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Assessing Responsive Building Envelope Designs through Robustness-Based Multi-Criteria Decision Making in Zero-Emission Buildings

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Abstract: Responsive building envelopes (RBEs) are central to developing sustainability strategies for zero emission/energy buildings (ZEBs). RBEs are a large group of complex technologies and systems, which is why multi-criteria decision making (MCDM) methods are helpful to navigate sustainability assessments considering various performance indicators. This article first provides a literature review of assessment criteria and key performance indicators for RBEs and an analysis of existing robustness-based MCDM methods. Then, a methodological approach to assess RBE designs in ZEB projects is proposed as an extension of a novel robustness-based MCDM method that normalizes the objective functions according to defined targets and combines them into one comprehensive indicator (MT-KPI), thereby eliminating the need to weight objectives. The proposed methodological approach is finally tested on a case study of a Norwegian ZEB, where five competitive RBE designs (including building integrated photovoltaics, phase change material, and electrochromic windows) and eight occupancy and climate scenarios are investigated considering three main performance areas: energy use, thermal comfort, and load matching. The results in the case study show that with the proposed MCDM approach the different designs have MT-KPI values between 1.4 and 12.8, where a lower value is better. In this specific case, the most robust building RBE alternative was identified as the one with electrochromic windows and a control based on incident solar radiation and indoor air temperature.

Keywords: building envelope; responsive; zero-emission buildings; robust designs; multi-criteria assessment; decision making; uncertainty scenarios

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1. Introduction

1.1. Strategies and Technologies for Zero-Emission Buildings

Improving the building sector is central to achieving the sustainability development goals and creating positive environmental, economic, and social impacts [1]. Zero-energy/emission building (ZEB) continue to be investigated worldwide as a pathway to decrease energy use and greenhouse gas (GHG) emissions in future buildings, reduce future energy-related costs, and improve indoor comfort [2,3]. Recently, the scope of ZEBs was progressively extended from a micro-level of independent single buildings to a meso-level that includes clusters of interconnected buildings and services such as neighbourhoods [4]. Therefore, the concept of zero- energy/emission neighbourhoods (ZEN) is increasingly explored as a way to achieve very low to null GHG emissions and energy use during the neighbourhood's lifetime [5–7]. In Norway, the Research Centre on Zero Emission Neighbourhoods in Smart Cities (ZEN Research Centre) was established in 2017 to develop solutions for future buildings and neighbourhoods with no GHG emissions towards a low carbon society [8]. The design of highly energy efficient building envelopes is crucial to achieving a zero-energy/emission balance at the building level [9] and has led to a growing emphasis on developing new building envelope concepts. Smart, adaptive, intelligent, dynamic, kinetic, advanced and responsive envelopes are some of the terms used to refer to building envelope systems that integrate new technologies and adopt complex behaviours [10–12]. In this article, we refer to these systems as responsive building envelopes (RBEs), using the same extension of the definition of climate adaptive building shells (CABS) [12] proposed in [13].

Examples of RBEs investigated in the past decade include double skin facades, Trombe walls, envelope-integrated phase change material (PCM), green walls, switchable windows, and dynamic solar shadings [14]. RBEs can provide many benefits ranging from improving environmental aspects and reducing energy use and GHG emissions [15] to increasing indoor environmental quality (IEQ) and leveraging higher building energy flexibility [16]. The latter benefit becomes particularly relevant when analysing ZEBs in a broader context, such as when they are part of ZENs, where implementing coordinated RBE strategies has an even larger potential for action due to the effect of scale.

In ZEBs and ZENs, as much as possible, building envelopes need to be designed to harvest renewable energy—either as electricity or heat—in addition to fulfilling energy and comfort requirements. Achieving a zero-energy/emission level then requires combining different types of RBEs, renewable energy technologies and energy storage solutions so that individual buildings, or ultimately a group of buildings at a neighbourhood scale, can reach a net-zero balance. These analyses are challenging and require systematic and integrated approaches based on multi-criteria decision making (MCDM) to assess overall performance. MCDM methods are widely used to support balanced evaluations considering various performance criteria [17,18]. They are often used in different methods to assess building performance and design, including methodologies focusing on performance robustness [19,20].

1.2. Novelty of the Proposed Research

This paper investigates the use of MCDM for analysing RBE designs in ZEB projects by addressing the following research questions:

- How to evaluate and compare performance of RBE designs with respect to different performance criteria using quantifiable indicators in the context of ZEBs?
- How can MCDM support the selection of the most robust RBE design solution considering operational uncertainties (such as climate change, occupant behaviour, etc.) in ZEBs?

The main contribution of this article is to demonstrate the combined use of a classification of quantifiable performance criteria and indicators with an overall MCDM methodology for analysing and assessing RBE performance in existing or future ZEB projects. The article's novelty lies in the investigation of the possibility of extending a verified robustness-based MCDM approach previously developed by one of this article's authors [21] to the assessment of RBEs. The method leads to a complete evaluation of RBE options under uncertainty by comparing alternative designs based on specific performance targets (set by standards and/or project's requirements) and yields a comprehensive multi-target indicator which accounts for any deviations from targets. The main advantage of this method is that it reduces the decision-making process to a single indicator regardless of the number of assessed performance criteria selected, eliminating the need for criteria weighting, which can be complex and biased.

The paper contributes to the development of systematic methodologies to aid decision-makers involved in ZEB projects to select the most suitable RBE solution among several design alternatives, considering stakeholder needs and available resources to reach ZEB targets. The application of the proposed methodology is demonstrated using a real ZEB located in a Norwegian neighbourhood intended to become a ZEN. This adds to the novelty of this research since the developed methodology is illustrated on a real building where the envelope designs, uncertainty scenarios, and KPIs are meaningful. Our methodology can easily be applied to other ZEB and/or ZEN projects, where various design alternatives and scenarios, different from those of this article, could be assessed.

The remainder of the paper is organised as follows. Section 2 presents a literature review of performance criteria and indicators for RBEs in ZEBs, including an overview of robustness-based MCDM approaches. Section 3 introduces a classification of performance criteria and indicators for RBE assessments in ZEB projects. Then, the MCDM approach adopted in this study is presented together with the overall methodological approach, the case study used, the performance criteria, and the key performance indicators (KPIs) assessed with their targets. In Section 4, the results of this article are presented and critically discussed. Finally, the main conclusions and future outlooks are given in Section 5.

2. Theoretical Background

2.1. Assessment Criteria and Indicators for Responsive Building Envelope Solutions

The assessment of RBE designs can be challenging because of the dynamic nature of RBE technologies and their simultaneous influence on multiple physical domains [14,22]. For this reason, several recent studies focused on defining criteria and indicators to assess the performance of responsive façades [23–25]. Attia et al. [23] investigated current adaptive façades (AF) trends, with a focus on their performance assessment. They identified the gaps in the performance evaluation of AFs and proposed an assessment framework with five main categories: maintenance durability and life cycle, user control and experience, building control and service, protective performance, energy and environmental performance. Each category includes several KPIs aiming at defining the assessment of requirements, performance criteria, and qualitative technical characteristics of AFs. Loonen et al. [24] proposed an analysis of existing classification approaches for AFs to identify their requirements and challenges. A new matrix to characterise AFs was proposed as a result. In this matrix, six main goals/purposes of AFs are identified, i.e., thermal comfort, indoor air quality, visual performance, acoustic quality, energy generation, and personal control. The authors state that one or several of the identified goals should be achieved by AFs, in addition to considering the overall energy use, CO_2 emissions, and life cycle cost. The goals proposed by the authors can be expressed using performance indicators and are often based on building codes or standards. Aelenei et al. [25] presented the findings of an analysis of existing concepts and case studies of AFs and proposed a new approach to characterising their performance. The specific purposes of façade/components with adaptive capacity were defined, aiming at recognizing the reasons behind the adoption of these façades. The identified purposes were the following: thermal comfort, energy performance, indoor air quality (IAQ), visual performance, acoustic performance, and control. Assessing the performance of RBEs in ZEBs and ZENs can be even more challenging than in the context of ordinary buildings, since it requires considering additional factors such as the interactions with a larger grid system. Taveres-Cachat et al. [13] identified three main (non-mutually exclusive) design purposes for RBEs in ZENs, i.e., energy performance, user needs, and demand side management (DSM). Such classification is also relevant for ZEBs as they are often connected to local energy grids and interact with a broader context. The addition of DMS to assess RBEs on a ZEB or ZEN scale as proposed in [13] aims to integrate strategies for intelligent energy management to increase grid-friendliness at larger scales, a concept also researched under the name "energy flexibility". The IEA EBC Annex 67 project "Energy Flexible Buildings" defines the energy flexibility of a building as: "The ability to manage its demand and generation according to local climate conditions, user needs, and grid requirements. Energy Flexibility of buildings will allow for demand side management/load control and thereby demand response based on the requirements of the surrounding grids" [26]. In ZEBs and ZENs, energy flexibility requires assessing the simultaneity of energy needs versus supply (i.e., load matching) and the match between import and export of energy with respect to the grid needs (i.e., grid interaction) [27]. Energy flexibility indicators can allow investigating alternative design solutions but they often lack specific target values because, for instance, increasing the load match may or may not be appropriate depending on the circumstances on the grid side [28]. The Norwegian ZEN Research Centre identified assessment categories, criteria, and KPIs based on previous project experience, existing assessment frameworks, and cross stakeholder inputs given in workshops. This resulted in a combination of quantitative and qualitative key assessment criteria and indicators described in [29]. The identified criteria and KPIs can be evaluated either on building-level or neighbourhood scale, and in some cases, on both levels.

2.2. Robustness-Based MCDM

Assessing multiple criteria in building designs inevitably creates design trade-offs. MCDM is a general concept consisting of different techniques to manage performance trade-offs due to conflicting criteria. This is based on the ranking or prioritization of alternatives, where each alternative cannot meet all the criteria on the same level, but the highest-ranking option will lead to the highest net profit. In MCDM, stakeholders differentiate various performance criteria by weighting them to show that achieving different criteria has a different value for the project actors. The decision-making step gets more complicated as more conflicting criteria are added and requires expertise to accurately weigh all criteria [21]. For example, Invidiata et al. [30] ranked the design strategies regarding comfort, environmental, and economic perspectives in an MCDM using input from 30 experts from different fields to define priorities and weightings for suggested criteria. Other multi-criteria decision-making techniques were also implemented in building design such as Multi-Attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP), Fuzzy Set Theory, Weighted Sum Method, and Weighted Product Method. For instance, AHP was used to select intelligent building systems [31], rank and compare energy management control algorithms for residential buildings [32], and select an optimal PCM to store heat from a ground source heat pump [33]. In addition to selecting a design package regarding different criteria, considering the impact of uncertainties (that influence the performance of different designs) is also a challenging issue. This procedure is known as decision-making under uncertainty. It shows that the building designs should perform well regarding multiple criteria under the current conditions and future uncertainties. An example of this is carried out by Rysanek et al. [34] where classical decision theories like the Wald, Savage, and Hurwicz criterion approaches were used to find the optimum building energy retrofits under technical and economic uncertainty. To show the impact of uncertainties in high-performance design selection, Kotireddy et al. [35] implemented performance robustness as a new criterion in addition to the actual performance of the building in a decision-making process. Homaei and Hamdy [21] defined robustness as the ability of a building to perform effectively and remain within the acceptable margins under a majority of possible changes in the internal and/or external environment. Based on this definition, they integrated robustness assessment with MCDM and developed a robustness-based decision-making approach called "T-robust approach". This method selects designs that perform considering multiple criteria under current conditions and future uncertainties. In this approach, the integration of robustness assessment to MCDM is done by introducing a new indicator called the multi-target key performance indicator (MT-KPI). The MT-KPI is defined based on the building's performance for given criteria and deviations from set performance targets. The approach yields a single performance metric and removes the need for weighting different criteria—which is not an easy task in real-world problems—by considering each criterion's target and penalizing the ouput based on the deviation from these targets. The T-robust approach also evaluates the robustness of the MT-KPI under the formulated uncertainties. In a previous article [21], one of the authors of this work evaluated the MT-KPI in a case study where energy use and comfort were the performance criteria. By running the robustness assessment, they succeeded in finding high performance and robust designs under uncertainties. The interested reader is referred to [21] for more details about the T-robust approach and the minimax method.

3. Materials and Methods

3.1. Classification of Performance Criteria and Indicators for RBE Assessment in ZEBs

One of the objectives of this paper is to provide a classification of quantifiable assessment criteria and indicators for simulation-based performance prediction of RBEs in ZEBs, considering three main categories: environmental/energy performance, user needs, and energy flexibility, as discussed in Section 2.1. This classification is meant to help assessing RBE alternatives in the early-design or renovation phase of building projects. The state-of-the-art review of performance criteria and indicators showed limitations that the classification proposed in this paper aims to overcome. Some of the assessment criteria identified in previous studies can only be assessed qualitatively, and even for the quantitative criteria, specific indicators and unit of measurement were not always provided. In this paper, only quantifiable KPIs are considered, to establish objective and comparable RBE performance assessments. Most publications on performance criteria and KPIs for RBE dealt with assessments at material level, whereas studies focusing on building or neighbourhood level performance are limited [23]. The proposed classification is meant to be used at the building scale but can also consider the broader scale of a neighbourhood. The literature review results shown in Table 1 indicate that most articles on RBE performance assessment at the building level focus on one or two evaluation criteria. Many studies on RBEs used single factors, such as energy saving potential [36–38], or coupled factors, such as energy efficiency and visual comfort [39–41] or visual comfort and thermal comfort [42,43]. Only a few studies analysing RBE performance include other additional criteria, such as energy efficiency, visual comfort, and thermal comfort [43,44]. The proposed robustness-based MCDM approach provides the assessment of one or more KPIs in each of the performance categories identified for the RBE performance evaluation (energy/environmental performance, user needs, and energy flexibility). Note that the evaluation of RBE through KPIs in the "energy flexibility" category was not directly deduced from the literature but was included in the proposed classification because they are acknowledged as essential to assess RBE designs in ZEBs, especially when they are part of a broader area that aims to reach a zero-emission target.

Table 1 summarizes quantitative assessment criteria and KPIs under each performance category identified in this article based on the literature review discussed in Section 2.1 and on the authors' personal elaboration. Note that this is meant to be a proposal for criteria and indicators' classification, where specific KPIs might more easily be examined at the building scale, while others might also result as suitable to the neighbourhood scale.

Table 1. Performance criteria and indicators for RBE assessment in ZEBs.

Performance Category	Assessment Criteria	Key Performance Indicators	Unit of Measurement	Ref.
Energy/ Environmental performance	Energy use	- Energy demand (total or per category e.g., heating, cooling, etc.)	kWh/yr or kWh/m^2/yr	[29,45,46]
		- Cooling load	kW/yr or kW/ m^2/yr	
		- Heating load	kW/yr or kW/ m^2/yr	
		- Embodied energy	kWh/yr or kWh/ m^2/yr	
		- Energy generation	kWh/yr or kWh/ m^2/yr	
		- Delivered energy	kWh/yr or kWh/ m^2/yr	
		- Exported energy	kWh/yr or kWh/ m^2/yr	
		- Energy balance (imported—exported energy)	kWh/yr or kWh/ m^2/yr	
	Climate change	- Embodied GHG	kgCO_2eq/yr or kgCO_2eq/m^2/yr	[47,48]
		- Energy use-related GHG emissions	kgCO_2eq/yr or kgCO_2eq/m^2/yr	
		- Total GHG emission	kgCO_2eq/yr or kgCO_2eq/m^2/yr	
		- Energy use related GHG balance	kgCO_2eq/yr or kgCO_2eq/m^2/yr	

Table 1. *Cont.*

Performance Category	Assessment Criteria	Key Performance Indicators	Unit of Measurement	Ref.
User needs	Thermal comfort	Global thermal comfort: - Indoor operative temperature - Predicted Mean Vote (PMV) - Percentage People Dissatisfied (PPD) - Comfort and/or discomfort hours Local thermal comfort: - Draught - Vertical air temperature difference - Radiant temperature asymmetry - Floor temperature	°C - % No. h or % % °C °C °C	[49–51]
	Visual comfort	- Daylight factor - Illuminance level - Glare index - Illuminance uniformity	% Lux - -	[50–53]
	Acoustic comfort	- Airborne sound reduction index - Reverberation time - A-weighted equivalent sound pressure level - Equivalent continuous sound level	dB s dB(A) dB	[50,51,54,55]
Energy flexibility	Grid interaction	- Grid interaction index - Generation multiple - Capacity factor - Dimensioning rate - Peak power load - Peak power generation - Peak power export - Grid control level	% - % % kW kW kW %	[29,56–58]
	Load matching	- Load match index - Load cover factor (self-generation) - Supply cover factor (self-consumption) - Loss of load probability - Load/Power shifting ability - Utilisation factor - Mismatch compensation factor	% % % - - % -	[29,56–58]

3.2. Extension of the T-Robust Approach

In [21], the T-robust approach was used for two criteria (energy and comfort) and four different robustness assessment methods (Max-min method, Best-case and worst-case method, Minimax regret method, and Taguchi method). In this paper, this approach was applied to select robust and high-performance designs based on three different criteria (energy use, thermal comfort, and load matching) where the minimax regret method was used to assess the robustness of the MT-KPI. The three chosen criteria, performance indicators, and corresponding targets are described in Section 3.7. For each indicator, there is a corresponding performance target and robustness margins ($KPI_{i,m}$) that creates different performance zones based on their feasibility. Note that a distinction should be made between "less is better indicators" and "more is better indicator". In the first case, a KPI_i lower than $KPI_{i,m}$ will lead to a feasible performance but a KPI_i greater than $KPI_{i,m}$ will lead to an unfeasible performance. The opposite will happen for a "more is better indicator". In this paper, among the three analysed performance criteria, the energy use is a "less is better" indicator, and the thermal comfort and energy flexibility are "more is better" indicators. The relative performance ($KPI_{i,rel}$) is defined based on the relationship between KPI_i and $KPI_{i,m}$, as shown in Equation (1).

$$KPI_{i,\ rel} = \frac{KPI_i}{KPI_{i,m}} \times 100 \tag{1}$$

The definition of the zones and the calculation of the MT-KPI depend on the number of performance indicators assessed. The different zones identified in this work are visually illustrated in Figure 1, where each color corresponds to one zone. Point (100,100,100) in Figure 1 shows the relative margin point at which the performance of the building considering all indicators is equal to the robustness margin. The eight different performance zones are created around the relative margin point.

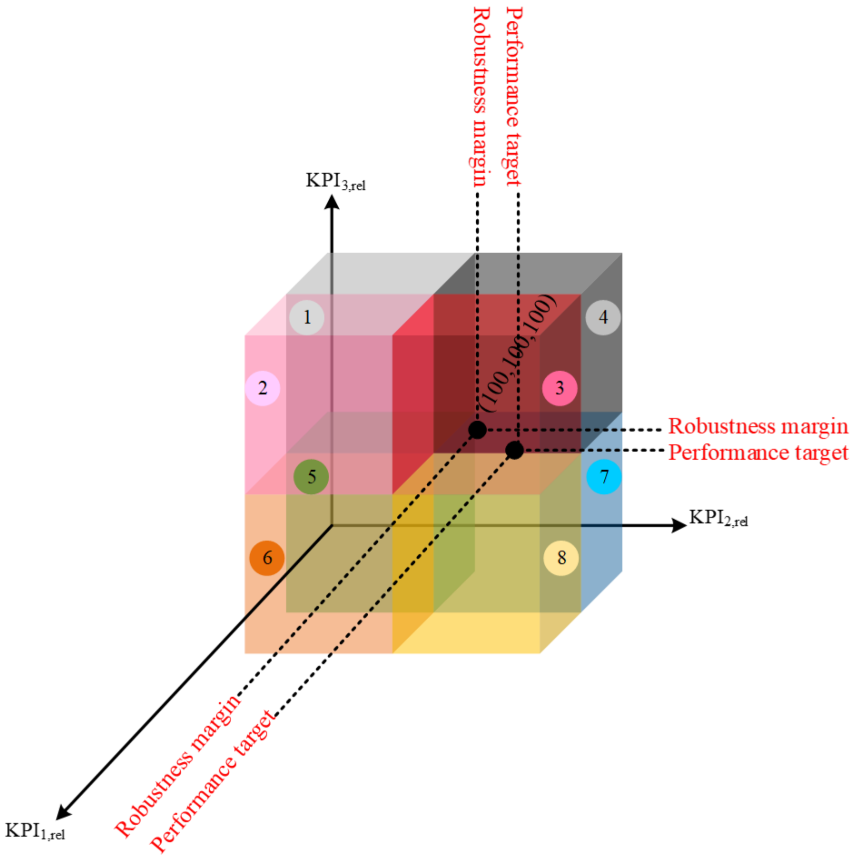

Figure 1. Illustration of performance zones for the MT-KPI.

Table 2 presents the formulas for the MT-KPI calculation for the KPIs considered in this study. The strategy for calculating the MT-KPI is one that penalizes design with a lower performance than the target set for each indicator (i.e., infeasible performance). As shown in Table 2, zone 6 is an extreme case where all indicators are outside the feasible boundaries and in which case the MT-KPI is the sum of the KPIs' difference with their corresponding robustness margins and acts as a penalty for the infeasibility of all three indicators. At the other extreme is zone 4 in which all indicators are within their feasibility bounds and for which the MT-KPI is calculated as the sum of the inverted difference between indicators and their corresponding robustness margins. Inverting the differences is used as a way of differentiating feasible designs. All the other zones are designs with different combinations of performance results which are feasible for some criteria and infeasible for others. In these zones, a penalty is applied for the infeasible indicators and the MT-KPI is defined for each zone based on the formulas shown in Table 2. To give an example, zone 1 has a feasible performance for KPI_1 and KPI_3, and an infeasible performance for KPI_2. Then, for the calculation of the MT-KPI in this zone, a penalty is applied for KPI_2. The calculations of the MT-KPI for each design under each scenario was done in this work by applying an automated MATLAB [59] algorithm. After calculating the MT-KPI, the minimax regret method allowed assessing the difference between the MT-KPI value for each design in each scenario and the minimum performance of each scenario across all designs. Based on the definition of the minimax regret method, this difference is called performance regret.

The maximum performance regret represents the highest deviation in each design, i.e., the largest difference between the worst performance and the best performance. The most robust design is then the one with the smallest maximum performance regret across all scenarios [23]. The calculation related to the minimax regret method was also done using an automated MATLAB algorithm, with the formulas shown in the Appendix A (Tables A1 and A2).

Table 2. Calculation of MT-KPI in different performance zones.

Num.	Performance Zone	Feasibility	MT-KPI
1	$KPI_{1,rel} \leq 100$; $KPI_{2,rel} < 100$; $KPI_{3,rel} \geq 100$	Feasible for KPI_1 and KPI_3	$(1/(100 - KPI_{1,rel}))$ $+(100 - KPI_{2,rel})+(1/(KPI_{3,rel} - 100))$
2	$KPI_{1,rel} > 100$; $KPI_{2,rel} < 100$; $KPI_{3,rel} \geq 100$	Feasible for just KPI_3	$(KPI_{1,rel} - 100)+(100 - KPI_{2,rel})+(1/(KPI_{3,rel} - 100))$
3	$KPI_{1,rel} > 100$; $KPI_{2,rel} \geq 100$; $KPI_{3,rel} \geq 100$	Feasible for KPI_2 and KPI_3	$(KPI_{1,rel} - 100)$ $+(1/(KPI_{2,rel} - 100))+(1/(KPI_{3,rel} - 100))$
4	$KPI_{1,rel} \leq 100$; $KPI_{2,rel} \geq 100$; $KPI_{3,rel} \geq 100$	Completely feasible	$(1/(100 - KPI_{1,rel}))+(1/(KPI_{2,rel} - 100))+(1/(KPI_{3,rel} - 100))$
5	$KPI_{1,rel} \leq 100$; $KPI_{2,rel} < 100$; $KPI_{3,rel} < 100$	Feasible for just KPI_1	$(1/(100 - KPI_{1,rel}))+$ $(100 - KPI_{2,rel})+(100 - KPI_{3,rel})$
6	$KPI_{1,rel} > 100$; $KPI_{2,rel} < 100$; $KPI_{3,rel} < 100$	Completely infeasible	$(KPI_{1,rel} - 100)+$ $(100 - KPI_{2,rel})+(100 - KPI_{3,rel})$
7	$KPI_{1,rel} \leq 100$; $KPI_{2,rel} \geq 100$; $KPI_{3,rel} < 100$	Feasible for KPI_1 and KPI_2	$(1/(100 - KPI_{1,rel}))+(1/(KPI_{2,rel} - 100))+(100 - KPI_{3,rel})$
8	$KPI_{1,rel} > 100$; $KPI_{2,rel} \geq 100$; $KPI_{3,rel} < 100$	Feasible for just KPI_2	$(KPI_{1,rel} - 100)+(1/(KPI_{2,rel}$ $-100))+(100 - KPI_{3,rel})$

3.3. Methodological Approach

Figure 2 shows the methodological approach proposed in this paper to assess RBE designs in ZEB projects. Note that the main general steps of the methodology are shown in the grey boxes, while the specific steps adopted in this work for the case study are in the white boxes.

Primarily, the main purpose and criteria for RBEs in the studied project should be defined based on the priorities of the stakeholders involved. Afterwards, relevant KPIs to assess RBEs in the ZEB project should be identified. The KPIs should be related to the main stakeholders' objectives, including for instance energy use, thermal comfort, and energy flexibility. The choice of the KPIs should be supported by the classification provided in Table 1. Then, specific performance targets should be identified for each KPI to assess how the performance of the building under the design conditions deviate from the defined targets. The performance targets can be based on requirements in building codes, or they can be set specifically based on the preference of stakeholders for a certain project. Based on the assumption in the T-robust approach, the examined designs should comply with a robustness margin of 5% from the target limit to be considered feasible solutions. Such a margin of 5% was selected for this study based on author's assumptions, but it could be changed depending on the preferences of the decision makers in the studied project. Several designs with RBE solutions for the analysed project should be identified, together with alternative scenarios to assess the effects of different uncertainties, such as changes in occupant behaviour and climate conditions. The next step involves the simulation-based performance prediction of all identified designs across all scenarios through specific software applications according to the chosen KPIs.

The robustness of the designs and scenarios is then assessed with an MT-KPI, which reflects the performance of the designs against multiple criteria and penalizes the solutions that do not meet a specific performance target. The performance robustness of the building designs is evaluated using a specific robustness indicator (i.e., minimax regret method) for the MT-KPI, as described in Sections 2.2 and 3.2, and allows selecting the design with the overall highest and most robust performance.

As shown in Figure 2, energy, thermal comfort, and building energy flexibility were selected as the performance criteria for the case study building in this article. Consequently, the authors chose annual energy demand, percentage of comfortable hours, and the load cover factor as the KPIs for the three mentioned criteria, respectively. These KPIs were selected by the authors to reflect the priorities of the specific project analysed, but other KPIs could be used in other studies to address different objectives and preferences of the decision makers.

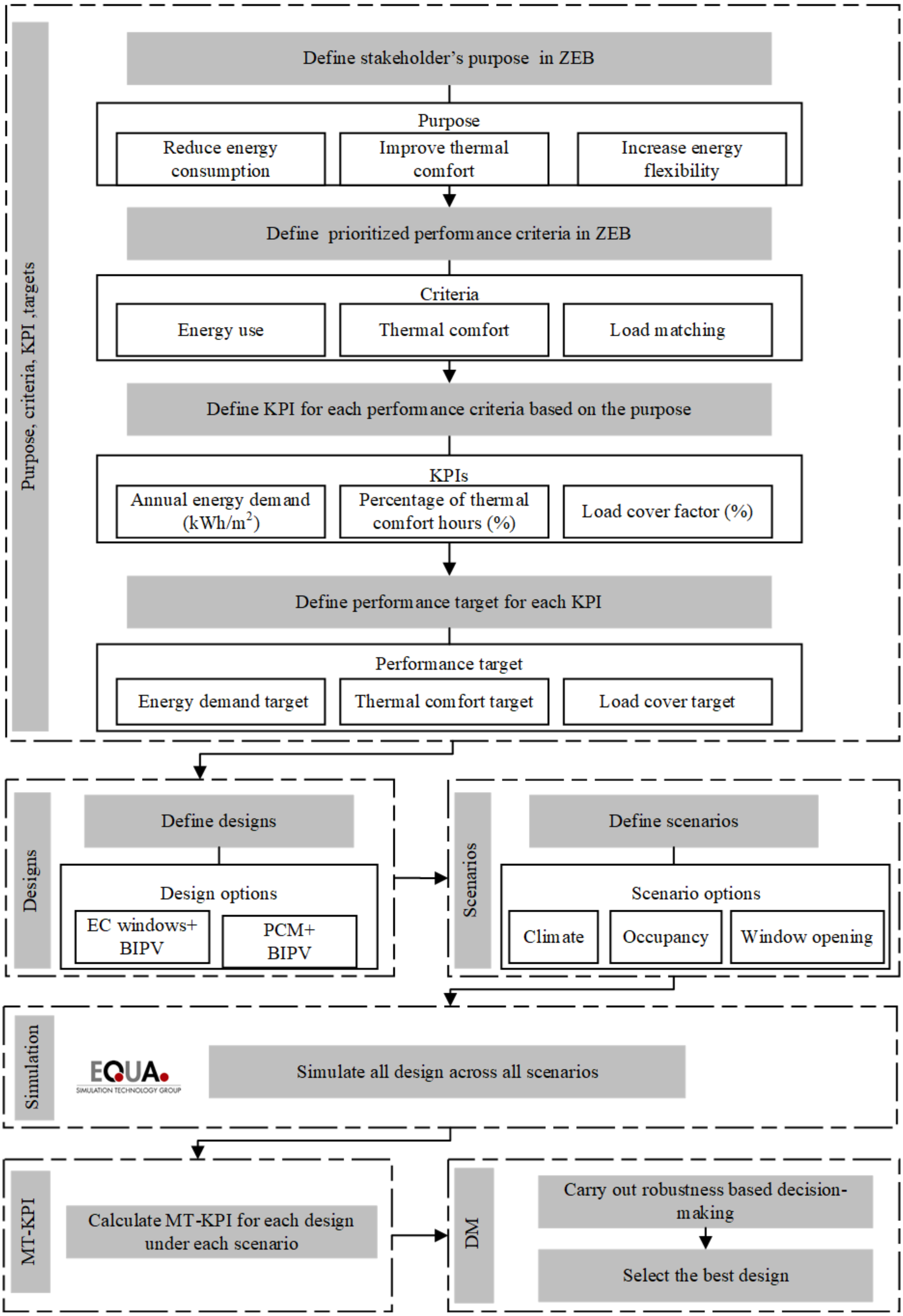

Figure 2. Methodological approach proposed in this article. The main general steps are in the grey boxes.

3.4. Case Study

To show the application of the approach, the Zero Emission Building Laboratory (ZEB-lab) located on the NTNU university campus in Trondheim (Norway) was used as a case study. This office building was finished in December 2020 and is connected to the local energy grid in an area that is intended to become a ZEN [60]. The building, shown in Figure 3, has 4 stories, with a total floor area of ca. 1725 m^2. The ZEB-lab was designed to achieve the ZEB-COM level [61] meaning that the building's renewable energy production compensates for total GHG emissions associated with the production of the building materials used, the construction phase, and the building operation [62] in a 60 year perspective. PV-panels are integrated in the entire roof surface and cover extensive parts of the facades to ensure sufficient renewable energy harvesting. The ZEB-lab has a compact volume and a wooden load-bearing system, with a highly insulated and airtight building envelope. The space heating is provided by a waterborne system supplied by an air source heat pump and a local heating grid. The heat pump also provides space cooling to two small research laboratories called the twin rooms. The ZEB Lab uses hybrid ventilation, which combines natural and mechanical ventilation, with a highly efficient heat recovery system. In particular, mechanical ventilation is based on a variable volume air (VAV) system providing temperature and CO_2 demand-controlled air flows. See Tables A3 and A4 in the Appendix A for more details about the building envelope and the technical building systems. A detailed model of the case study building, for all the identified designs and scenarios, was created in the dynamic simulation software "Indoor Climate and Energy software" (IDA ICE), version 4.9 beta [63].

Figure 3. Pictures of the case study building. Copyright: Nicola Lolli/SINTEF.

IDA ICE was validated in several studies with respect to CEN standards and ASHRAE standard [64–66]. The possibility of modeling RBE technologies in IDA ICE, including PCM and electrochromic (EC) windows, was reviewed in several articles, such as Refs. [67,68]. The prediction accuracy of IDA ICE for PCM simulation was tested and validated against experimental results by Mazzeo et al. [69] and Cornaro et al. [70]. EC window modelling in IDA ICE implies the use of a detailed windows' model with dynamic parameters in different states and with various light angles, through custom control macros that can be implemented to activate their shading. Finally, the calculation accuracy of PV energy generation in IDA ICE was also validated, as shown in [71].

3.5. Analysed RBE Technologies

The analysed case study was planned as an arena where new and innovative solutions can be developed, investigated, tested, and demonstrated in a mutual interaction with building's occupants. Energy demand reduction, thermal comfort improvement, and building load covering by on-site energy generation were identified by the stakeholders as the main priorities to be addressed when testing new possible technologies in the building. Therefore, two RBEs, i.e., EC windows and PCM, were selected as alternative designs to be combined with the existing installed RBE technologies, which are building integrated photovoltaics (BIPV) and responsive window screens. The aim was to assess the possible benefits of new innovative designs with respect to the identified performance objectives. The use of PCM in lightweight buildings characterised by low thermal inertia can lead to a higher thermal storage capacity. Several studies proved the positive effects of PCMs on indoor comfort and energy use [72]. To simulate PCM in walls, IDA ICE uses a PCM model with different temperature-enthalpy equations to determine liquid-solid phase transitions. The cycling between phases is modelled as a hysteresis meaning that the current state depends on past states of the system. The "mode" variable in the model is used to identify the five different physical states, i.e.,: "mode -2" solid phase; "mode 2" liquid phase; "mode -1" solidification phase; "mode 0" inversion during the solidification/fusion process; "mode 1" fusion process. The heat capacity and the temperature of the PCM layer are calculated as a function of the enthalpy and the "mode" variable at each time step.

EC windows are effective in preserving solar gains in winter, while reducing the heat load in summer and glare from the sun. Using EC windows rather than normal windows with external screens arguably provides a better connection to the outdoors for users with smoother and inaudible transitions between different shading states, allowing light to penetrate even in the darkest state [73]. IDA ICE uses a detailed window model for EC window implementation, where the optical and thermal properties of all the panes and spacers are represented. Multiple reflections and solar absorption in each pane are considered to calculate angle-dependent optical properties based on ISO 15099:2003 [74]. The EC glass tint can be automatically controlled by standard or custom control algorithms created directly in the IDA ICE macro interface, which allows changing window optical properties based on, for instance, indoor operative temperature and/or daylighting levels.

3.6. Analysed Designs and Scenarios

Five design configurations were defined for the case study building, as illustrated in Table 3. Table 4 shows an overview over the main parameters used in the designs and scenarios concerning the internal gains, exterior and interior blinds, PCM, and electrochromic windows. Eight scenarios were overall evaluated in this paper, addressing two main parameter categories: climate conditions and occupant behaviour.

i. Climate scenarios

To assess the influence of climate uncertainties, two weather files were evaluated. The first one was a standard typical meteorological year (TMY) weather file in EPW format for the location of Trondheim (Norway) and represented the current climatic conditions. The second one was obtained by morphing the first weather file using the "CCworldWeatherGen tool" [76], which is based on the widely accepted General Circulation Model (GCM) HadCM3 and the IPCC's A2 emission representing a medium-high scenario. The resulting weather file accounts for potential impacts of climate change and represented possible future weather conditions for the year 2050 in Trondheim.

Table 3. Details of the five designs considered in the case study demonstration.

Design	Description
D1	As built case study (reference design), with: BIPV on the roof, south, west, and east facing facades; external screens on the south facade, internal curtains on the west and east facades, and no solar protection on the north façade.
D2	Reference design (D1), with PCM added as a layer in all facades and same screens/curtains as D1.
D3	Reference design (D1), with PCM added as a layer in all facades with internal curtains on south/east/west facades.
D4	Reference design (D1), with EC windows on all facades and control macro 1 (different tinting states as a response to incident radiation level and indoor air temperature. See Table 4).
D5	Reference design (D1), with EC windows on all facades and control macro 2 (different tinting states as a response to incident radiation level and daylighting level in the zone. See Table 4).

Table 4. Key parameters for the analysed designs.

Input Category	Value	Reference or Comment
Occupancy schedule and rate	Variable	Schedules based on standard NS/NSPEK 3031:2020 [46]; number of occupants based on as-built seating plan. Daily power profile variation shown in Figure A1 in Appendix A.
Heat gain from occupants	5 kWh/m^2	Average specific value for the whole building, with 1.2 MET per person and people number per room given in Table A5 in Appendix A. This value aligns with [46].
Equipment power	3.2 W/m^2	Average specific value for the whole building, including only typical office electrical equipment (laptop, PC, screens, etc.). Value in line with as-built documentation. Daily power profile variation set as the same as for occupancy. See Figure A1 in Appendix A.
Artificial light power	4.7 W/m^2	Average specific value for the whole building, with dynamic LED lighting strategy in which artificial lighting is used to complement daylighting until an illuminance of 500 lux is reached on the work plan. Value in line with as-built documentation. Daily lighting profile variation based on setpoints and occupancy. See Figure A1 in Appendix A.
Amount of solar radiation on façade to trigger shading signal for exterior and interior blinds	If solar elevation $\leq 29°$ $\rightarrow$ 79 W/m^2 If solar elevation > 29° $\rightarrow$ 198 W/m^2	As-built control strategy.
PCM	Thickness: 15 mm Melting point: 22–23 °C Cp > 170 kJ/kg (in range 13–28 °C) Density in solid state: 1500 kg/m^3	Melting-solidifying around 20 °C was chosen because it was found to be preferable in heating-dominated climates [75].
Electrochromic windows	U-value: 0.8 W/m^{2}K G-value (min/max): 0.25–0.48	Two control macros: Macro 1 (in D4): proportional shading control based on external solar radiation on window in range 100–300 W/m^2 and KPI control of indoor air temperature (setpoint 24 °C). Macro 2 (in D5): proportional shading control based on external solar radiation on window in range 100–300 W/m^2 and KPI control for daylighting level (500 lux setpoint). See Figures A2 and A3 in Appendix A.

ii. Occupancy schedule

Two occupancy schedule cases were implemented in the model. The first one used occupancy profiles based on those recommended in [46], as shown in the Appendix A, Figure A1. In this schedule, most modelled zones had two main peaks in the occupancy during the hours 9:00–11:00 and 13:00–15:00, and a relatively limited occupancy for the rest of the working hours (7:00–9:00 and 15:00–17:00). The only zone in the building with a different occupancy schedule was the canteen, where occupants were assumed to be present only between 11:00 and 13:00 for lunch. The second occupancy case considered the possibility of people staying longer after regular work hours on the first and third floors. These floors are used by employees and students from the university, a portion of which are likely to work overtime until 20:00. See occupancy schedules in Figure A1 in the Appendix A.

iii. Window opening strategies

Two alternative strategies were used for window opening. The first strategy assumed all windows were always closed, while in the second strategy, the occupants could open all openable windows when the indoor air temperature was higher than a threshold value and the air temperature outside was lower than the indoor air temperature. See more details in Table 5. The second strategy was implemented in IDA ICE through control macros based on a PI-control. The five designs were analysed across all eight scenarios, leading to a total of forty cases simulated in IDA ICE over a one-year period. Table 5 summarizes the parameters and their combination for all scenarios.

Table 5. Summary of the main parameters for all the scenarios analysed.

Parameters		Scenarios							
		1	2	3	4	5	6	7	8
Climate	1. Current weather	x	x	x	x				
	2. 2050 weather					x	x	x	x
Occupancy schedule	1. Based on NS3031 schedules	x	x			x	x		
	2. Based on NS3031, with longer stay of university employees			x	x			x	x
Window opening strategy	1. All windows closed	x		x		x		x	
	2. All automatically openable windows open if Tindoor > Tout, Tindoor > 24 °C, and room is occupied; all manually openable windows open if Tindoor > Tout, Tindoor > 25 °C, and room is occupied		x		x		x		x

3.7. Analysed KPIs and Targets

To assess the performance of the designs and scenarios defined for the case study, three KPIs from Table 1 were chosen to reflect the main priorities of the project stakeholders.

The first KPI analysed in this article is the annual energy demand of the building for heating, ventilation, cooling, and lighting. The target value for this KPI was based on the requirement of the Norwegian building technical regulation, TEK17 [77], which sets the total energy demand, including energy for space and ventilation heating, space and ventilation cooling, ventilation fans and pump, lighting, domestic hot water (DHW), and electrical equipment. The target value for the first KPI was set to 30 kWh/m^2, which represents a reduction of 60% of the energy demand requirement of TEK17 for office buildings, excluding electrical equipment and DHW energy use. This percentage reduction from the reference value was deducted from the target values for a similar KPI defined in [29], where the highest credit for the energy demand KPI is given to a reduction from 50% to 60%. The robustness margin allows 5% tolerance from the performance target, which leads to 32 kWh/m^2.

The second PI is related to the thermal comfort level in the building, given as the percentage of hours within comfort category II, as defined in EN 15251:2007 [78]. In this latter standard, three main comfort categories are identified, based on an adaptive comfort model where occupants with sedentary physical activities can freely adapt their clothing level to indoor/outdoor thermal conditions. The comfort category II considered in our study represents normal level of expectation in new buildings. The target value for this KPI was set to 100% of occupied hours within thermal comfort category II. The robustness margin allows a 5% tolerance from the performance target, which leads to 95%. The KPI was evaluated first for each one of five representative long-lasting working areas in the case study building and then as an average value for all five rooms. This allowed to have an overall picture of the comfort conditions in the whole building, as the chosen rooms are those mostly occupied and spread across all four floors with different façade expositions. Note that the analysis of hours in category II of EN 15251 focuses on the combination of the thermal comfort hours both in heating and cooling condition, therefore the identification of extreme scenarios is quite complex and is out of the scope of the article.

The third KPI is the load cover factor (self-generation), which represents the percentage of the electricity demand that is covered by on-site electricity generation. This KPI is one of the available load matching factors, which aims to describe the degree of the utilization of on-site energy generation in relation to the actual energy demand. The hourly analysis of the load cover factor offers a useful picture of the correlation between on-site demand and energy supply. An hourly resolution was therefore chosen in this study to evaluate this KPI for the different RBE designs, and the target value was set to 100% because a high coverage of the energy demand on-site was desired. The robustness margin allows 5% tolerance from the performance target, which leads to 95% as a robustness margin for the load cover factor.

4. Results and Discussion

4.1. Performance Assessment of Designs and Scenarios

Figure 4a shows the results for the energy demand (for heating, cooling, and lighting) for the five designs across the eight analysed scenarios. Scenario 1 and scenario 8 had the highest and the lowest energy demand in all the examined designs, respectively. For designs, D4 showed overall the lowest energy demand values across all scenarios. The energy demand for room and ventilation heating represented the main contribution to the total energy demand (ca. 65–80%), followed by lighting (ca. 20–30%), and cooling (ca. 1–4%). The use of a morphed climate file for 2050 in scenarios 5-8 had the highest impact on the energy demand with a reduction of ~25% compared to results with the TMY weather file (in scenarios 1–4). Figure 4b illustrates the results of the average percentage of hours in category II (according to EN 15251) in the main rooms assessed for the five designs across the eight scenarios. All designs and scenarios had appropriate thermal comfort conditions. Scenario 8 in D2 had the highest percentage of hours in category II (98%) while scenario 1 in D3 had the lowest percentage (89%). In D3, the use of PCM in external walls combined with interior curtains on the south/east/west facades led to the worst thermal comfort among designs, especially for south-facing rooms whose facades are characterised by very large windows leading to high solar gains in summer and significant heat losses in winter. Then, as the case study building is in a heating-dominated climate, a significant part of the unacceptable hours with respect to the thermal comfort is related to underheating hours. Figure 4c illustrates the load cover factor for the five designs across the eight scenarios analysed. The results show that D1 and D2 scored lowest for this KPI, with values in the range 43–48%. D3, D4, and D5 on the other hand yielded higher load cover factors reaching up to 50%. Since the energy generation from the PV system with the two climate files employed is similar in all designs/scenarios, the value for this KPI mainly depends on the size of the building load, its duration, and timing. Generally, the use of the assessed RBE technologies led to a higher load cover compared to the reference design thanks to reducing peak loads and shifting loads. Using PCM combined with external screens on the south façade and interior curtains on east/west facades (D2) led to a small decrease in the energy demand ((-2)–(-3)%) and a slightly bettered thermal comfort (1–1.5%) compared to D1, but the load cover factor remained almost the same. Substituting external screens with interior curtains on the south façade in D3 generally led to a lower energy demand (ca. -10%) and a higher load cover factor (4–7%) compared to D1, and D3 performed particularly well in scenarios using the future weather climate file. However, the thermal comfort decreased in all scenarios.

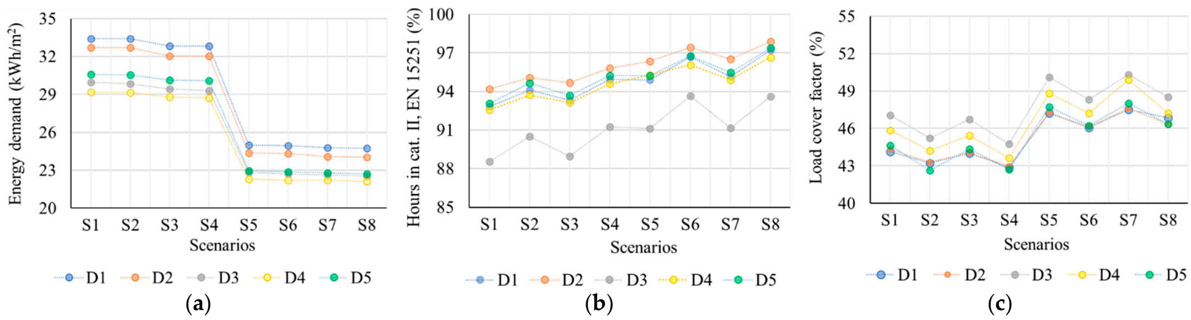

Figure 4. Results of the three performance indicators for the five analysed designs across the eight scenarios: (**a**) Energy demand results (including only heating, cooling, and lighting). (**b**) Thermal comfort results (average % of hours in cat. II of EN 15251 in five main rooms). (**c**) Load cover factor results.

When using EC windows (D4 and D5), it was possible to improve the performance regarding the energy demand KPI (especially for heating and lighting) and the load cover factor KPI, without significantly reducing the thermal comfort compared to the reference design, D1. The design with the shading control macro for EC windows based on indoor air temperature (D4) was particularly high performing with a lower energy demand ((−10)–(−12)%) and higher load cover factor (1–5%) compared to D1 but did not clearly outperform D3 in most cases except for thermal comfort.

Based on the performance assessment described in this sub-section, the selection of the best design is not trivial as some designs performed well but with a certain variation across scenarios. Figure 5 shows a closer comparison between D3 and D4, which were the two designs that stood out among all the others in terms of performance. However, even the comparison of only two designs with respect to several KPIs is not straightforward and would also be time- and resource-demanding in real-world problems.

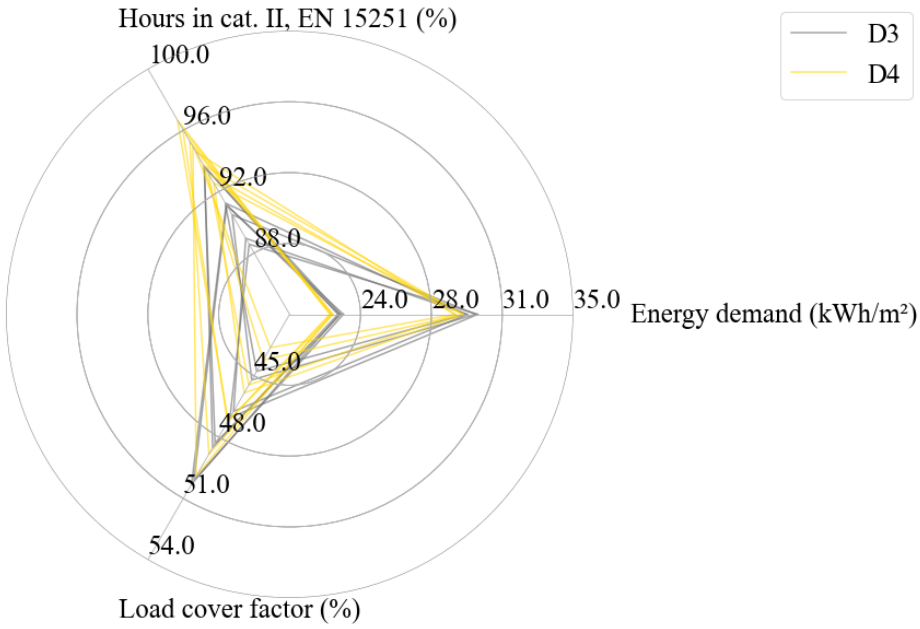

Figure 5. Comparison of the results for all KPIs in D3 and D4 across the eight scenarios.

Given the complexity of the performance assessment for the choice of the best design, the robustness-based MCDM assessment was performed to facilitate the selection of the design that was most robust under uncertainties and had optimal actual performance.

4.2. Robustness-Based MCMD Assessment

In this section, the results of the T-robust approach are presented. Figure 6 summarizes the results for all design and scenarios using the same eight performance zones that were previously introduced in Section 3.2 (see Figure 1 and Table 2). The three highlighted planes inside the graph in Figure 6 are drawn at the robustness target values of each KPI, to visualize the performance zones. As evident in Figure 6, the distribution of the performance of the five designs across the eight scenarios seems categorised into two main groups, which show the performance of the analysed designs in the current and the 2050 weather conditions. The graph in Figure 6 illustrates that a switch from the current to 2050 climate file will lead to a decrease in the energy demand and an increment in the percentage of hours in category II and the load cover factor. An increase in the percentage of hours in category II shows that the 2050 weather file will decrease the number of underheating hours that can happen during a year. When it comes to the comparison of the designs' performance targets, the following observations can be listed:

- With respect to the energy demand target, all the designs will experience an energy demand higher than 30 kWh/m^2 at least in one of the suggested scenarios, except for D3 and D4. D1 and D2 also have scenarios with an energy demand higher than the robustness margin for this KPI (32 kWh/m^2).
- When it comes to the comfort performance target, which is 100% of hours inside category II, all designs have a performance lower than the target; however, all designs except D3 present scenarios with a performance higher than the robustness margin (95%).
- Regarding the load cover factor target, all the designs across all scenarios experience a performance lower both than the target corresponding to 100 % and the robustness margin of 95%.

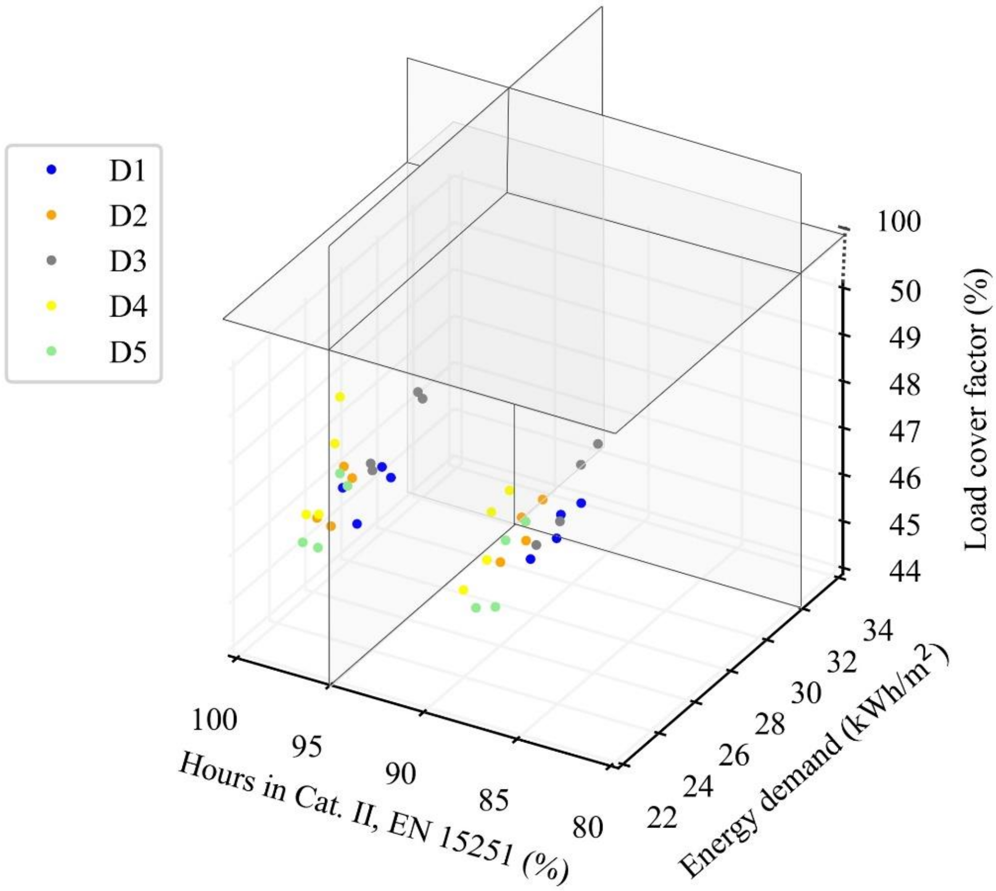

Figure 6. Energy demand vs. percentage of hours in Category II of EN 15251 vs. load cover factor, for the five designs across the eight scenarios. The three highlighted planes show the robustness margins for each indicator.

Based on these observations, the choice of the best design among those analysed in this study is not straightforward and would be even more complex when facing a higher number of designs and scenarios. Therefore, the T-robust approach was developed to help building decision makers in finding a high performance and robust design by benefiting an automated algorithm that can be run by just specifying the design performance targets.

The results of the robustness assessment with MT-KPI are shown in Figure 7. In the T-robust approach, the MT-KPI allowed differentiating between feasible and infeasible designs by considering the performance targets. The robustness of each design was analysed based on the minimax regret method, as described in Section 3.2, where the maximum regret across all scenarios was assessed and its minimum value led to the most robust design.

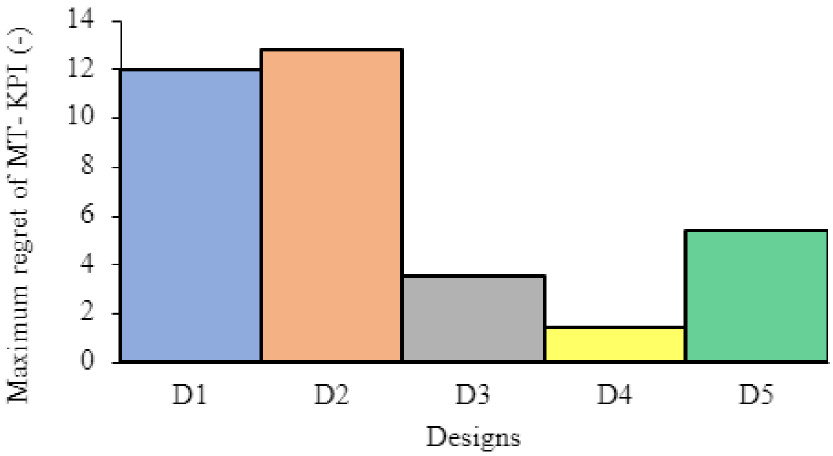

Figure 7. Calculated maximum-regret for MT-KPI of the five designs. A low value shows the most robust design.

Figure 7 shows that, among the suggested design, the minimum value of the maximum regret is achieved by D4. As mentioned before, in the T-robust approach, the preferences are automatically incorporated into the MT-KPI by using a performance target. The result of the T-robust approach shows that D4 is a design that is not only performing well with respect to the performance targets for the three considered criteria, but it also has the highest robustness when exposed to the considered uncertainty scenarios. This is also in line with the observations which stemmed from the discussion in Section 4.1, as D4 has the lowest energy demand across all scenarios presents a middle range of hours in category II and is one of the designs with the highest load factor.

4.3. Simulation Model Assessment

In this section, the results from the simulation of the model in IDA ICE are discussed and assessed against findings from similar studies. The simulation results could not be validated with measurement data, as the case study office was recently built and no data for the real energy use were available for the reference design nor for the other hypothetical RBE-based designs considered in this research. However, specific results obtained in this article are compared with those of similar studies to verify their overall reliability. The heating energy demand of a Norwegian ZEB comparable to the case study building of this research, as described in [79], was in line with that estimated with IDA ICE in the current study for all designs/scenarios (in the range of 20–30 kWh/m^2 for the reference design). Additionally, the results obtained in the designs with EC windows are comparable with those obtained in a similar case study, i.e., [68], where two control strategies based on indoor temperature and lighting were assessed for a representative building in Trondheim. As in this article, the authors of [68] found that the EC window controlled by operative temperature could provide the highest yearly energy saving, up to 20%, compared to a building equipped with reference windows with no control strategies. Finally, the results of the designs with PCM are also compared with those of a similar study, i.e., [75], where a building with a ca. 15 mm PCM layer, integrated backside the interior finish layer of external wall and roof, was examined in different climate conditions. In [75], the authors found that, in heating-dominated buildings, by using a PCM with a melting point at around 20 °C, the annual energy saving was around 2–3% in Nordic climates; this result is in line with what we found out with the use of PCM in external walls coupled with external screen on south facade and internal screens on east/west facades (D2).

Using a fully planned ZEB-COM building as a case study for this work also allowed determining a more specific threshold for total delivered energy. Based on the project documentation, the total annual energy use to reach the ZEB-COM balance had to be below a critical threshold of 4.5 kg CO_2 eq./m^2/yr or 35 kWh/m^2/yr (including system losses and excluding the PV contribution). This had been calculated during the building planning and construction based on the actual materials used, data records for the construction site emissions, and carbon emissions from the Norwegian energy grids (local district heating grid and electricity). The total annual delivered energy estimated through IDA ICE for the various designs was in the range 29–32 kWh/m^2, which is consistent with the abovementioned threshold. Note that only for the as-built design, D1, it can be asserted that all its scenarios achieve the zero-energy balance over the entire lifetime, based on the results of the life-cycle assessment available in the project documentation. The other designs, D2−D5, certainly achieve the zero-energy balance in the operational stage, given the very high energy generated by PVs that is over 80 kWh/m^2/yr. However, a detailed life-cycle assessment should be performed for D2–D5 designs and scenarios if the objective is to verify the zero-energy/emission balance over the building lifetime, by also including the contribution from the construction and material stages.

5. Conclusions

This article focused on the assessment of responsive building envelope (RBE) designs in zero energy/emission buildings (ZEBs) using a robustness-based multi-criteria decision making (MCDM). A literature review of key assessment criteria and indicators for RBE analysis led to the classification and selection of assessment indicators used in this paper. Unlike in previous research, only quantifiable KPIs were considered to establish objective and comparable performance assessments. The methodological approach proposed was an extension of a novel robustness-based MCDM method that normalizes the objective functions into a single multi-target key performance indicator (MT-KPI). The method combines robustness assessment and decision-making aspects and allows identifying the most appropriate design alternative by not only comparing several designs to each other but also specific performance targets.

The innovative extension of the methodological approach was tested on a case study of a recently built ZEB connected to the local energy grid and located in a Norwegian zone that is intended to become a zero-energy/emission neighbourhood (ZEN). Five competitive designs and eight occupancy and climate scenarios were assessed and compared through three performance indicators focusing on energy use, thermal comfort, and load matching. The analysed designs included a combination of three main RBE technologies, which were building integrated photovoltaics, phase change materials, and electrochromic windows.

The findings of this paper show that the proposed approach helped selecting the most robust building design more easily than if one were to separately compare the performance indicators, without the need for weighting the objectives and with less dependency on the scenario conditions. The results of the performance assessment highlight the difficulty of defining the best design, especially when several scenarios are evaluated under uncertainties in relation, for instance, to building occupation and future climate. This would be even more challenging in real-word projects, where decision makers often have resource and time constraints. Furthermore, as the case study of this article is a real ZEB recently built in Norway, the chosen examined indicators also allowed to gain insight into critical aspects of such buildings, contributing to the definition of benchmark values for explored performance indicators. The flexibility of the method used in this article indicates that it could be applied to other case studies where it could provide insights into design options for new buildings but also for renovation or building extension projects. Indeed, the freedom of choice when it comes to performance criteria and targets make the approach versatile and the single indicator output makes it compatible with parametric performance assessments and even single objective numerical optimization.

This article focuses on assessing RBE designs in ZEB projects, which can support the optimization of the balance between several energy flows at the building and more generally at the neighbourhood scale. This can be useful for the active management of the energy purchased and/or renewably harvested and can also enhance user comfort and acceptance by supplying an interactive interface with the outdoors. As several RBE technologies are available, a systematic breakdown of the properties and requirements of these technologies is needed to build a portfolio of solutions that can lead to the zero-emission goal for buildings and neighbourhoods. Furthermore, the modelling approach, as well as the modeler's skills and the tool used, represent key aspects when dealing with a system at different scales. The complexity required to simulate clusters of buildings could be handled through lumped capacitance models and grey box approaches, which are less input-intensive than whole building simulation models used in software such as IDA ICE, which was employed in this study.

Several actors involved in a building process could make use of the methodology of this article, including architects, engineers, consultants, and other decision makers. Such actors can be supported in the selection of high performance and robust designs, which should meet specific requirements even under uncertainties that arise in the life cycle of the building.

The study in this article presents some limitations that should be addressed by future research. First, the methodological approach proposed was applied to a single ZEB, but future research could focus on different case studies, including clusters of buildings and neighbourhoods. In this article, a three-criteria robust design problem was addressed, but future studies could extend the analysis to tackle more than three performance indicators. Moreover, the work developed in this study could be developed even further and be integrated with artificial intelligence approaches as part of scenario modelling for digital twins and cyber-physical systems to evaluate the robustness of a system or identify its vulnerabilities [80].

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Nomenclature

AF	Adaptive façade
AHP	Analytical Hierarchy Process
BIPV	Building integrated photovoltaics
CABS	Climate adaptive building shell
CEN	European Committee for Standardization
D_i	Design (with i = 1,2,3,4,5)
DHW	Domestic hot water
DSM	Demand side management
EC	Electrochromic
EN	European norm
GHG	Greenhouse gas emission
IAQ	Indoor air quality
IDA ICE	IDA Indoor Climate and Energy software

IEQ	Indoor environmental quality
IPCC	Intergovernmental panel on climate change
ISO	International Organization for Standardization
KPI	Key performance indicator
LED	Light emitting diode
MAUT	Multi-Attribute Utility Theory
MCDM	Multi-criteria decision making
MET	Metabolic equivalent of task
MT-KPI	Multi-target key performance indicator
PCM	Phase change material
PMV	Predicted mean vote
PPD	Percentage People Dissatisfied
PV	Photovoltaics
RBE	Responsive building envelope
TEK17	Norwegian building regulation
TMY	Typical meteorological year
VAV	Variable air volume
ZEB	Zero emission/energy building
ZEB-COM	ZEB level (C = construction; O = operation; M = materials)
ZEB-lab	Zero Emission Building Laboratory
ZEN	Zero emission/energy neighbourhood
A_m	Maximum performance of design m across all scenarios
B_m	Minimum performance of design m across all scenarios
C_n	Minimum performance of each scenario
C_p	Specific heat capacity
$KPI_{i,rel}$	Relative performance for indicator i
$KPI_{i,m}$	Robustness margin for indicator i
$KPI_{n,m}$	Performance of design m across scenario n
$R_{n,m}$	Performance regret of design m across scenario n

Appendix A

Table A1. Finding the maximum and minimum performance of a design across scenarios and best performance for designs and scenarios [21].

Design	**Scenarios**					**Max and Min Performance Across Scenarios**	
	S_1	**S_2**	...	**S_i**	**S_n**	**Maximum Performance (A)**	**Minimum Performance (B)**
D_1	KPI_{11}	KPI_{21}	...	KPI_{i1}	KPI_{n1}	A_1 = max (KPI_{11}, ... , KPI_{n1})	B_1 = min (KPI_{11}, ... , KPI_{n1})
D_2	KPI_{12}	KPI_{22}	...	KPI_{i2}	KPI_{n2}	A_2	B_2
...			...				
D_i	KPI_{1i}	KPI_{2i}	...	KPI_{ii}	KPI_{ni}	A_i	B_i
D_m	KPI_{1m}	KPI_{2m}	...	KPI_{im}	KPI_{nm}	A_m	B_m
Minimum performance for each scenario (C)	C_1 = min (KPI_{11}, ... , KPI_{1m})	C_2	...	C_i	C_n		
Best performance of all designs across all scenarios						D = min(B) = min(C)	

Table A2. Calculation of performance regret of designs across all scenarios [21].

Designs	Performance Regret (R)			
	Scenarios			
	S_1	S_2	...	S_n
D_1	R_{11} = KPI_{11}- C_1	R_{21} = KPI_{21}- C_2	...	R_{n1} = KPI_{n1}- C_n
D_2	R_{12} = KPI_{12}- C_1	R_{22} = KPI_{22}- C_2	...	R_{n2} = KPI_{n2}- C_n
...			...	
D_i	R_{1i} = KPI_{1i}- C_1	R_{2i} = KPI_{2i}- C_2	...	R_{ni} = KPI_{ni}- C_n
D_m	R_{1m} = KPI_{1m}- C_1	R_{2m} = KPI_{2m}- C_2	...	R_{nm} = KPI_{nm}- C_n

Table A3. Main envelope parameters for the case study building.

Design Parameters	Value	Note
U-value, external walls	0.15 W/(m^2K)	Wooden frame with 300 mm mineral wool insulation
U-value, windows/door	0.77 W/(m^2K)	Triple glazed with argon filling and wood frame
Solar factor, g-value, windows	0.53	
Visible transmittance, T-vis, windows	0.71	
U-value, roof	0.09 W/(m^2K)	Wooden structure with 450 mm mineral wool insulation
U-value, slab on ground	0.10 W/(m^2K)	Concrete slab on 250 mm of EPS insulation. Equivalent U-value for ground transmission
Normalised thermal bridge	0.04 W/(m^2K)	
Air leakage at 50 Pa	0.3 h^{-1}	
Window-to-wall ratio	27%	

Table A4. Main building systems' parameters for the case study building.

Design Parameters	Value	Note
Heat pump, COP	3.8	Air-to-water heat pump
Heat pump, total heating capacity	30 kW	
Heating set-point	21 °C 07:00–17:00 Monday-Friday, occupied building 20 °C 17:00–24:00 Monday-Friday, non-occupied building; 15 °C 22:00–07:00 every day	
Heating distribution system (supply/return temperatures)	47/35 °C	Waterborne radiator system
Cooling set-point	24 °C	
Ventilation supply airflow rates	2.5 L/s/m^2	
Ventilation, supply air temperature	17–24 °C	Based on the exhaust air temp.
Ventilation, specific fan power	1 kW/m^3/s °C	
Ventilation, heat recovery efficiency	85%	Rotary heat exchanger
DHW, average hot water use	5 kWh/m^2/year	
PV façade, area	502 m^2	
PV roof, area	456 m^2	
PV façade, average efficiency	16.9%	Monocrystalline silicon
PV roof, average efficiency	21.5%	Monocrystalline silicon
PV facade, installed capacity	83 kWp	
PV roof, installed capacity	98 kWp	

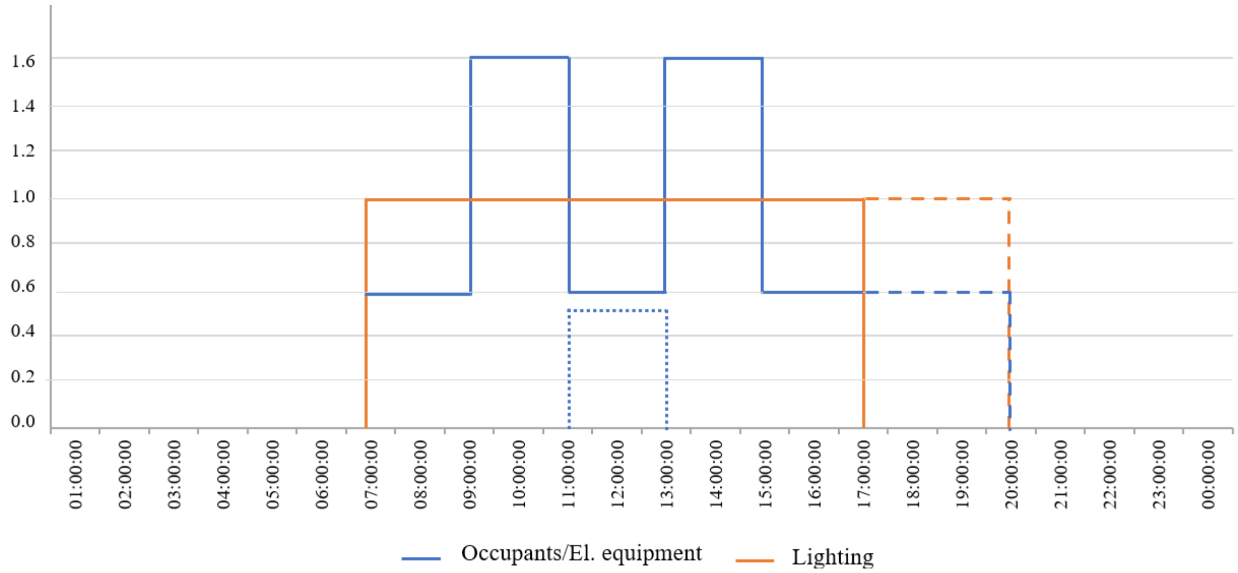

Figure A1. Profile schedules used for occupancy, electric equipment, and lighting in the analysed scenarios. * The dashed blue and orange lines denote scenarios 2, 3, 7, and 8, which imply a longer stay of occupants in specific rooms. ** The dotted blue line denotes the occupation profile for the canteen, which is the only zone whose occupation differs from the rest of the modelled zones.

Table A5. Number of occupants set in the models for all rooms, with the profile schedules shown in Figure A1.

Modelled Building Zones	Number of Occupants
Ground floor south, canteen	78
Ground floor, middle zone, auxiliary	1
Ground floor, north zone, auxiliary	1
1st floor south, Tween room 1, working zone	7
1st floor south, Tween room 1, working zone	7
1st floor south, middle zone, auxiliary/meeting	1
1st floor north, working zone	9
1st floor north, auxiliary/lobby	2
2nd floor south, working zone	8
2nd floor south, meeting room 1	3
2nd floor south, meeting room 2	1
2nd floor middle, auxiliary/meeting	3
2nd floor north, working zone	12
2nd floor north, auxiliary/lobby	2
3rd floor north, teaching room	28
3rd floor north, auxiliary/meeting	15
3rd floor middle, auxiliary	0
3rd floor south, auxiliary	0
Secondary stairway	0

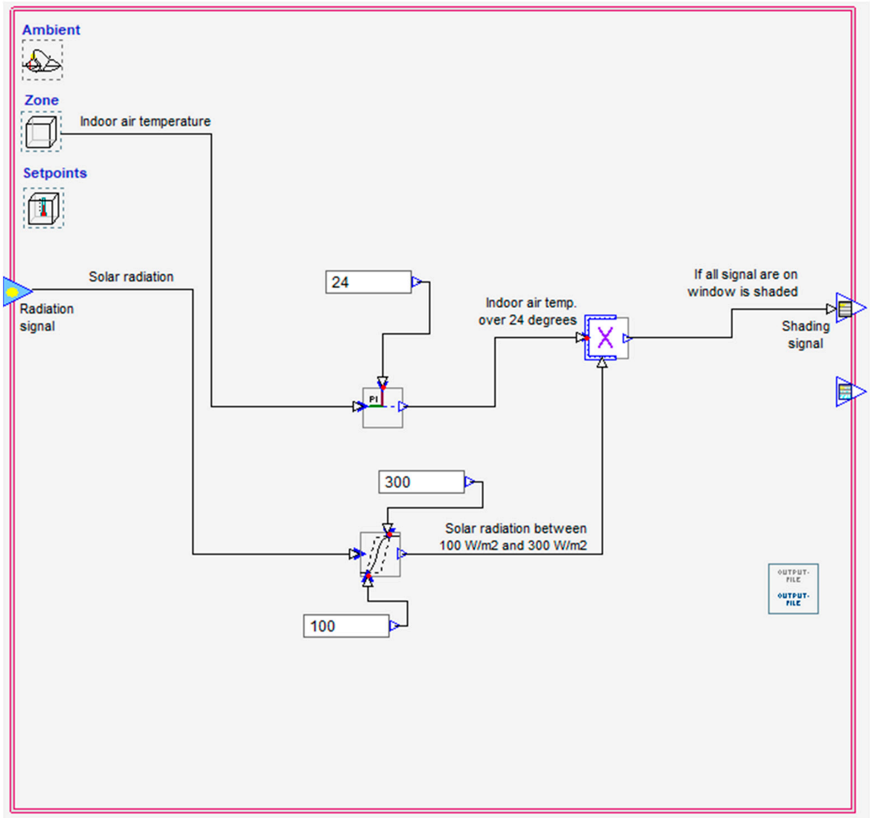

Figure A2. Control macro used for EC windows in design 4.

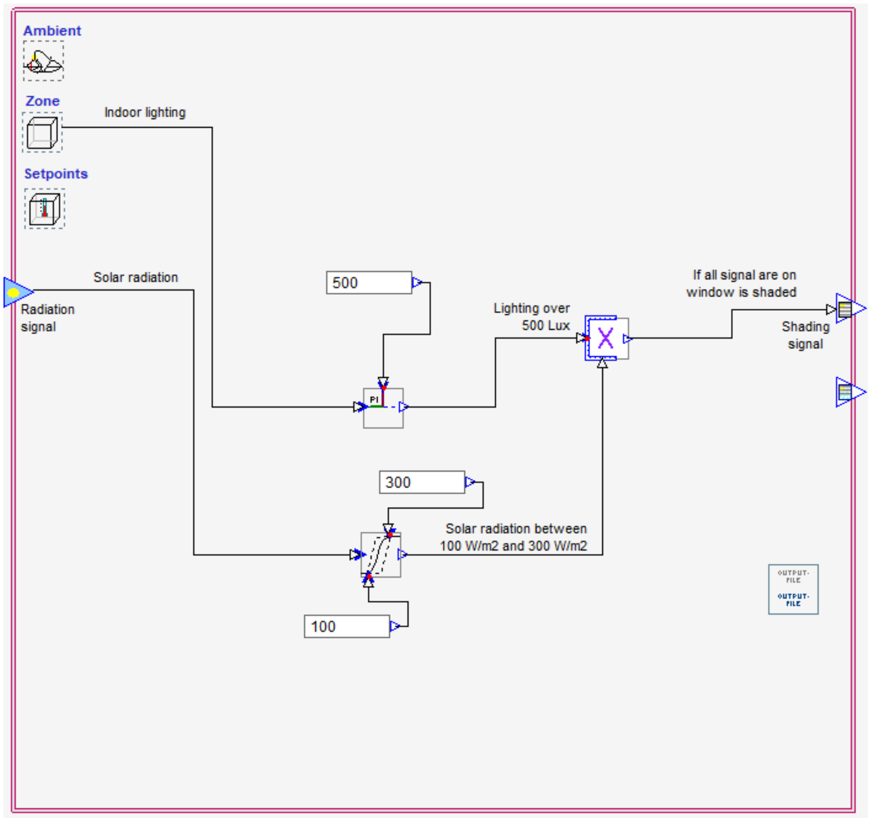

Figure A3. Control macro used for EC windows in design 5.

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