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Optimal balance between energy demand and onsite energy generation for robust net zero energy buildings considering future scenarios

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OPTIMAL BALANCE BETWEEN ENERGY DEMAND AND ONSITE ENERGY GENERATION FOR ROBUST NET ZERO ENERGY BUILDINGS CONSIDERING FUTURE SCENARIOS

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ABSTRACT

Net-zero energy buildings have usually very low energy demand, and consequently heating ventilation and air conditioning (HVAC) systems are designed and controlled to meet this low energy demand. However, a number of uncertainties in the building use, operation and external conditions such as climate change and occupant behaviour can influence the energy demand. Considering these variations, the currently designed net zero energy buildings will not always be able to provide the required indoor environmental quality. A proper balance between energy demand, HVAC and renewable energy systems needs to be investigated to meet the performance requirements over the building life span. Therefore, in this work, performance optimization of various net zero energy building designs, with different energy demand and onsite energy balance, is carried out under uncertainties due to future scenarios to minimize the performance variation across all future scenarios. The design with optimal performance and low performance variation across all scenarios is identified as the most preferred robust design solution.

INTRODUCTION

New buildings and renovations are designed using sustainability frameworks to meet the 2020 targets of European building performance directive (EPBD, 2010). The aim of frameworks is to support building design and operation with minimum environmental impact and optimum indoor environmental quality (IEQ), i.e. low-energy or ideally net-zero energy buildings (NZEB). In spite of the overall improvement obtained so far, sustainability frameworks face major challenges regarding the performance robustness of NZEB (Tuohy, 2009). NZEB designed based on these frameworks are having very low heating and cooling energy demands. However, IEQ problems are observed in some low energy buildings, indicating their lack of robustness (Mlecnik et al, 2012). Overheating risks in the dwellings built using the Passivhaus concept is an example of IEQ problems (McLeod et al., 2013). IEQ problems can be related to a number of uncertainties in the building use (occupant behaviour), external conditions (climate change) etc. (Jenkins et al., 2009). Buildings and building services systems must be robust such that climate changes or other than intended use by occupants must not result in great variations of the energy consumption or indoor environment. Robustness, in this work, is defined as the ability of a building to have optimal performance and minimum performance variation across future scenarios. Traditional buildings and building services systems are robust; however, this robustness is obtained at the expense of high energy consumption and consequent environmental impacts due to related CO_2 emissions. On the other hand, NZEB with low energy demands might be more sensitive to the uncertainties due to future scenarios. Hence, a proper balance between energy demand and onsite energy generation is essential in designing long-lasting robust NZEB.

The robustness of low energy buildings should be assured not only for the near future, but also for the whole life span of the building (Fawcett, 2012). The assessment of robustness over the life span requires the use of scenarios, in order to describe more conservative or extreme prognostics. Future climate and building usage are some of the several aspects that may affect building performance on this longer time scale. These aspects are rarely taken into account in the design of NZEB, potentially compromising their performance in the future. Hoes et al. (2011) carried out robustness assessment of building performance under uncertainties due to occupant behavior. Van Gelder (2014) presented the design guidelines for robust low energy dwellings for various user types and future economic scenarios. In both studies, the proposed robust design solutions, that are least influenced by occupants, can be largely influenced by climate change. Therefore, it is essential to design robust NZEB under uncertainty considering a range of building future use and climate scenarios to guarantee the required performance over the whole building life span.

Hence, this article focuses on a methodology to optimize the performance robustness of NZEB designs under uncertainties due to future scenarios. The proposed methodology is applied to a case study to identify preferred robust design for occupant and

climate scenarios. The details of the design optimization and performance assessment methodology are discussed in the next section.

METHODOLOGY

The following steps are used in the design optimization and performance assessment methodology to find the preferred optimal and most robust designs for future scenarios:

1. Create future scenarios
2. Set up building designs
3. Simulate performance of each design for all future scenarios
4. Assess performance of each design using multiple performance indicators
5. Select optimal and most robust designs

The future scenarios are created based on building future use and climate change. Several design parameters are varied uniformly to obtain multiple designs with different energy demand and onsite energy generation balance as shown in Figure-1. The onsite energy generation system capacity is optimized such that each design is net zero energy under the most extreme scenario. This leads to plus energy designs for all the remaining scenarios. Design variants and future scenarios are described in detail in section case study and scenarios.
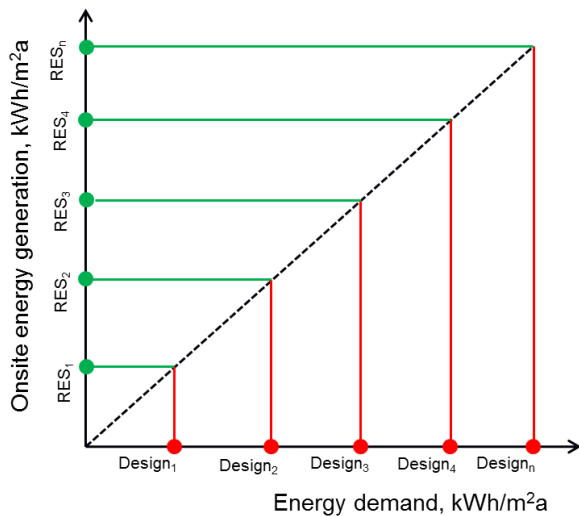

Figure-1 Balance between energy demand and onsite generation of various designs.

Performance assessment

The performance of each design is simulated for all occupant and climate scenarios. The performance of each design is assessed using five performance indicators, namely electricity consumption for heating and ventilation, total electricity consumption of the building, overheating hours, global cost and additional investment cost as shown in Figure-2. Each performance indicator is an objective in multi-objective optimization. All these performance

indicators are relevant in selecting a robust design. For instance, electricity consumption for heating and ventilation helps in determining the robustness of HVAC systems and total electricity consumption of the building will determine the robustness of onsite energy generation systems. However, this robustness should not be achieved at the expense of overheating risks, high investment and operating costs (global cost). In general the decision maker will be interested in a trade-off solution. Furthermore, depending on the end user each performance indicator may have a different weight in the decision making process. For example, if the end user is a home owner, then probably his design selection criteria depend heavily on overheating hours and operating costs (global cost). Compared to for example a policy maker, who is more focused on energy consumption (and CO_2 emissions). All these performance indicators are compared against additional investment cost, which enables us to select a cost optimal design or to carry out trade off with respect to the other performance indicators and to the robustness of these performance indicators.
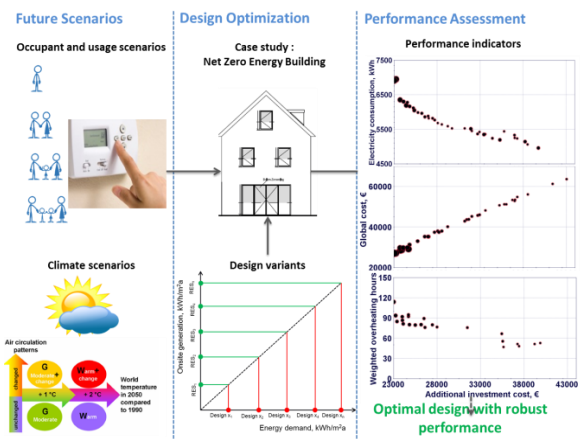

Figure-2 Performance assessment methodology.

Robust design selection

The median value of a performance indicator (PI) across all scenarios is the target value for selecting the optimal performance. The performance spread of a PI is used as a robustness indicator of a design, and is defined as:

$$PIspread = PImax - PImin \qquad (1)$$

In this research the preferred design is defined as the design with low median value and minimum spread across all scenarios. For instance, compare design-1 and design-2 in Figure-3. Both designs have the same median value but design-2 shows a smaller spread across all scenarios. So design-2 is regarded as more preferred (and robust) compared to design-1. On the other hand, design-2 and design-3 show the same performance spread, but design-3 has a lower median value. Hence, design-3 is the preferred design. The performance spread can be used to select preferred robust design based on a single performance

indicator. For comparison of multiple PIs with different units, all PIs are normalized which results in the relative performance variation (RPV). RPV of a PI is the ratio of its performance spread to its median value across all scenarios.

$$\text{PI } RPV = \text{PI}spread : \text{PI}median; \text{ If PI}median > 0$$
$$\text{PI } RPV = 0; \text{ If PI}median = 0 \qquad (2)$$

The RPV indicates the relative deviation of performance from the median value. The preferred robust design is based on low median values and low relative performance variations of all PIs. If a design has a zero median value for a PI, then performance spread is used to select the preferred robust design.
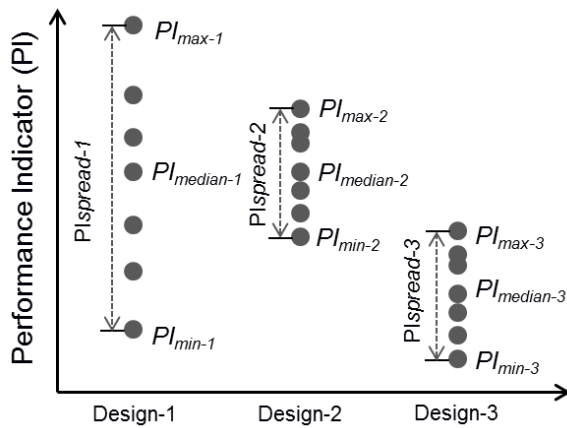

Figure-3 Design solutions with performance spread caused by scenarios (each dot represents a scenario).

CASE STUDY AND SCENARIOS

A corner (semi-detached) terraced house, a typical Dutch residential house, (RVO, 2013) is chosen as the case study building. It is a three-storey building, as shown in Figure-4, with a heavyweight construction. The building is divided into three thermal zones for calculating the temperature and energy demand of each zone.

Ground floor   *First floor*   *Second floor*

Figure-4 A typical Dutch corner terraced house (RVO, 2013).

The living room and kitchen at the ground floor form the first zone, three bedrooms in the first floor constitute the second zone, and the attic in the second floor is the third zone. Heating is supplied by air source heat pump and the building is ventilated with balanced mechanical ventilation with a heat recovery unit. Natural ventilation (free cooling) is used in summer instead of mechanical cooling. It is an all-electric building and total electricity consumption for heating, ventilation, lighting and appliances of the building is met by an onsite photovoltaic system. LG photovoltaic panels with an efficiency of 18.3% are chosen in this study (EON, 2015).

Design variants

Building envelope properties like insulation levels, window to wall ratio (WWR), infiltration etc. are considered as design variants in this study as shown in Table-1. Insulation levels and window properties are varied in combination to form designs with energy demand ranging from traditional buildings to passive houses. Automatic shading control is used for windows based on radiation levels.

Table-1 Design variants considered in this study.

Parameter	Input	Min	Max	Step
Walls, roof, floor	Rc (m²k/W)	2	10	10
Windows	U value (W/m²K)	0.4	2.8	10
Infiltration	ach	0.12	0.60	5
WWR	%	20	60	3
Window shading	On if radiation is greater than (W/m²)	250	350	3
Window shading	Off if radiation is less than (W/m²)	200	300	3

Scenarios

The following occupant, usage and climate scenarios are considered in this study.

Occupant scenarios

Four occupant scenarios are formulated based on Dutch building occupant statistics (CBS, 2014). Scenario-1, a single person, represents 36% of the Dutch households and scenario-2, a two-person family, accounts for 33% of the Dutch households (CBS, 2014). Similarly, for occupant scenarios 3 and 4, families of three and four persons occupy the building respectively. The main difference between these scenarios is the heat gain due to the number of occupants in the building.

Usage scenarios

For each of the occupant scenario, three usage scenarios are considered based on energy usage in the building. Low usage represents a very concise energy users, medium usage represents an average energy user and high usage represents a wasting energy user. Heating set point temperatures, lighting

and appliances usage, internal heat gains density, ventilation rates and occupant presence are varied for three usage scenarios as shown in Table-2. The heating set points and occupancy patterns are chosen from VROM/WWI (2010). The evening occupancy profile represents 19% of the Dutch households and the all-day occupancy profile accounts for 48% (VROM/WWI, 2010).The heating set point during unoccupied hours is 14°C for all scenarios. Internal heat gains due to lighting, appliances etc. is based on NEN7120 (2011) with an average internal heat gain of 4 W/m^2. Electricity consumption for lighting (RVO, 2013) and appliances (Papachristos, 2015) for medium usage scenario is in line with an average electricity consumption of about 3500kWh for lighting and appliances by Dutch households (CBS, 2014). Ventilation rate for three scenarios is chosen based on Hoes et al. (2011).

Table-2 Summary of usage scenarios.

Parameter	Low	Medium	High
Heating set point, °C	18	21	23
Ventilation, ACH	0.9	1.2	1.5
Occupancy profile	Evening	Evening	All day
Electricity use for lighting , W/m^2	1	2	3
Electricity use for appliances , W/m^2	1	2	3
Internal heat gains due to lighting & appliances, W/m^2	2	4	6

Climate scenarios

Four climate scenarios (G, G+, W. W+) proposed by the Dutch Royal meteorological institute (Van den Hurk et al., 2006), as shown in Figure-5, are used in this study.
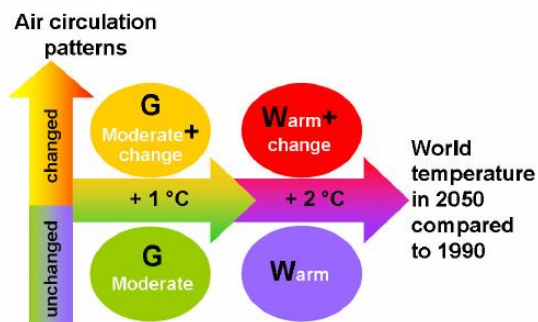

Figure-5 Change in global temperature predicted for 2050 for four climate scenarios (Van den hurk et al., 2006).

These scenarios are based on global mean temperature rise and atmospheric air circulation patterns. Scenario G represents a moderate increase of the global temperature of +1°C in 2050 whereas scenario W represents an extreme case of an increase of +2°C in 2050 relative to 1990. Scenario G and W do not take into account changes in air circulation patterns whereas scenario G+ and W+ include

changes in air circulation patterns along with rise in global mean temperature. Hourly weather data generated for all climate scenarios is used in the simulations.

Performance indicators

The following performance indicators are chosen in this study to assess the building performance for future scenarios.

Electricity consumption

The annual electricity consumption for heating and ventilation (EC_Heating and ventilation, kWh) is used to assess the HVAC system robustness. Total annual electricity consumption for heating, ventilation, lighting and appliances (EC_Total, kWh) is used to assess the PV system robustness.

Weighted overheating hours

Thermal comfort is evaluated based on maximum and minimum acceptable indoor temperatures as proposed by Peeters et al. (2008). Weighted overheating hours (WTOH) are the total number of weighted hours exceeding the allowable indoor temperatures during occupancy in a year. A weighting factor is assigned for every excess degree than allowable indoor temperatures.

Global cost (GC)

Global cost is evaluated based on investment cost, replacement cost and operating costs (Hamdy et al., 2013). Global cost (net present value) is evaluated for 30 years, which is the service life span of energy systems like HVAC and PV systems. Operating costs, which are zero or negative in this study, as all design solutions either produce more energy or are self-sufficient, are calculated using the current energy prices (CBS, 2014) and average inflation rate for the past 20 years in the Netherlands. Investment cost in this study is the additional amount required by design variants to achieve net zero/plus energy design. The fixed costs like land, workmanship, HVAC system price etc. are not considered. The range of additional investment cost required for few design variants is tabulated as in Table-3. Additional investment cost includes the cost of insulation materials (Kingspan, 2015), windows (Lente-accord, 2015), infiltration rate (Hamdy et al., 2013), and PV system (EON, 2015).

Table-3 Range of investment cost for different design variants.

Parameter	Range	Additional investment cost	Range, €
Insulation	2-10 m^{2}K/W	13.8-55.1€/m^2	3109-18445
Windows	2.83-0.4 W/m^{2}K	21-185€/m^2	533-4699
PV system	8-12 kWp	1.68€/Wp	13440-20160

RESULTS AND DISCUSSION

Performance of design solutions

Performance assessment of all designs is carried out with TRNSYS for all scenarios. The simulated electricity consumption for heating and ventilation and weighted overheating hours of all designs are shown in Figure 6. Each dot represents the median performance of a unique design solution, i.e. a unique combination of the design parameters and PV system size. The design solutions represent different standards ranging from traditional building to passive house standards. To get a better understanding of the design variants, Rc values of the walls and infiltration rates are indicated with colors in the scatter plots for illustration. Figures 6a and 6b show the Rc values and Figures 6c and 6d show the infiltration rates. The figures show that electricity consumption for heating and ventilation decreases with higher Rc values and lower infiltration. One can easily distinguish the effect of insulation levels on electricity consumption for heating and ventilation; however, the impact of infiltration is widely dispersed. In overall, designs with high Rc value and low infiltration rates are having very low electricity consumption.

On the other hand, more scattered clouds are observed for weighted overheating hours for selected design variants as shown in Figures 6b and 6d. It shows that overheating hours are relatively less influenced by building envelope properties, but more by occupant behaviour. Similar to electricity consumption, one can distinguish the impact of insulation levels on overheating hours; however, it is hard to distinguish the effect of infiltration rates. High overheating hours are observed in the designs having high Rc values (7-10m^{2}K/W) and low infiltration rates (0.12ACH). The designs with low Rc value and high infiltration rates (old buildings) are having low overheating hours but at the expense of high electricity consumption. Similarly, the designs with high Rc value and low infiltration rates (passive house) are having very low energy demand but results in high overheating risks. The designs with intermediate Rc values (3.5-6m^{2}K/W) and medium infiltration are having optimal performance. Moreover, it also depends on other design variants like window properties, window to wall ratios etc. which is not shown in the figures.

Example of design selection based on multiple performance indicators

As mentioned in the methodology, the relative performance variation (RPV) can be used to select a design based on multiple performance indicators. A design can be selected based on any performance indicator and carry out trade off with other performance indicators. For instance, one can choose a design that has low overheating hours and carryout
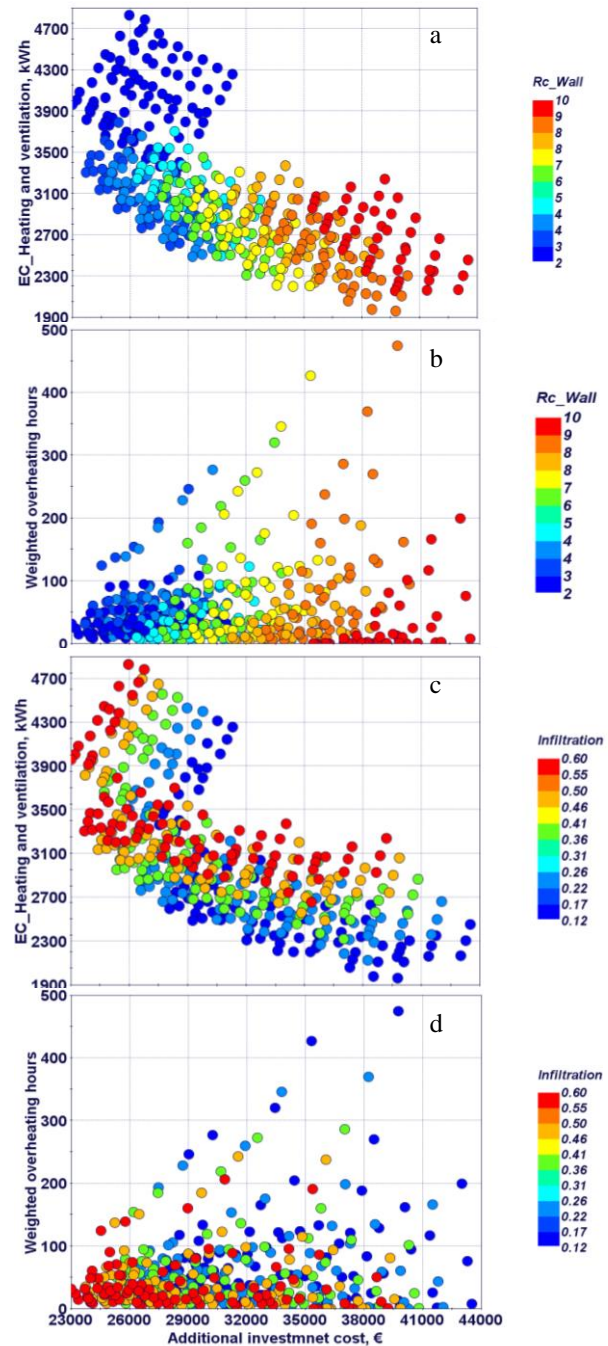

Figure-6 Scatter plot showing the electricity consumption for heating and ventilation, overheating hours and investment cost of all design variants for occupant and usage scenarios; the colors indicate the values for the Rc values for walls (Figures 6a and 6b) and for infiltration rates (Figures 6c and 6d).

trade off with other performance indicators. As an example, Figure-7 shows the performance spread, relative performance variation and median value for all performance indicators across occupant and usage scenarios against the additional investment cost (design). The colour of each bubble represents the performance spread across all scenarios and the bubble size depicts the relative performance variation. The preferred design for a decision maker

is based on low median values and low relative performance variations of the PI's. To illustrate this, three designs for three different decision makers (DM) are chosen as shown in Figure-7. DM1 represents a homeowner, he prefers designs with low overheating hours and low global cost. DM2 represents a building service company, which prefers solutions with relatively lower energy demand and low overheating hours and DM3 represents a policy maker/grid operator, who prefers solutions with very low energy demand.

To choose a design out of the three solutions based on multiple PIs for each of the decision maker, the RPV and median values are compared. It can be observed that designs 1 and 3 of DM1 are having low RPV for electricity consumption (Figures 7a and 7b) whereas design 2 is having a lower median value. Moreover, designs 1 and 3 results in low overheating hours (Figure 7d) compared to design 2. Designs 1 and 3 are more preferred compared to design 2, however, design 1 is having relatively lower global cost and additional investment cost. Hence, design 1 is the most preferred solution as it is least sensitive to the scenarios and results in low overheating hours, global cost and additional investment cost.

Similarly for DM2, designs 1 and 2 are having low RPV for electricity consumption (Figures 7a and 7b) whereas design 3 is having a lower median value. The risk of failure is higher for design 3 compared to other designs, because of its higher RPV. Design 2 is more preferred compared to design1 as it has low overheating hours. In case of DM3, the most preferred solution is design 1 as it has low RPV for electricity consumption. Though design 2 has very low median value for energy demand, it is not the robust solution because of high overheating hours with huge spread. If a single solution need to be chosen of all selected designs (Figure-7) without taking into account of DM, the design 1 with additional investment cost of 23992€ having Rc value of 3.5m^{2}K/W, WWR of 40%, infiltration of 0.48ach is the most preferred solution because of its low RPV, low overheating hours and low global cost.

Design selection considering all possible design solutions

The same method as described above can be used to select the preferred design solution out of all possible designs. For this purpose, the Pareto front is calculated for each performance indicator by considering additional investment cost, median value of a performance indicator and relative performance variation as objectives. These Pareto fronts for all performance indicators, except overheating hours, for occupant and usage scenarios are plotted in Figure-8. All design solutions are plotted for overheating hours so that one can chose a design based on RPV of other performance indicators and carryout trade off with overheating hours. It can be observed from Figure-8,
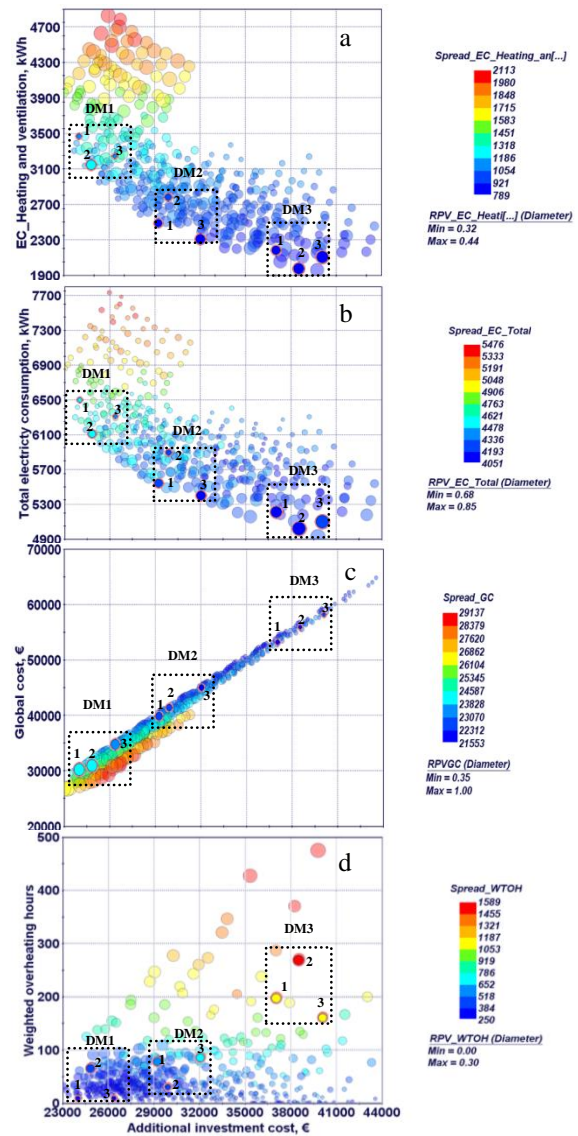

Figure-7 Illustration of robust design selection for occupants and usage scenarios.

that the most of the designs with high insulation levels have high RPV for electricity consumption (Figures 8a and 8b) even though they have minimum performance spread. These designs with high RPV are more sensitive to scenarios indicating lack of robustness. On the other hand, the designs with low insulation levels are having low RPV for electricity consumption and thus are more preferred. When overheating hours are taken into account, the designs with low median value and low RPV can be found across all balances i.e. low insulation levels to high insulation levels (Figure 8d). The preferred design can be selected based on required additional investment cost to achieve net zero/plus energy. When global cost is considered in selecting the design, it largely depends on the end user to choose a design that has very low net present cost (low insulation levels) with huge spread or the design that has very high net present cost (high insulation levels) with low spread (Figure 8c). However, selected

design should not yield very high global cost i.e. robustness of a design should not be at the expense of very high investment and global costs. Nevertheless, to choose a design for all PIs it depends mainly on decision maker. For instance, homeowner (DM1) prefers designs with low insulation levels (Rc of 3.5-5) and additional investment cost of 23000-29000€. Similarly, for policy makers/grid operators (DM3) the designs with low energy demand (high insulation levels) which have additional investment cost of 35000-44000€ are more preferred. For all decision makers, the design is selected based on trade-off between RPV and the additional investment cost.
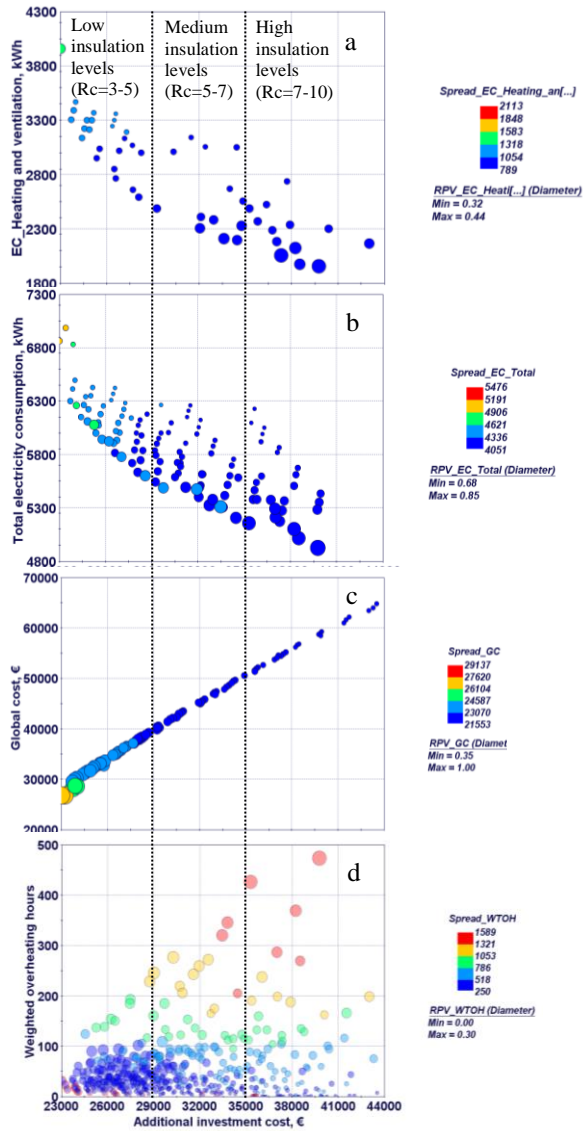

Figure-8 Optimal designs for occupant and usage scenarios.

Design selection considering climate scenarios
The same method is applied to select a preferred robust design for climate scenarios. Pareto fronts for all performance indicators for climate scenarios are plotted in Figure-9. It is worth noting that to study the effect of climate change, design optimization and performance assessment is carried out with a fixed occupant and usage scenario. A family of two and medium usage scenario is considered, which represents average Dutch household (CBS, 2014). It can also be observed from the similar performance spread for electricity consumption by heating and ventilation systems and the total electricity consumption (Figures 9a and 9b). Moreover, the performance spread of all PIs is much lower for climate scenarios compared to occupant and usage scenarios. It indicates that the designs are more sensitive to occupant and usage scenarios than climate scenarios. However, overheating risks are more with climate scenarios. The designs with high insulation levels are having low RPV for electricity consumption (Figures 9a and 9b) for climate scenarios in contrast to occupant and usage scenarios (Figures 8a and 8b). Similarly the designs with low insulation levels are having high RPV for climate scenarios compared to that of occupant and usage scenarios. However, the designs that are on the Pareto front for both occupant and climate scenarios
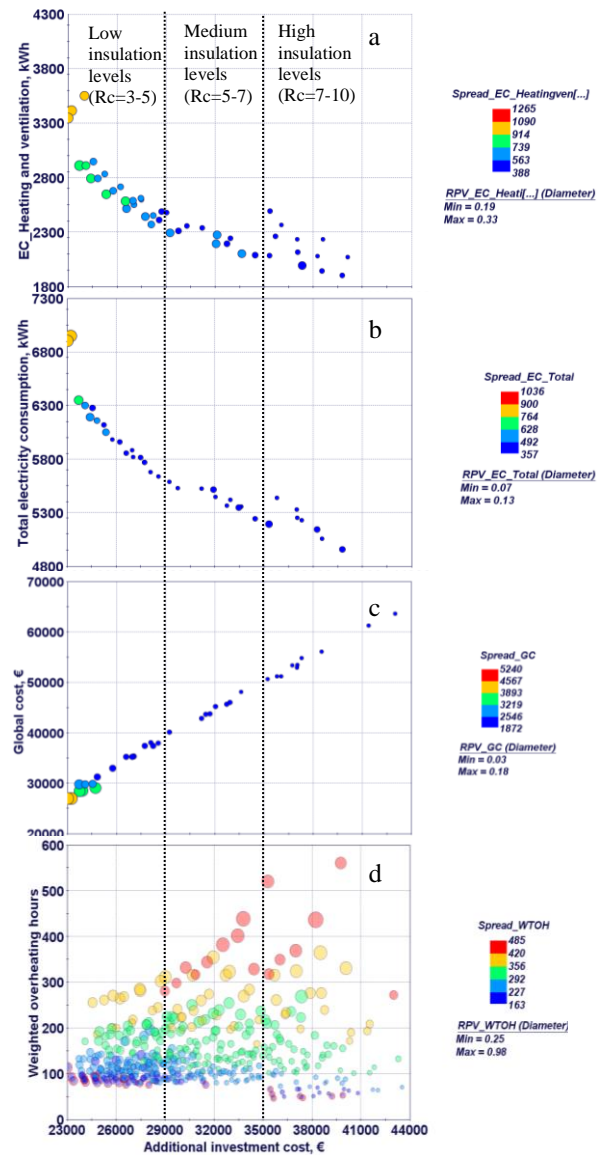

Figure-9 Optimal designs for climate scenarios.

(Figure-8 and Figure-9) are more preferred solutions for all future scenarios. It is worth noting that the PV system for these designs varies from 44-56m^2. The PV system size is very large as it has to meet net zero criteria for extreme scenario. For the same designs, PV system size reduces by 16±3.5 m^2 if the criterion is to meet the median energy demand. To identify a robust design across all future scenarios, it is recommended to combine climate scenarios with different occupant and usage scenarios.

CONCLUSIONS

- The present work presents a novel methodology in identifying robust net zero energy designs. Robust design can be easily selected using optimal performance and relative performance variation across all scenarios.
- Performance spread of all performance indicators is much lower for climate scenarios compared to that of occupant scenarios, indicating that the designs are more sensitive to occupant behavior than climate change. The designs with low insulation levels are found to be more robust for occupant and usage scenarios whereas the designs with high insulation levels are found to be more robust for climate change.
- The robust design selection largely depends on the end user of the designs (decision maker). Using the current methodology, the decision maker can chose a robust design by prioritizing a performance indicator and carrying out trade off with robustness of other performance indicators and required additional investment cost.
- The proposed methodology also provides a decision maker with information to trade off investment in improving building insulation levels with that of energy generation systems (energy balance) and robustness of design.
- In order to find the robust design across all future scenarios, the performance assessment need to be carried out by combining the climate scenarios with occupant and usage scenarios. Different energy systems and their combination and additional design variants like thermal mass, etc. might yield better robust design solutions. This will be our future work.

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