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Using sensitivity analysis to improve the efficiency of a Net-Zero Energy vaccine warehouse design

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ABSTRACT

A critical step in the design of a Net-Zero Energy building is the reduction of energy consumption, so that consumption can be cost-effectively offset by renewable energy production. In this paper, we present a method to inform the design of Net-Zero Energy buildings through the identification of influential energy efficiency measures. A regression-based global sensitivity analysis is used to quantify the relative importance of both individual design parameters and bilinear interactions between parameters. This allows for the identification of the specific two-way interactions between parameter pairs, rather than an evaluation of the influence of interactions for each parameter in a lumped manner as is commonly used in building performance simulation. The relative importance of both building control and architectural design parameters are assessed, and are used to help evaluate the importance of utilizing an integrated design method for reducing building energy consumption. The case-study building investigated is a primary vaccine warehouse, a vital part of the vaccine cold chain in the developing world. As this building type has not received adequate attention in the field of building performance simulation, this paper makes a significant contribution towards an improved understanding of the energy efficient design of these warehouses.

1. Introduction

The concept of the Net-Zero Energy building is a promising solution towards reducing the substantial energy consumption of our built environment. As a result, these sustainable buildings have recently begun to receive significant attention from the international community [1–3]. A vital step in the design process of a Net-Zero Energy facility is the reduction of the building energy consumption through the use of energy efficiency measures [4,5]. Building energy modeling can play a key role in the identification of potential energy efficiency measures, and can help to ensure that design decisions are informed by the impact that that they will have on the building energy consumption. However, while it is widely accepted that energy modeling is an integral component of any performance-based design process, it is often underutilized in design practice to help identify the most influential energy efficiency measures and in turn guide the focus of resources towards the most promising solution space.

The first way in which the utility of energy modeling is reduced in practice is the method by which it is applied. In a study of methodological approaches to designing environmentally sustainable buildings, Hansen and Knudstrup conclude that the most common way that energy modeling is implemented is by using a case-based approach [6]. In this type of approach, several design concepts are created and then energy modeling is used to help select the best solution, possibly with minor modifications. With this type of reactive approach, the ability of building simulation to inform design decisions is severely limited, as there is no way to exploit a greater understanding of how the design parameters impact energy consumption. An improved approach that generates such an understanding is the combined use of uncertainty and sensitivity analysis. Uncertainty analysis allows for the characterization of uncertainty in a model output as a result of variations in model inputs, and sensitivity analysis allows for the identification of the relative importance of each input in determining the output uncertainty. Together, these two complimentary analysis techniques can quantitatively inform a designer how each parameter under consideration will impact building energy consumption. This type of analysis is also highly valuable for informing analysis in later NZE design stages, such as cost-effectively optimizing

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renewable energy supply and building energy efficiency. The sensitivity analysis increases the effectiveness and efficiency of such optimizations, focusing designers on a select group of influential parameters.

Several previous studies in the literature advocate for the use of uncertainty and/or sensitivity analysis as a valuable method for informing the building design process [7–10]. Shen and Tzempelikos studied the relative importance of a variety of design parameters on the building thermal and lighting energy performance on private offices in Philadelphia [9]. The results of their sensitivity analysis indicate that window-to-floor ratio and glazing type are the driving parameters in determining total energy consumption for all tested orientations except when the office faces south. Hygh et al. used a regression-based sensitivity analysis to investigate the annual energy consumption of an office building across five climate zones in the US [10]. The results of their study suggest that a multivariate regression model can be used as a suitable substitute for running numerous ad hoc building models during early design. As a result, both the sensitivity analysis formed from the regression model and the model itself can be used to help guide the design of the facility early in the process. While studies such as these show the value of sensitivity analysis in theory for prioritizing energy efficiency measures, Attia et al. examined the effectiveness of sensitivity analysis for informing Net-Zero Energy design in practice [11]. This was done through focus group experiments with architectural engineers, professors, and students. They found that for the architectural engineers, the use of building performance simulation coupled with sensitivity analysis reduced the energy consumption of all proposed designs by an average of 48%, as compared to designs in which the groups were not given any building performance simulation tools. This supports the value of building performance simulation coupled with sensitivity analysis not only in theory, but also in practice.

A second limitation of current energy modeling methods is the design space that is analyzed. In the design of a new building, the common impression exists that the most important characteristics for determining its energy efficiency are the physical design parameters such as the insulation thickness and window glazing properties [12]. However, several recent studies emphasize that building operational control variables, such as temperature set-points, can also have a substantial impact on energy consumption [12–14]. Wang et al. [13] investigated the impact of changes in operations-related variables including HVAC controls, lighting controls, and plug loads on the energy consumption of an office building across four US climate zones. The results of the analysis indicate that the HVAC controls, such as temperature set-points, are highly influential and can increase the building energy consumption by as much as 70%. Ruiz et al. compared the relative importance of uncertainty in several different types of variables, including physical design parameters and operational variables, on the energy consumption of an office building in several European climates [14]. They determined that the heating temperature set-point is the third most influential parameter for determining the fuel consumption of the building in Lisbon, with only the window and wall U-Values being more significant. Studies such as these support the analysis of building control parameters during design, and show that ignoring variation in this parameter type can neglect potentially large energy savings.

Unlike physical design parameters, building operational control variables can be actively changed during the life stages of the building post construction, such as during commissioning, operations, and maintenance. For instance, a study conducted on 20 daylit spaces in the Midwest found considerable discrepancies between how the spaces were designed to function, and how they in fact functioned as a result of improper commissioning [15]. By re-commissioning the systems, the authors were able to improve the median energy savings of the systems from 23% to 63%, as compared to using no daylighting. A substantial variation in building energy consumption as a result of changes in building control parameters emphasizes the importance of an integrated design method in producing a Net-Zero Energy building. In an integrated design method, the personnel responsible for the building post construction are actively involved in the building design process [16], including individuals such as the building manager and the building owner. The inclusion of these individuals allows for them to buy-in to the performance goals of the project, in order to help increase the chances that the building will be commissioned and maintained as designed.

This paper proposes an improved method to quantify the impacts of a large number of design parameters on building energy consumption, an integral part of the Net-Zero Energy building design process. A Monte Carlo-based uncertainty and sensitivity analysis is used to quantify the relative importance of 31 architectural design and 13 building control parameters. Through the use of a multivariate regression including bilinear terms, the relative importance of both individual parameters and interactions between parameter pairs is quantified. While main effects regressions are commonly used for sensitivity analysis [10,11,17], no previous sensitivity analyses including bilinear interactions were found in the building performance simulation literature. It should be noted that though previous regression-based analyses in building performance analysis have included interaction terms [10,18], these did not include bilinear interaction terms in the regression from which sensitivity indices are calculated. The inclusion of bilinear interaction terms allows the design team to gain an improved understanding of the influential energy efficiency measures, as the analysis indicates not only whether interactions are important, but which specific ones are influential.

The proposed method is applied to the case study of a primary vaccine storage warehouse, a key component of the vaccine supply chain in developing countries [19]. As an extensive set of building control and architectural design parameters is studied, this analysis allows for an assessment of the relative importance of an integrated design method for this building type. The primary vaccine warehouse is a building type which has received minimal attention in the field of building performance simulation, as the only two previous studies that examine this building type [20,21], were conducted as part of the same project as the research in this paper. Therefore, this study contributes to both the building performance simulation and global health domains, as the results can be used to help inform the design of energy efficient primary vaccine warehouses. The demanding design environment of the developing world highlights the importance of using building energy modeling to inform the selection of energy efficiency measures. Due to the inherent resource limitations of working within this context, it is imperative that the available resources are focused on the most promising means for reducing building energy consumption.

2. Methodology

2.1. Outline of methodology

The relative importance of the design parameters for a primary vaccine warehouse building type was investigated through a case study method. This case study used the recently drafted layout submitted to the Tunisian Ministry of Health for a new national vaccine warehouse. Fig. 1 shows the framework of the methodology implemented in this paper. It was assumed that the draft layout is representative of the primary vaccine warehouse building type, and so was used as the preliminary building layout. From this layout, an