in heating demand and risks in the introduction of cooling demand.

Savings in space heating demand

Below, the improvement in Space Heating Demand (SHD) and risks in Space Cooling Demand (SCD) by implementing each energy retrofit package are brought per building type compared with reference demands from UMGO in Fig. 7 and Fig. 8 respectively [5]. It is noted that only for detached housing, the SH/SC requirements for BENG are different. The reference space heating and space cooling demand for BENG requirement are from [5] which changes per building type and is brought in Table 8 as a reference for lines in Fig. 7 and Fig. 8. It is noticed that the sum of the two yield BENG which for a residential building like mentioned before should be below 55 [kWh/m²/yr].

The results of space heating suggest a considerable gain from base cases to P1. However, from P1 to P3 the gain is not as significant. The same trend for optimum insulation thickness has been proven by similar research [40]. This effect comes only from increasing the insulation levels and improving the glazing and airtightness. The results for P4-P6 on the other hand show a significant reduction of heating demand being sourced only from changing the ventilation system. The results also show the high impact of HRV on space heating by comparing the space heating results of packages 1 to 4 package 2 to 5 and package 3 to 6. This high impact has been reflected also in other research [18].

On the other hand, the HRV adds to the electricity demand by 148.9 [kWh/yr.]. Using a CO2 emission factor of 526 [gr/kWh] from [41], this translates to 78.3 [kg/yr.] of CO2 emission. For comparison of the electricity emission per kWh of electricity demand to that of gas, considering 56.1 [kg/GJ] of CO2 emission (from [42]) and a boiler efficiency of 90%, the CO2 emission of gas sourced heat is 224.4 [gr/kWh]. This means that each kWh of electricity demand emits as much emission as 2.35 kWh of gas-sourced heat. Looking at the detached housing, the smallest savings in SHD (upgrade from base 1975–91 to P1) is about 120 [kWh/m²/yr.] *122.4 [m²] = 14.688 [MWh/yr.]. This shows a CO2 emission reduction of 3296 kg due to less gas demand. Comparing to 78 kg of added emission due to more electricity demand in implementation of HRV, the emission savings from less heating demand largely outweigh the emissions for added electricity demand.

Overheating risk

By improving the airtightness and insulation of the building, as expected the space heating demand decreases. However, the risk of overheating might be introduced which initially did not exist. In a heating-dominated climate like the Netherlands, often the only cooling measure in residential buildings is natural ventilation. For such houses, improving the airtightness/insulation level of the building makes the indoor temperature during summer prone to overheating after the retrofit since the only cooling measure is limited and also more insulation dampens the night-time cooling effect. Other sources of overheating such as the Urban Heat Island effect are also present and increase the risk of overheating. Therefore, it is important to know how much cooling the new building envelope demands. In Fig. 8, the cooling demand with a set point of 25 °C (according to [43]) is brought for each design to quantify overheating risks that come with retrofitting.

The highest cooling demand as expected is for detached housing. This is due to having more surface area exposed to outside temperature while also having no shading effect from the buildings.
Fig. 7. Space heating demand per design compared with different requirements from [5] (Heating setpoint = 20 °C).
Fig. 8. Space cooling demand per design compared with different requirements from [5]
on either side of it as opposed to semi-detached or terraced housing.

On the other hand, semi-detached housing shows to have the least cooling demand which is not expected following the logic of adjacency while terraced-middle has no solar gain on two sides of the building. This can be because all buildings have a large window (towards the south in terraced housing and towards the west for detached housing as can be seen in Appendix B) which considerably changes the solar heat gain while semi-detached housing does not have such element. Therefore, less solar heat gain yields less cooling demand. In terraced housing, on the other hand, the middle house appears to be less demanding in terms of cooling compared with the side house which again is due to less solar gain for the middle house compared with the side house.

The cooling demands for the packages with HRV are the same as without since the same required ventilation rate of 0.7 [l/s/m²] was assumed for natural ventilation as for heat recovery mechanical ventilation. Cooling demands are negligible compared with heating demand. This means that while heating demand is reduced significantly, comparatively cooling demand has not increased. This is because the same constant rate of ventilation is assumed both for natural and mechanical ventilation. As in reality ventilation rate changes, the lower it is, the higher the cooling demand becomes (using the parametric tool in the software for the extremely low ventilation case of 0.1 [l/s/m²] the cooling demand increases up to 5 times). This sensitivity to air exchange rate comes from the highly air-tight infiltration of 0.15 [l/s/m²] which is insignificant compared with a minimum ventilation rate of 0.7 [l/s/m²] and therefore makes the model overly sensitive to the ventilation rate in terms of cooling demand. This high sensitivity to air exchange is in line with the findings of [18]. The effect of extra heat loss due to ventilation has already been visualized with HRV (i.e., P4 compared with P1).

The results suggest that all packages do not introduce extra cooling demand which has also been confirmed by other research provided with sufficient ventilation [18].

### 1.4.1.3. Robustness assessment.

In the methodology section how to formulate future scenarios were determined. Considering 3 heating set points, 2 internal gains from lighting, 2 internal gains from the appliance and 2 climate scenarios, 24 combinations are possible. The robust design is eventually chosen by regret methods as argued in the methodology. However, visualizing the performance spread can give insight into the amount of uncertainty that is expected from each building across all 24 future scenarios. First, the performance spread is presented. Then the maximum regrets per design are brought to indicate the most robust package per building type.

#### Performance spread

The performance spread of all designs, in terms of space heating demand, are brought below in box and whisker plots (Fig. 9). In each plot, the upper extreme and the lower extreme (the line), as well as upper quartile and lower quartile and median (the rectangle) and average (the cross) are visualized.

The results for space heating demand across all building types suggest that both the spread and the median value of performance decreases from P1 to P6 which means the uncertainty in space heating demand becomes smaller with deeper energy retrofit while the relative impact increases as the demands become smaller. The presence of the HRV also appears to reduce the performance spread significantly which shows the high dependency between the space heating demand and the heat loss through ventilation/infiltration in the analysed building types.

#### Mini-max regret method

Following the mini-max regret method, the maximum regret per design for space heating could bring insight into the robustness of the design. The normalized maximum regrets (maximum regret/least maximum regret across building type) for easier comparison are brought in Table 8. Looking at the normalized maximum space heating regrets, package 1 is about 2.5 times less robust compared with package 6. Besides, packages with HRV appear to be on average about twice more robust than the packages without HRV.

In terms of space cooling, the maximum regrets are not relevant since packages performed the same regarding the introduction of the cooling demand.

### 1.4.1.4. Investment analysis.

The investment costs for floor, wall, roof, glazing and PV have been calculated by multiplying the m² required by the cost per m². The first 3 retrofit packages only differ in the ventilation system and airtightness from the other 3 packages. Therefore, the investment cost for floor/wall/roof insulation and glazing across all building types are the same for P1 = P4, P2 = P5 and P3 = P6. The breakdown of the investment cost per retrofit package is brought in Fig. 10. Looking at Fig. 10, the investment cost for wall insulation of each package changes considerably across building types. The reason for that is the different external wall area across building types so that for the same insulation level (each package), the building type most exposed to the outside (detached) has the highest investment cost for wall insulation compared with the building type least exposed to the outside (terraced-middle). The investment cost also changes from P1 to P3 for the same building type and that is due to thickening insulation or better glazing.

The investment cost of airtightness improvement is the same across all building types to be 1958€ (for airtightness 0.15 l/s/m²). For the packages with the HRV system (P4, P5, P6) the required investment excluding installation cost is 1500€ while for the first three packages this cost does not apply.

Lastly, the cost of the PV module is also calculated by the cost per installed area. By filling the rooftop of each building type, the generation potential of each building type is calculated. The cost per [m²] of panels is 307€ and each panel is 1.63 [m²] which yields

---

### Table 8

Performance matrix and regret matrix from [21]

| $s_1$ | $s_2$ | ... | $s_n$ |
|-------|-------|-----|-------|
| $d_1$ | $P_{11}$ | $P_{12}$ | ... | $P_{1n}$ |
| $d_2$ | $P_{21}$ | $P_{22}$ | ... | $P_{2n}$ |
| ...   | ...   | ...   | ... | ...   |
| $d_m$ | $P_{m1}$ | $P_{m2}$ | ... | $P_{mn}$ |

---

P4 compared with P1.)
The investment costs are: Detached (20 modules) 9,995 €, semi-detached (18 modules) 8,995 €, Terraced-middle/side (15 modules) 7,496 €.

Investment vs. Gain: which package is the most economical? Investors are often interested in a criterion that compares the available options in terms of required investment per unit of preferable gain. This helps them choose the most economical design. In this research, the investment per unit of saved energy is chosen to deliver such insight.

Assuming the same investment cost to improve the insulation levels from both base construction periods (1965–74 and 1975–91), in Fig. 11, the average investment per MWh of saved space heating demand is brought for retrofit packages. The results illustrate that first, it is more economical to invest in older buildings since the starting building envelope performs further away from thermally optimal, and second, package 4 seems to be the most economical package among others for both base construction periods. Package 4 represents an improvement to current regulation standards for the building envelope combined with HRV. The cost-effectiveness of improving building regulations and installation of HRV have been found by [7][16] and [12] respectively.

The payback period (PBP) offers extra insight into the financial feasibility of these retrofit packages. It is assumed that the heating system is a gas-fired boiler.

**Table 9**

| Standard req. | Detached | Semi-detached | Terraced-side | Terraced-middle |
|---------------|----------|---------------|---------------|-----------------|
| Unit          | SHD      | SCD           | SHD           | SCD             |
| BENG          | 17.4     | 6.8           | 20.9          | 2.1             |
|               | 15.5     | 4.0           | 9.2           | 3.0             |

499.76 [€/panel] [21].
If a high efficiency (90%) gas heater is responsible for space heating, with an average gas price of 0.63 [€/m³] according to [21] and assuming a calorific value of 40 [MJ/m³] for gas, the price of gas-sourced space heating (excluding the cost of heating system) would be 63.00 [€/MWh]. This compared with the range of investment required for 1[MWh] of saved space heating demand from Fig. 7 yields PBP ranging from about 4.7 years for the most economical investment (Upgrade from base case 1965–74 to P4) and about 7.2 years for the least economical investment (upgrade from base case 1975–91 to package 3) on average across all building types.

Lastly, the gains from PV panels in terms of annual electricity generation per module is 180[kWh]. Hence: Detached (20 modules) = 3.60 [MWh], Semi-detached (15 modules) = 3.24 [MWh], Terraced-middle/side (15 modules) = 2.70 [MWh]. Assuming a lifetime of 20 years for PV system, the cost of generated electricity over the lifetime is 0.07 [€/kWh] which is significantly cheaper compared to grid electricity of 0.21 [€/kWh].

Investment vs. Gain: which typology is the most economical? Below the breakdown of Fig. 11 per building type for the improvement from the base case of 1965–74 and 1975–91 are brought in Table 10 and Table 11 respectively. Generally, the more the floor area of the building and the more extensive the retrofit package, the larger the total investment cost and saved space heating demand becomes. However, sometimes the effect of one dominates the other. Table 12.

The results suggest that for the buildings built before 1975 (Table 10) the effect of investment cost is more dominant than different saved energies across building types to retrofit first (Package 4). This is in line with the conclusions previously drawn from Fig. 11 and shows that the effect of energy savings outweighs the effect of different investment costs. However, for the newer construction period not only the same conclusion applies (Package 4 is the most economical across archetype) but also there is an economical archetype to start with (semi-detached). This is because the reduced investment cost due to having one less side of the external wall outweighs the reduced saving for having a smaller floor area. This effect magnifies while upgrading to the passive house building envelope. Lastly, as mentioned earlier, since the only difference between the packages 1–3 and 4–6 is HRV, the benefit made from applying HRV is also visible by comparing the numbers from the relevant set of packages.

1.4.2. Discussion

1.4.2.1. Base-case modelling and validation. The deviation between the simulated and reference values for the base case shows good
agreement. However, it is important to realize that there are fundamental differences between the calculation method of this research (IES VE) and the calculation method for UMGO reference values (NEN 7120). The differences in calculation method cause the difference in assumption as well. It was attempted to reduce the assumption differences as much as possible (i.e., use the same constant heating setpoint). Despite these deviations, UMGO is the only public and widely used database in the Dutch context for comparison of the results to check if they are in the same order.

Considering the scope for which the concept of building typology has been created, direct averaging of measured data on the building level, averaged across building types could not improve model validation. This is because the detail in measured data contradicts the simplifications made to be able to categorize the building stock. Yet with proper handling of the simplifications in the definition of archetypes, measured reference values could be generated which aids with better model validation. It is noted that the deviations in calculation methods do not disqualify either of them and simply show different complexity levels for different purposes. Lastly, the deviation between the results and UMGO is theoretical. Another possible concern in making use of the results is between the theoretical and actual demands from measured data. According to [44] the theoretical demand can deviate from actual demand from about 20% underestimation of demand for energy-saving labels (A) to 100% overestimation for energy-wasting labels (G). Reasons such as higher standards for comfort in better energy labels due to higher average income and vice versa was given for such mismatch. For label C there appears to be a relatively good match between the two. In the district of De Maten, since most labels are with label C [22], such deviation is not a concern.

**Difference in the calculation method**

To start with, the calculation method in UMGO is based on Energy Index (EI) calculations which using 150 characteristics of the building (i.e., building type, age, glazing, heating system etcetera) calculates its energy demand following NEN 7120 [11 12]. On the other hand, the calculation method of IES VE is based on dynamic hourly BES, the required input for which was explained in detail in the methodology section. The question is, why the extra detail is useful for the aim of this research?

The answer is to capture a part of the Homeowner’s perspective in decision making for the policymaker. As mentioned before, the homeowner values thermal comfort in contrast to the policymaker. These interactions are vital for an energy package to be implemented and ignoring them can delay the energy transition in the building sector. As a result, in this research, the intention was to include simplified thermal comfort analysis while mainly focusing on the policy maker’s KPIs to be investment cost and CO2 emission.

The differences between IES VE and UMGO calculation method are briefly explained below to give insight into the sources of deviation.

- **Time step:** In IES VE the calculation time step is at most 1 h while in NEN the data are averaged over a month. This simplification neglects transient effects and loses the dynamics of heat transfer. In addition, monthly calculations disallow thermal comfort analysis in contrast to hourly simulations.
- **Heat calculations:** Heat transfer in IES VE is modelled for radiation, convection, and conduction. In NEN 7120, the calculations are often based on tabulated data and correction factors to include the effect of thermal mass, losses in piping and the like.

**Table 10**

| Building types       | P1   | P2   | P3   | P4   | P5   | P6   |
|----------------------|------|------|------|------|------|------|
| Detached             | 2.53 | 2.39 | 2.18 | 1.36 | 1.21 | 1.00 |
| Semi-detached        | 2.67 | 2.53 | 2.38 | 1.33 | 1.17 | 1.00 |
| Terraced-middle      | 2.89 | 2.78 | 2.62 | 1.30 | 1.18 | 1.00 |
| Terraced-side        | 2.71 | 2.58 | 2.40 | 1.34 | 1.19 | 1.00 |

* Unitless

**Table 11**

| Building types                        | P1   | P2   | P3   | P4   | P5   | P6   |
|---------------------------------------|------|------|------|------|------|------|
| Detached (122.4 m²)                   | € 326| € 403| € 500| € 300| € 367| € 450|
| Semi-detached (113.4 m²)              | € 312| € 390| € 474| € 287| € 351| € 421|
| Terraced-middle (104.8 m²)            | € 327| € 406| € 495| € 303| € 368| € 443|
| Terraced-side (104.8 m²)              | € 316| € 392| € 474| € 291| € 352| € 418|

**Table 12**

| Building types                        | P1   | P2   | P3   | P4   | P5   | P6   |
|---------------------------------------|------|------|------|------|------|------|
| Detached (122.4 m²)                   | € 620| € 751| € 902| € 497| € 598| € 722|
| Semi-detached (113.4 m²)              | € 450| € 556| € 668| € 382| € 464| € 553|
| Terraced-side (104.8 m²)              | € 615| € 748| € 889| € 489| € 588| € 698|
| Terraced-middle (104.8 m²)            | € 558| € 682| € 806| € 440| € 528| € 621|
- Heating setpoints: The same heating setpoint of 16.5 °C was used in model validations to avoid deviations that could be mitigated. In UMG0, the demands for buildings constructed before 2006 (bestaande woningen in Dutch) are referred to AgetschapNL calculations which is based on Energy Index (EI) Calculations with a setpoint of 16.5 °C [34].

- Total air exchange rate: In terms of ventilation, a constant natural ventilation rate of 0.7 [l/s/m²] was assumed which depend on wind direction/speed, temperature difference or other factors. In NEN 7120 however, the heat loss due to air exchange is calculated on a monthly time-averaged basis from NEN 8088. For better precision, [38] has researched the airtightness of Dutch buildings and listed specific air leakage per construction period or building types. However, since in the case of infiltration the wind pressure around the building changes while airtightness tests are conducted for a certain pressure difference, it is not possible to use those values as infiltration rates without a transform function. However, the high and low averages of airtightness spread across the chosen building types are given by [38] as 0.8 and 0.5 [l/s/Pa]. The chosen values of 0.6 and 0.8 [l/s/Pa] are in line with this finding.

Other sources could marginally cause deviation between simulations and references.

- Thermal mass: One of our assumptions that could potentially affect the space heating demand is the thermal mass we assumed. According to [45], the effect of thermal mass on energy demand (a few percent) is smaller than its effect on thermal comfort while the effect of insulation values and the solar gains are more significant. In IES VE thermal mass is calculated from the properties of construction materials. In UMG0 however, thermal mass is considered through utilization factors. Regardless, both models include thermal mass and its effect on heating demand is relatively small. Thus, the dependency of thermal mass and heating/cooling demand could be neglected.

- Weather: The weather file used in this research for the location of Amsterdam from EnergyPlus while the weather file used in UMG0 is based on NEN 5060. The monthly averaged outside temperature in UMG0 calculations (which is NEN 5060) can deviate from –1.6 °C up to 1.5 °C from the EnergyPlus Weather file and is on average + 0.4 °C higher. This could marginally affect the heating and cooling load considering the dynamic nature of hourly simulation in IES VE.

Lastly, the presence of active cooling is not a deviation source. This is because the results for space heating are calculated with active cooling turned off. In addition, the cooling demands are relatively insignificant compared with heating demand. Therefore, even marginally, they cannot affect the heating demand in the base case through thermal mass.

1.4.2.2. Design performance. As mentioned in the literature review, building typologies are essentially not defined for building level analysis in terms of defining exact savings from implementing energy retrofit measures. Therefore, the results are applicable on large groups of buildings where the effect of local deviation is less relevant. The smaller the scale of analysis is, the less representative the results found in this report become as the effect of occupant behaviour, building geometry/orientation, urban heat island effect, thermal set points and so forth become statistically significant in the building.

Keeping that in mind, the findings can be used on the city level as diversity within a city can lower the effects of local deviation. As a result, the space heating gains, the space cooling demand and the investment cost are to be used with caution on the building level.

Building profile

For the gain calculations, there is a so-called “building profile” that should be kept constant during the calculation of gains/risks per retrofit package. The building profile consists of a set of assumptions that can change the heating demand of the building yet have no relationship with the building envelope or the ventilation system (which changes from base case to retrofitted building), such as heating/cooling setpoints, occupancy, internal heat gains.

Ideally, the building profile used in the simulations should be the average of mentioned variables per building type and construction period. Since this information is not available, an average profile as follows is chosen. The heating setpoint of 20 °C and the cooling setpoint of 25 °C with internal gains of 2 + 2 [W/m²] for lighting and appliance heat gain are chosen, respectively. The cooling and heating setpoints are the intermediates between the extremes from robustness analysis while the cooling setpoint is simply a measure for comparison of overheating risk.

1.4.2.3. Robustness assessment. The robustness assessment was performed to consider the effect of performance deviations based on uncertainty in assumptions made which can alter the building performance. These uncertainties can be either in Usage (internal gain, heating setpoints) or climate change. Although not all the elements in modelling future scenarios were included in this research, extreme values have been chosen for proper robustness assessment. The effect of occupancy (number and presence profile of occupants) has not been considered. However, it only affects the internal gain which was already investigated through appliance and lighting gain extremes.

1.4.2.4. Investment analysis. The cost calculations for some parts were from commercial websites (glazing and HRV) which makes them reliable even for building level but for the insulation improvement of floor/wall/roof and airtightness improvement, the used references are from the literature which could deviate per building type. This is because the reference costs are per required m² and this can easily be affected by a change in geometry between each reference building and the real situation. In addition, all other costs with regards to installation are excluded from this analysis (i.e., presence of air ducts for implementation of HRV).

1.5. Conclusion and future work

Based on the presented results, the following conclusions can be made and used as guidelines towards energy saving in Dutch housing stock for the analysed building types.

- Since the focus of this report was mainly on energy-saving measures for space heating demand rather than on energy-generating measures and their different configuration, the upgrade to current regulation standards for building envelope seems to be 40–50% more economical than the upgrade to BENG in terms of return on investment or PBP with current energy tariffs.

- In general, the older a house is, the more energy wasteful it becomes. Therefore, giving priority to the renovation of old houses can be the most economical and financially attractive as was also confirmed with the results of this research.

- HRV seems to be highly effective on the energy demand of building types even when improved to current regulation standards in terms of insulation and glazing. This could also be seen by comparing the PBP of packages with and without HRV. One potential problem would be implementing the required air ducts for mechanical ventilation in old houses and the relevant
costs. This requires further research. It is also noted that the performance of HRV is dependent on airtightness improvement which is the case in all suggested packages (P1-P6). Also, in terms of CO₂ emissions, the added electricity demand for HRV is negligible compared to savings in space heating it offers.

- The results show that in a district containing the analysed building types, energy retrofitting to package 4 (current regulations + HRV) is the most economical. Across building types, semi-detached housing seems to be the most financially attractive building type to renovate.

- The simulation results do not show BENG performance when upgrading to BENG insulation levels. This might be due to implementing high U-values from the literature assigned to triple glazing which improves rapidly. The reference for cost calculation of glazing shows that in the market there already exists double glazing with a U-value of as low as 1.1 [W/m²/ K] while the U-value assumed in this report was one of the worst-performing double glazing to be 1.8 [W/m²/K] and even the triple glazing we considered with U of 1.4 [W/m²/K] theoretically performs worse than such high-performance double glazing. Moreover, despite the marginal effect, the U-value of the door was kept constant at 3 [W/m²/K] which in BENG standards is 1.4 [W/m²/K] [39]. This added to the reference U-value for the window mentioned in the same reference ranging from 0.8 to 1 [W/m²/K] can justify the minor deviation between the reference and simulated BENG performance. Implementing such high-performance measures can potentially reduce the space heating demand to BENG reference requirements. The same argument applies to realize a better performance than simulated for the current regulation standards.

- Savings made in space heating through insulation if not combined with sufficient ventilation can cause overheating risks. This risk is more critical for the packages where natural ventilation is present (P1, P2, P3) which is dependent on wind speed and the open area for the airflow (can be opened window or natural ventilation ducts). It is suggested that no airtightness improvements are applied unless a mechanical ventilation/-cooling system is installed due to a high risk of overheating and occupant discomfort during summer.

- For the houses with high uncertainty in occupant behaviour, i.e., rental houses or social housing, P6 (improving airtightness of the house combined with HRV and BENG insulation/glazing requirement) performs 2.5 and 1.3 times more robust in terms of space heating demand than P1 and P4, respectively.

The following improvements for better accuracy in the results can be made.

- HRV compatibility: The compatibility of archetypes for implementation of HRV as a highly effective measure could be further researched.

- Building profile: As the gain calculations were based on an assumed building type which was the same across all building types, further research on a typical and average building profile (which includes occupant behaviour) is required. Furthermore, building envelope thermal properties for the base case are based on national archetypes mentioned in [34], the actual values, in reality, deviate slightly throughout the construction period or even from district to district within the same construction period.

- Energy retrofit packages: In this research, the focus was mostly on energy-saving measures for space heating. However, other measures such as different heating systems or electricity usage for lighting/appliance, drain water heat recovery etcetera could be further investigated. PV panels were only shown as for potential generation capacity per building type which can be researched in more detail, considering differences in generation by the change in tilt/azimuth angle, different types of PV/T or thermal collector are also interesting fields for further research. Moreover, the resulted performance deviation from uncertainty in assumed and realized R-values and U-values of the offered packages (after implementation) could also be investigated. Lastly, in the case of a more in-depth PV analysis, the addition of optimum battery size and no feed-in tariff could also be further investigated.

- Overheating risk: Although the overheating risk in this research was translated into cooling demand, the corresponding measures to mitigate its effects were not investigated. With the implementation of high-performance glazing (U-values of around 1.0 W/m²/K and below) or poorly ventilated dwellings, the overheating chance as mentioned before increases rapidly. Measures such as shading, active ventilation, ground source heat storage could help reduce the risk of overheating. These could be researched further especially in the case of detached housing (which is most prone to overheating according to [46]). In addition, implementation of more detailed thermal comfort analysis techniques (such as adaptive thermal comfort), could bring new insight.

- Energy analysis approach: The taken approach in this study was the bottom-up building physics-based approach. However, the effect of different macro-level variables such as GDP or energy costs or inflation rates could also impact the optimum strategy which was not researched here. The perspective of other stakeholders and their interactions: We have chosen the homeowner as the main stakeholder of this paper. The same analysis could be performed from other stakeholder perspectives with different KPIs such as policymaker with KPI of CO₂ emission which brings new insight. In the case of CO₂ reduction as KPI, Marginal Abatement Cost Analysis could be performed to rank the packages in terms of cost of reducing the environmental pollution. The interaction and overlaps of similar interests between these stakeholders could be insightful.

CRediT authorship contribution statement

Soheil Alavirad: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. Saleh Mohammadi: Conceptualization, Methodology, Resources, Supervision, Project administration. Pieter-Jan Hoes: Conceptualization, Methodology, Formal analysis, Resources, Supervision, Project administration. Luyi Xu: Formal analysis, Resources, Supervision. Jan L.M. Hensen: Conceptualization, Methodology, Supervision.

Declaration of Competing Interest

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

Appendix A

Reference floor plan
Detached
Semi-detached

Terraced-side

(continued on next page)
Appendix B

Geometries
Detached

Semi-detached
References

[1] IPCC, “ADOPTION OF THE PARIS AGREEMENT - Paris Agreement text English,” 2016. Accessed: Jul. 06, 2018. [Online]. Available: https://unfccc.int/sites/default/files/english_paris_agreement.pdf.

[2] M. Mulder and P. Perey, “Gas production and earthquakes in Groningen reflection on economic and social consequences,” Groningen, 2018. Accessed: Jul. 06, 2018. [Online]. Available: https://www.rug.nl/feb/news/2018/180605-gas-production-and-earthquakes.pdf.

[3] BVO, “Infoblad Trias Energetica en energieneutraal bouwen,” 2013. Accessed: Jul. 20, 2018. [Online]. Available: https://www.rvo.nl/sites/default/files/Infoblad_Trias_Energetica_en_energieneutraal_bouwen-juni_2013.pdf.

[4] F. Filippidou, N. Nieboer, H. Visscher, Are we moving fast enough? The energy renovation rate of the Dutch non-profit housing using the national energy labelling database, Energy Policy 109 (Oct. 2017) 488–498, https://doi.org/10.1016/ENPOL.2017.07.025.

[5] P. Nuiten et al., “Uniforme Maatlat Gebouwde Omgeving (UMGO) voor de warmtevoorziening in de woning-en utiliteitsbouw Versie 4.2,” Eindhoven, 2018. Accessed: Jun. 26, 2018. [Online]. Available: https://www.rvo.nl/sites/default/files/Uniforme_Maatlat_Gebouwde_Omgeving_UMGO_4.1.pdf.

[6] G.M. Mauro, M. Hamdy, G.P. Vanoli, N. Bianco, J.L.M. Hensen, A new methodology for investigating the cost-optimality of energy retrofitting a building category, Energy Build. 107 (2015) 456–478, https://doi.org/10.1016/j.enbuild.2015.08.044.

[7] F. Ascione, N. Bianco, G. De Stasio, G.M. Mauro, G.P. Vanoli, Multi-stage and multi-objective optimization for energy retrofitting a developed hospital reference building: A new approach to assess cost-optimality, Appl. Energy 174 (2016) 37–68, https://doi.org/10.1016/j.apenergy.2016.04.078.

[8] J. Fernandez-Luzuriaga, L. Del Portillo-Valdes, J. Flores-Abascal, Identification of cost-optimal levels for energy refurbishment of a residential building stock under different scenarios: Application at the urban scale, Energy Build. 240 (2021) 110880, https://doi.org/10.1016/j.enbuild.2021.110880.

[9] F. AlFaris, A. Juaidi, F. Manzano-Agugliaro, Energy retrofit strategies for single-family housing typologies: Three Toronto case studies, Energy Build. 116 (2016) 522–534, https://doi.org/10.1016/j.enbuild.2016.01.022.

[10] O. Irulegi, A. Ruiz-Pardo, A. Serra, J.M. Salmerón, R. Vega, Retrofit strategies towards Net Zero Energy Educational Buildings: A case study at the University of the Basque Country, Energy Build. 144 (2017) 387–400, https://doi.org/10.1016/j.enbuild.2017.03.030.

[11] R. Gupta, A. Howard, M. Davies, A. Mavrogiani, I. Tsoulou, N. Jain, E. Oikonomou, P. Wilkinson, Monitoring and modelling the risk of summertime overheating and passive solutions to avoid active cooling in London care homes, Energy Build. 252 (2021) 111418, https://doi.org/10.1016/j.enbuild.2021.111418.

[12] R. Gupta, A. Mavrigiannaki, G. Piganta, M. Assimakopoulos, M. Isaac, R. Gupta, D. Kolokotsa, M. Laskari, M. Salari, L.A. Meir, S. Isaac, Examining the benefits and barriers for the implementation of net zero energy settlements, Energy Build. 230 (2021) 110564, https://doi.org/10.1016/j.enbuild.2020.110564.

[13] R. Kotireddy, P.-J. Hoes, J.L.M. Hensen, A methodology for performance robustness assessment of low-energy buildings using scenario analysis, Appl. Energy 212 (Feb. 2018) 428–442, https://doi.org/10.1016/j.apenergy.2017.12.066.

[14] I. Gaeta, P.-J. Hoes, J.L.M. Hensen, Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy, Energy Build. 121 (Jun. 2016) 188–204, https://doi.org/10.1016/j.enbuild.2016.03.038.

[15] R. Kotireddy, R. Loonen, P.-J. Hoes, J.L.M. Hensen, Building performance robustness assessment: Comparative study and demonstration using scenario analysis, Energy Build. 202 (2019) 109362, https://doi.org/10.1016/j.enbuild.2019.109362.
