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Probabilistic design and analysis of building performances: Methodology and application example

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ABSTRACT

Both building performance analysis and multi-criteria performance optimisation often use deterministic simulations. Since many influencing parameters are generally inherently uncertain, this may lead to unreliable predictions of design impact. Therefore, this paper proposes a probabilistic analysis and design method to incorporate these uncertainties. The embedded Monte Carlo based uncertainty and sensitivity analyses investigate the output distributions. To greatly reduce computational efforts, meta-models can be incorporated, replacing the original model. Additionally, multi-layered sampling schemes are used to subject all design options to the same uncertainties and to check the validity of optimisation results for potential scenarios. Since reliability is a key aspect in this methodology, the paper also focuses on output convergence and method reliability.

To optimise both average performances and spread, effectiveness ε and robustness R_P are introduced as output uncertainty indicators, inspired by robust design. Here, effectiveness is defined as the ability of the design option to optimise the performance, while robustness is defined as the ability to stabilise this performance for the entire range of input uncertainties.

The successive methodology steps are explained using a simplified application example.

1. Introduction

Building performance analysis and design targets the examination and optimisation of the building performances. Analyses typically assess performances of a known construction for comparison with performance criteria, while designs do the same for a number of potential solutions in a search for the optimal solution. For example, the analysis of Abuku et al. [1] examines the impact of wind-driven rain on mould growth risk, indoor climate and energy consumption in historic brick buildings, while the design of Verbeeck and Hens [2] minimises energy use, environmental impact and financial costs for extremely low-energy dwellings.

Both studies, and many others with them, make use of deterministic simulations, hence neglecting the inherent variability and uncertainty of geometries and configurations, of material and component properties, of internal loads and boundary conditions, of economical and environmental parameters,. . . A deterministic approach may hence lead to inconclusive analyses and non-optimal designs, and a probabilistic methodology is therefore to be preferred. And while a lot of work has already been done with respect to probabilistic analysis and design in building performance assessment, much of this has focused on specific and delimited issues. The current state-of-the-art thus remains highly fragmented. This article therefore aims at merging that fragmented knowledge into a structured and comprehensive methodology for probabilistic analysis and design in building performance assessment.

Section 2 explains the background and objectives of this paper. The global methodology is introduced in Section 3 and extensively explained and illustrated in Section 5. As an example, the net present cost of a low-energy dwelling is optimised for several scenarios to obtain a robust cost-effective dwelling. This case study is described in Section 4. Finally, Section 6 discusses further research opportunities.

2. Background and objectives

The methodology for probabilistic analysis and design in this paper is built on several state-of-the-art principles to calculate and analyse the output uncertainty. Each of these principles is briefly explained in this section.

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2.1. Monte-Carlo-based techniques

Probabilistic procedures have been introduced into building physics over the last decades, often inspired by other engineering disciplines [3]. Two fundamental aspects are *uncertainty quantification* and *sensitivity analysis*, to transform the variabilities of the input to the uncertainties of the output and to identify these input parameters that are most dominant in this transformation. Due to the complex, non-linear and transient character of most building performance problems, Monte-Carlo-based techniques are often preferred for these goals.

Since the first steps of Lomas and Eppel [4] and Macdonald and Strachan [5] in probabilistic analysis in thermal building simulation, a huge progress has already been made in terms of time efficiency. Output convergence and sampling efficiency have been studied, resulting in quasi-Monte Carlo sampling schemes instead of random sampling as generally described by Janssen [6] and illustrated by Burhenne et al. [7]. Furthermore, Eisenhower et al. [8] introduced the use of *meta-models* into building energy optimisation. Meta-modelling allows replacing a time-inefficient model by a model with a highly reduced calculation time.

However, in the probabilistic studies mentioned above, the input parameter variations were often arbitrarily chosen, what may of course influence the output uncertainty as well. Selecting the most dominant parameters with sensitivity analysis, eases collecting the input data. If a sufficient number of measurements is available, the input distributions of these parameters can be determined based on Bayesian calibration [9,10]. Unfortunately, this is usually not the case. Most dominant parameter distributions are thus usually chosen as accurately as possible.

2.2. Probabilistic output analysis

As a consequence of the above-mentioned probabilistic procedures, the resulting building performance indicators in probabilistic analysis or design are no longer single-valued, but are to be evaluated based on their probability density distribution. Booth and Choudhary [10] visually compared output distributions for some refurbishment measures in order to decide how to cost-effectively retrofit the UK housing stock. Although they describe the overall methodology extensively, the question how probabilistic output distributions should be numerically evaluated and optimised in probabilistic design is not answered.

This in turn introduced considerations of robustness into building performance design, to allow not only an assessment of the mean performance but also of its possible spread around that mean. In *robust design*, mean performance is indeed optimised while spread is minimised [11], resulting in a design that can resist the influence of uncontrollable factors as good as possible [12]. In previous studies such as Hoes et al. [13], robustness was however only examined after optimal design solutions were selected, partially missing the benefits.

2.3. Paper objectives

Literature shows that much effort has been put in efficiently calculating output uncertainties in probabilistic analysis and some in using these uncertainties for decision making in probabilistic design; however, this is still highly fragmented. Taking into account the described achievements and shortcomings, this paper proposes an efficient way to combine and improve these elements in an overall applicable, structured and comprehensive methodology for probabilistic analysis and design to quantify performance spread and to compare several design options.

First of all, all design options are combined with the same uncertain parameter values, as is done in robust design [14] and for example also by Booth and Choudhary [10]. Furthermore, in many analyses or designs the explicit evaluation of the result for different scenarios – be they defined based on user behaviour, economic parameters, climate change, . . . – may be wanted as suggested by Hopfe and Hensen [15]. This asks for the formulation and application of Monte Carlo multi-layered uncertainty schemes.

To enable numerical evaluation of these schemes, *effectiveness* and *robustness* indicators are proposed, inspired by robust design. Effectiveness is defined as the ability of the design option to optimise the performance, while robustness is defined as the ability to stabilise this performance for the entire range of input uncertainties.

As the proposed methodology may rapidly result in a high computational cost, even for very time-efficient models as those in referred literature, it is preferable to replace the original model with a simpler and much faster meta-model [8]. Furthermore, both convergence and sampling efficiency are crucial to overcome time issues while obtaining reliable results [6], as well as sensitivity analysis to select and determine input parameter distributions based on measurements or expertise [10].

In literature, probabilistic design seems to be more challenging and applications are less widespread. The major advance of the methodology proposed in this paper is thus in terms of probabilistic design, whereas probabilistic analysis is seen as a special application.

3. Global methodology

To reliably incorporate uncertainties in all aspects of performance analysis and design, this paper proposes a comprehensive probabilistic methodology, of which the main ideas were introduced in Section 2.3. Four main steps can be distinguished (see Fig. 1), of which only the main aspects are discussed here, while they are explained and illustrated in more detail in the referred subsections of Section 5. Following some ideas on robustness from manufacturing design in the output evaluation, effectiveness and robustness indicators are introduced.

3.1. Methodology overview

The probabilistic design methodology consists of four steps (see Fig. 1): preprocessing, preliminary screening, updating and probabilistic design. These steps analogously select the input parameters and distributions (step 1), determine the most dominant input parameters and develop a meta-model to improve calculation efficiency (step 2), update the input distributions (step 3), and finally perform the actual probabilistic design (step 4).

Contributing input parameters of this probabilistic design can be divided into three categories. *Design parameters*, such as the preferred air tightness or thermal resistance, are fully controllable. They are the unknown parameters in the design process, but once a *design option* is selected, the parameter values are known. Inherently *uncertain parameters*, such as workmanship and user behaviour, are completely uncontrollable by the designer as their values are neither known in the design process nor after, but they can significantly influence the design performance. Finally, *scenario parameters* are inherently uncertain parameters dealing with potential future scenarios, such as economic or climatic evolutions, for which an explicit evaluation is wanted.

The probabilistic design (step 4) is therefore performed through a Monte Carlo loop with a multi-layered sampling scheme which enables sorting parameters by their conceptual meaning. By ascribing these parameter categories to a different layer in a multi-layered sampling scheme as shown in Fig. 2, all design options are subjected to the same uncertainties and a direct comparison for