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A methodology for performance robustness assessment of low-energy buildings using scenario analysis

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HIGHLIGHTS

- A novel methodology for performance robustness assessment is proposed.
- Multi-criteria assessment is carried out using predicted performance and robustness.
- The minimax regret method is used to identify robust designs.
- A multi-criteria decision making strategy is implemented to select robust designs.

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ABSTRACT

Uncertainties in building operation and external factors such as occupant behavior, climate change, policy changes etc. impact building performance, resulting in possible performance deviation during operation compared to the predicted performance in the design phase. Multiple low-energy building configurations can lead to similar optimal performance under deterministic conditions, but can have different magnitudes of performance deviation under these uncertainties. Low-energy buildings must be robust so that these uncertainties do not result in significant variations in energy use, cost and comfort. However, these uncertainties are rarely considered in the design of low-energy buildings and hence, the decision making process may result in designs that are sensitive to uncertainties and might not perform as intended. Therefore, to reduce this sensitivity, performance robustness assessment of low-energy buildings considering uncertainties should be assessed in the design phase. The probability of occurrences of these uncertainties are usually unknown and hence, scenarios are essential to assess the performance robustness of buildings. Therefore, a non-probabilistic robustness assessment methodology, based on scenario analysis, is developed to identify robust designs. Maximum performance regret calculated using the minimax regret method is used as the measure of performance robustness. In this approach, the preferred robust design is based on optimal performance and performance robustness.

The proposed methodology is demonstrated using a case study with a policymaker as the decision maker. The proposed methodology can be used by designers and consultants to aid decision makers in the design phase to identify robust low-energy building designs that deliver preferred performance in the future operation.

1. Introduction

Energy efficiency and CO_2 emission reductions in buildings are typically achieved by improving building insulation levels, using energy efficient technologies and integrating renewable energy technologies in the built environment [1–3]. Considering the high economic efforts required for the implementation of these measures in the built environment, it is important to ensure that these measures deliver the preferred performance over the building's life span. However, in conventional design practice, building performance is predicted based on a set of assumptions about building operation. Many uncertainties arise in the operation of a building such as household size and their corresponding behavior and external factors, such as climate change and policy changes. These uncertainties in building operation, climate change and policies may influence the building performance, which could cause variations in energy use, operational costs and comfort. The potential impact of these uncertainties is very high in low-energy buildings [4,5] resulting in possible deviation during operation compared to the predicted energy performance in the design phase [6], and could also lead to thermal comfort issues such as overheating [7–11]. These uncertainties are rarely considered in the design of low-energy buildings and hence, the decision making process may result in designs

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that are sensitive to uncertainties [12,13] and might not perform as intended. To ensure intended performance, oversized energy systems are typically used in conventional design practice, which require high investment and operating costs [14,15]. Therefore, robust designs are essential to deliver preferred performance [14–16] at low costs and to attain robust designs, performance robustness taking into account these uncertainties should be assessed and considered during the design phase [17]. Performance robustness, in this work, is defined as the ability of a building to maintain the preferred performance under uncertainties arising from the building's operation and from external conditions.

1.1. Performance robustness assessment based on scenario analysis

In the building context, performance robustness assessment approaches are broadly categorized in two types – the probabilistic approach [18–20], where probabilities of uncertainties are assumed to be known, and the non-probabilistic approach [21–23], where probabilities of uncertainties are unknown. In many cases, the designer has limited or no information about the probability of the occurrence of uncertain situations, and it is thus difficult to quantify the associated risks. For instance, in most cases it is unknown during the design phase what type of households will occupy the building over its life span and what their corresponding behavior will be. Similarly, large uncertainties are associated with climate change projections [24,25]. In addition, it is difficult to probabilistically define uncertainties in the future economy such as electricity prices and policy changes [22]. As such, one way to proceed is to use 'scenarios', which can be understood as formulated alternatives when probabilities of uncertainties are unknown [26,27] and can be used to integrate uncertainties into the performance robustness assessment [13,26]. Scenarios are used to present a range of possible alternatives so that the performance robustness of designs can be assessed based on how different designs perform in each of these alternatives [28]. For instance, using scenario analysis, the risk can be quantified based on an optimistic or a pessimistic approach using the best-case and the worst-case scenarios.

The non-probabilistic robustness assessment approach is typically used to identify robust designs through the use of scenarios. For instance, non-probabilistic decision rules have been implemented to identify robust building retrofits under technical and economic uncertainties by [22], and this research demonstrated that this approach was useful for scenario modelling and it allowed for easier identification of robust designs among other alternatives. Similarly, [21] carried out building performance robustness assessment considering scenarios dealing with uncertainties in user behavior. The preferred robust design using this method is more robust to user behavior but could result in very uncomfortable indoor temperatures, as observed in their previous study [29]. This overheating risk will be even higher in the future due to climate change [7,9,11,30] and hence, it is important to include uncertainties in climate change in the design process [31,32]. Climate change scenarios are included in performance robustness assessment by [11,23,33]. In the reported research, robustness assessment is carried out separately for user scenarios [21,23], technical and economic scenarios [22] and climate scenarios [11,23,33]. Furthermore, implemented robustness measures do not take all scenarios into account and the likely occurrence of any scenario is unknown in the future. In addition, a design that is robust to a scenario could be sensitive to other scenarios. As such, a performance robustness assessment considering all scenarios is essential. Different robustness assessment methods based on scenario analysis are compared to aid decision makers for selecting robust designs [34]. These methods include the max-min method, the best-case and worst-case method [13], and the minimax regret method [35] and it was found that the choice of a robustness assessment method heavily depends on the purpose and decision makers approach towards risk in decision making [34]. In this work, we implement a non-probabilistic robustness assessment approach based on scenario analysis that considers uncertainties in occupant behavior and external factors.

1.2. Scope of this article

It is clear from literature that there is a lack of a holistic methodology for performance robustness assessment considering future scenarios that aids decision makers in design decision support considering performance robustness among other performance indicators. In practice, the design decision making process is a complicated and difficult task, especially when it involves decision makers with multiple and conflicting performance requirements [36]. The difficulty of the decision making task increases significantly if uncertainties are also included, and this issue is rarely addressed in the building performance context [13]. It is important to assess robustness of designs considering multiple performance criteria under uncertainties arising from the building's operation (e.g. occupant behavior) and from external factors (e.g. weather conditions) in order to enhance confidence in design decisions [16]. Therefore, to bridge this methodological gap, this article proposes a computational methodology that integrates uncertainties in multi-criteria assessment using scenario analysis to quantify robustness and facilitate the selection of robust designs for decision makers. We implement multi-criteria performance assessment and multi-criteria decision making considering performance robustness and provide different methods of identifying robust designs using trade-off solutions and a multi-criteria decision making method. Furthermore, sensitivity analysis is carried out to identify the most influencing scenarios and to enable decision makers to take extra measures for reducing their influence. It is demonstrated how the proposed methodology can be used in the design process to identify robust designs and enhance design decision making. In this paper, the proposed methodology is applied to a case study for policymakers.

This paper is organized as follows. In Section 2, the steps of the proposed computational performance robustness assessment methodology are described. The minimax regret method used to identify robust designs in the present context is also discussed in Section 2. In Section 3, the proposed methodology is demonstrated using a case study for a policymaker as the decision maker. The details of design space, future scenarios and performance indicators for performance robustness assessment are described in this section. Multi-criteria assessment and multi-criteria decision making approaches to select robust designs for the policymaker are also discussed in this section. The practical use of the proposed methodology is discussed in Section 4. A summary of the methodology along with main conclusions are presented in Section 5.

2. Proposed computational performance robustness assessment methodology

2.1. Overview

The proposed computational performance robustness assessment methodology is shown in Fig. 1. Each step is described below and in further detail in the following subsections.

Step 1: Identify decision makers and based on decision maker's preferences define the following:

1a. Building design space
1b. Future scenarios
1c. Performance and robustness indicators

Step 2: Set up a building performance simulation model and simulate the performance of the design space for future scenarios with defined performance indicators.

Step 3: Multi-criteria performance assessment: Carry out performance assessment considering multiple performance indicators and